USE OF ER12 HYDROCARBON REFRIGERANT IN AUTOMOBILE AIR-CONDITIONERS
SAFETY REPORT

PREPARED FOR

BORAL ENERGY

PREPARED BY

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Title:
Boral Energy
Use of ER12 Hydrocarbon Refrigerant in Automobile Air-Conditioners
Safety Report

QA Verified: J. Brini		**Date:** 5.09.99

EXECUTIVE SUMMARY

Esanty Refrigerants, a division of Boral Energy, has developed and marketed a hydrocarbon refrigerant named ER12. This refrigerant has been used successfully in automobile air-conditioners, in Victoria since 1995, and in South Australia, since 1997.

Although allowed in Victoria and South Australia, use of hydrocarbon refrigerants for automobile air-conditioning is not permitted under the Dangerous Goods Regulations in New South Wales, and needs formal approval from the Department of Mines and Energy in Queensland. Esanty has previously requested approval to supply ER12 for automotive use in Queensland, but permission was refused on the grounds of inadequacies in the safety report submitted with the request.

Boral Energy commissioned Granherne Pty Ltd to undertake a study to:

- independently assess whether it is safe to use ER12 refrigerant in an automobile air-conditioning system;
- identify risk management measures for implementation by Boral Energy; and
- prepare a more comprehensive and traceable Safety Report with risk assessment to Boral Energy management that will satisfy the regulatory requirements in the various States in the Commonwealth.

This Safety Report addresses the hazards associated with automotive hydrocarbon refrigerants through the product life-cycle, with an emphasis on the hazards of refrigerant leaks in vehicles, and on the hazards of gas charging and disposal in a workshop. The study included detailed analysis of the consequences of refrigerant leaks in the engine bay or passenger compartment of a vehicle (either in motion or stationary), the frequency with which such an event may occur, and the resultant risk to vehicle occupants. This Safety Report also addresses the issues of safety management and training of personnel in the safe storage and handling of ER12 in workshops.

The study focused on the use of ER12 as a replacement for HFC refrigerant in existing designs of automobile air-conditioning systems. Some hardware design changes were reviewed as part of the assessment, but a detailed analysis was not considered.

A systematic identification of the hazards of ER12 was undertaken covering the life cycle activities of refrigerant manufacture, refrigerant use and handling in the workshop, use of ER12 in automobile air-conditioning system, and disposal of the refrigerant. A number of hazard identification techniques were used. These included:

- Failure Modes and Effects Analysis;
- scenario based hazard identification;
- consultations with government, industry and motorist association bodies;

- surveys of workshops in various States involved with automobile air-conditioning, using both hydrocarbon and non-hydrocarbon refrigerants;
- physical inspection of air-conditioning components with accredited air-conditioning mechanics; and
- a comprehensive review of available published literature.

Where there was inadequate data available to support the study, experimental work was undertaken throughout the 14-month course of the project. Extensive tracer gas experiments were conducted along with selected experiments with ER12, to determine the behaviour of gas released inside a vehicle passenger compartment. ER12 experiments covered a range of credible hole sizes, and various operating modes of the automobile air-conditioning system.

A combined mathematical model of gas release and gas mixing was developed, using established formulae and correlations based on the experimental results. This model was used to predict the concentration-time profile in a vehicle passenger cabin under a wide range of conditions, including a decaying gas release rate representing refrigerant system depressurisation following a leak.

The following conclusions were reached from the experimental data and modelling of gas mixing in the passenger cabin:

- Under all conditions, good mixing of the vapour occurs within the passenger compartment.
- For all the event scenarios analysed, the refrigerant vapour concentration in the passenger cabin would not reach the lower flammability limit (LFL).
- The only conditions under which a refrigerant-air mixture would reach 50% of LFL were a large leak into the passenger cabin of a vehicle parked in an enclosure, and a catastrophic leak into the passenger cabin when the vehicle vents are closed (i.e. air-recirculation mode).

Analysis of potential fires and explosions in the passenger cabin and in the engine bay was undertaken using established consequence analysis tools. To maintain conservatism in the analysis, an average vapour concentration of 50% LFL was taken as the impairment criteria for ignition, rather than LFL concentration. This allowed for potential areas of incomplete mixing in the cabin, where the vapour concentration could exceed 50% LFL.

The following conclusions were reached from the fire and explosion analysis:

- For the hazardous scenarios analysed, the ignition of a potential release of ER12 refrigerant in the passenger cabin is likely to result in a flash fire rather than an explosion, as near stoichiometric concentrations are never reached.

- The ignition of vapour would not result in fatality to driver or passenger.

- The duration of the flashfire was of the order of 0.5 second, and therefore an ignition of vapour would not result in second-degree burns to driver or passenger, but may result in first-degree burns.

- The pressure rise resulting from the ignition of refrigerant release in the engine bay is vented through the opening at the floor of the engine bay, and hence the pressure rise would be very low, and insufficient to cause significant secondary damage.

- The ignition of a vapour release in the engine bay would have no adverse effect on persons in the passenger cabin.

The above results were found to be consistent with similar independent studies carried out in the USA.

Those scenarios that were identified to have potential adverse effect on people were carried forward for quantitative risk assessment. This required estimation of the frequency of refrigerant releases. The latter data was statistically estimated from data gathered from literature reviews, and from a survey of 68 automobile workshops in four Australian States, in order obtain results with statistical validity.

The potential for ignition of leaked ER12 refrigerant was determined by actual measurement of the voltage, current and inductance of a number of automotive electrical components, using the facilities of the University of New South Wales. Components were eliminated from further consideration if they did not carry the current, or store the energy, required to ignite the gas. Remaining components, i.e. those theoretically capable of igniting a release of ER12, were reviewed with respect to their potential for exposure to the released gas. Other research studies have demonstrated that neither lit cigarettes nor the in-car cigarette lighter can ignite a flammable mixture of hydrocarbon vapour.

The Event Tree Analysis technique was used to calculate the overall risk of injury to a vehicle occupant from use of ER12 refrigerant. The frequency of each initiating event, and other data required for the event tree analysis, were obtained wherever possible from Australian sources. Sensitivity analysis of critical parameters was also carried out.

The maximum risk of injury from the use of ER12 refrigerant in automobile air-conditioning unit was calculated to be 1 chance in 4 million vehicle-years. The risk ranged from 1 in 4-million vehicle-years to 1 in 21 million vehicle-years, depending on the size of the motor vehicle, and the design of the air-conditioning system.

Since the study found that there is no risk of fatality, it was not considered appropriate either to postulate fatality risk criteria, or compare with any existing fatality risk criteria. However, the injury risk was compared with those arising from motor vehicle accidents in Australia.

It was found that the risk of injury from the use of ER12 was approximately 7,000 times less than the risk of serious injury from motor vehicle accidents.

It was concluded that the risk from the use of ER12 is low, and very much lower than the risks faced by drivers and passengers in everyday use of vehicles on the road.

In order to ensure the integrity of the equipment in service, and to safeguard the accredited mechanic handling the refrigerant in the workshop or wrecking yard, a number of safety management procedures were identified. It is recommended that Boral Energy management implement these recommendations to improve overall safety of the use of ER12 in automobile air-conditioning systems.

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ABBREVIATIONS

Abbreviation	Explanation
(s)	second
AC	Air-conditioning
ACH	Air Changes per Hour
ADL	Arthur D. Little Inc.
AIRAH	Australian Institute of Refrigeration, Air-conditioning and Heating Inc.
Amps	Amperes
AS	Australian Standard
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
atm	atmospheres
BS	British Standard
CFC	Chlorofluorocarbon
cm	centimetre
CMR	Christian Michelsen Research (Norway)
Concn	concentration
DME	Department of Mines and Energy (Queensland)
DOE	Department of Energy (WA)
E	stored energy
EB	Engine Bay
EPA	Environment Protection Authority (Federal)
ER12	Trading name for Esanty Refrigerant
ETA	Event Tree Analysis
FMEA	Failure Modes and Effects Analysis
FORS	Federal Office of Road Safety
g	grams
GRI	Gas Research Institute (USA)
GWP	Global Warming Potential
HAZID	Hazard Identification
HAZOP	Hazard and Operability Study
HC	Hydrocarbon

Abbreviation	Explanation
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
HNBR	Nitro-butyl Rubber
hr	hour
HSE	Health and Safety Executive, UK
I	current
J	Joule
kg	kilogram
kg/kmol	kilograms per kilomole
kg/s	kilograms per second
kHz	kilo Hertz
kPa	kilo-Pascals
kPag	kilo-Pascals (gauge)
L	Litre, Inductance
LCD	Liquid Crystal Display
LFL	Lower Flammability Limit
LPG	Liquefied Petroleum Gas
m^3	cubic metres
m^3/h	cubic metres per hour
m^3/s	cubic metres per second
mA	milliAmpere
MFESD	Metropolitan Fire and Emergency Services Board (Victoria)
mH	milliHenry
mJ	milliJoules
mm	millimetres
MSDS	Material Safety Data Sheet
MVAC	Motor Vehicle and Air-Conditioning
MVRIC	Motor Vehicle Repair Industry Council
NATA	National Association of Testing Authorities
°C	degrees Celsius
ODP	Ozone Depletion Potential
PAG	Polyalkylene glycol
PC	Passenger Cabin

Abbreviation	**Explanation**
ppm	parts per million
PSH	pressure switch high
QLD	Queensland
QRA	Quantitative Risk Assessment
R	resistance
r/h	right hand
R12	CFC Refrigerant
R134a	HFC Refrigerant
R22	HCFC Refrigerant
R290	Refrigerant notation for Propane
R600a	Refrigerant notation for Iso-butane
RAA	Royal Automotive Association
RAC	Royal Automotive Club
RAPID	UNSW Research and Professional Information Delivery
SAA	Standards Association of Australia
SMS	Safety Management System
TEAP	Technical and Economics Assessment Panel
TOC	Technical Option Committee
Tx Valve	Thermostatic Expansion Valve
UFL	Upper Flammability Limit
UNEP	United Nations Environment Program
UNSW	University of New South Wales
US EPA	United States Environment Protection Agency
V	Volts
yr	year

GLOSSARY

1E-06	1×10^{-6}. Exponential notation, meaning 1 chance in 1 million.
Accident Event	A specific event or sequence of events that have a significant unwanted and unintended impact on the safety or health of people, on property or on the environment.
Auto-ignition Temperature	The temperature at which a flammable vapour, when released to air, can ignite spontaneously when within flammability limits, without the aid of an external ignition source.
Failure Modes and Effects Analysis	A technique used in hazard identification. It is a tabulation of each piece of equipment, identification of its failure modes, and the effects of such failures in terms of safety and operability of the unit.
Flammability Limit	A flammable gas can only burn in air within a narrow range of concentrations. This range is known as the flammability range. The lower and upper values of this range are knows as the lower and upper flammability limits. For ER12, these limits are 1.9% and 9.5% by volume in air.
Frequency	The likelihood of occurrences of an event within a defined time interval (usually one year).
Hazard	A ***Hazard*** is a ***potential*** source of serious harm to people, property or the environment.
Ignition Energy	The energy required to ignite a vapour-air mixture between the flammability limits. It is often expressed in milliJoules.
Quantitative Risk Assessment (QRA)	A structured method of quantifying the risks of a hazardous activity and using the results to make decisions through relative ranking, comparison with an Acceptance Criteria, if available, or value judgements.
Risk	***Risk*** is defined as the possibility of fatality, serious injury, damage to property or environmental damage created by the hazard. The magnitude of the risk is a function of the probability of the unwanted incident and the severity of its consequences. For example, if the likelihood of a major hydrocarbon release and fire is, say, one chance in one hundred thousand per year, and

the probability of a fatal injury due to that event is, say, one chance in ten, then the **risk** of fatality from the particular **hazard** is one in a million per year. The total risk is the sum of all risks from all identified hazards.

Risk is generally expressed per time unit, normally chosen as one year. Thus, risk is expressed as occurrence of the unwanted incident per year.

Stoichiometric	The chemical composition of a flammable vapour-air mixture, that would result in the total consumption of available air in the mixture for **complete** combustion of the vapour. The stoichiometric composition is generally mid-way between the lower and upper flammability limits.

1. INTRODUCTION

1.1 Background

1.1.1 Boral Energy and ER12 Refrigerant

Esanty Refrigerants (Esanty) has successfully developed and marketed an Australian hydrocarbon (HC) refrigerant product, named ER12, as an alternative to the hydrofluorocarbon (HFC) refrigerants. The latter is currently being used widely as a replacement for the chloroflurocarbon (CFC) refrigerants. The ER12 refrigerant has been used in automobile air-conditioners in Victoria, South Australia and Western Australia since 1997. In late 1997, Esanty became a division of Boral Energy, which is a Top 100 listed company with a global turnover of approximately A$5 billion.

1.1.2 Need for Safety Report

At the time of writing this Safety Report, the existing legislative framework in New South Wales and Queensland prevent the use of HC refrigerants in automobile air-conditioners.

In Queensland, its use requires an approval from the Chief Gas Examiner, Queensland Department of Mines and Energy, under Section 4(c) of Regulation 108A of the Queensland Gas Regulations 1989. (This Section is reproduced in **Appendix 15**). A submission had been made to Queensland Department of Minerals and Energy in 1997 (Ref.1), but consent was refused on the grounds of insufficient information on safety (Ref.2).

In New South Wales, the Dangerous Goods Regulation 1978, as amended in 1995, Clause 281A states that “a person must not put any liquefied flammable gas in the air-conditioning system of a motor vehicle”.

1.1.3 Safety Report Preparation

Granherne Pty Ltd (Granherne) has been commissioned by Boral Energy to prepare a detailed independent Safety Report on the use of ER12 refrigerant in automobile air-conditioners. The report was to be based on the previous submission in Queensland, the response of the Queensland government, consultations with government stakeholders and industry bodies, published results of earlier research in this area, and conduct additional research that proved necessary during the course of the work.

The objectives of the Safety Report are to:

- independently assess whether it is safe to use ER12 refrigerant in an automobile air conditioning system,

- identify risk management measures that will allow Boral Energy to ensure that the ER12 refrigerant product is handled in a safe manner,

- prepare a comprehensive and traceable Safety Report, including a quantitative risk analysis, for Boral Energy management, and

- prepare a document that will satisfy the regulatory requirements in the various States of Australia, in particular New South Wales and Queensland.

The study involved conducting a comprehensive hazard identification and risk assessment of the life cycle phases of hydrocarbon refrigerant ER12 for automobile air–conditioners. In preparing the Safety report, Granherne has conducted its own research and reviewed reports available in the public arena relating to the use of hydrocarbons and air-conditioning systems including:

- American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE);
- Arthur D. Little Inc. (ADL);
- Australian Institute of Refrigeration Air-conditioning and Heating Inc. (AIRAH);
- Christian Michelsen Research of Norway (CMR);
- Gas Research Institute (GRI);
- United Kingdom Health and Safety Executive UK (HSE);
- United States Environment Protection Agency (US EPA);
- Unisearch (research division of UNSW - electrical engineering); and
- University of New South Wales (UNSW).

Granherne also directly consulted with government agencies and motor vehicle associations for information including:

- Federal Environment Protection Authority (EPA);
- Federal Office of Road Safety (FORS);
- Queensland Department of Mines and Energy;
- Royal Automobile Association (RAA) of South Australia;
- Standards Australia;
- The Royal Automobile Club (RAC) of Western Australia;
- Victorian Metropolitan Fire and Emergency Services Board (MFESB); and
- Western Australian Department of Energy (DOE),

In addition Granherne also approached Australian motor vehicle manufacturers and air-conditioning specialists for input into the study.

It is expected this Safety Report will be submitted by Boral Energy to relevant regulatory authorities in the various States in the Commonwealth.

1.2 Scope and Objectives

1.2.1 Objective of Safety Report

The objectives of the Safety Report are to:

- independently assess whether it is safe to use ER12 refrigerant in an automobile air-conditioning system,
- identify risk management measures that will allow Boral Energy to ensure that the ER12 refrigerant product is handled in a safe manner,
- preparation of a comprehensive and traceable Safety Report with risk assessment to Boral Energy management, and
- prepare a document that will satisfy the regulatory requirements in the various States of Australia.

1.2.2 Scope of Safety Report

The scope of the Study Report has been broken into distinct and interlinking sections that covers the following:

Hazard Identification

- Comprehensive review of Esanty's previous submission to Queensland Department of Mines & Energy (Ref.1).
- Comprehensive review of the Queensland Gas Examiner's response, including the submissions received by the Gas Examiner from various Government agencies, industry and consumer associations (Ref.2).
- Review of available literature on the safety assessment of hydrocarbon refrigerants for automobile air-conditioning systems.
- Systematic identification of hazards in each stage of life cycle through workshops using the Failure Modes and Effects Analysis (FMEA) technique, Scenario Based Hazard Identification, consultations and surveys.

Life Cycle Considerations

- Identification of safety issues involving the life cycle of the ER12 refrigerant from:
  - manufacture and storage of ER12 refrigerant;
  - use of ER12 refrigerant in automobile air-conditioning system;
  - maintenance/ gas charging/ repairs; and
  - disposal of ER12 refrigerant.

Risk Assessment

- Quantification of potentially hazardous events involving ER12 refrigerant;
- Assessment of ignition potential;
- Estimation of refrigerant leak frequency data by consultations, surveys and data collection;
- Determination of hazardous event frequencies using the Event Tree Analysis (ETA) technique;
- Assessment of risk for each life cycle phase. Quantification of risk wherever possible;
- Evaluation of risk tolerability with reference to available risk criteria; and
- Identification of risk management measures where appropriate.

1.3 Structure of Safety Report

The structure of the Safety Report has been divided into six distinct parts as outlined in **Table 1.1**.

TABLE 1.1
STRUCTURE OF REPORT

Section	**Description**
Part I	***Automobile Air Conditioning System and ER12 Refrigerant***
2	A general description of the automobile refrigeration cycle and its components
3	A general introduction to the benefits of hydrocarbon refrigerant, particularly the environmental impacts. An introduction to Boral Energy. An overview of the physical properties of ER12 refrigerant
4	A discussion of the compatibility of ER12 refrigerant with automobile air conditioning components and lubricants

TABLE 1.1
STRUCTURE OF REPORT

5	An outline of the life cycle phases of the ER12 refrigerant, from manufacture, handling and use in automobiles, through to disposal
Part II	***Study Methodology***
6	An outline of the study methodology, together with a flowchart of the conduct of the Safety Case. Criteria used in the assessment. Discussions of the limitations and advantages of risk assessment
7	A summary and justification of the assumptions made in the assessment
Part III	***Hazard Identification and Leak Rates***
8	Results of formal Hazard Identification for ER12 automobile refrigeration, based upon findings from the FMEA, HAZID, consultations and surveys. List of potential hazardous scenarios to be investigated in the assessment
9	Basis for the assessed refrigerant leak sizes and corresponding leak rates
Part IV	***Hazard Consequence Assessment***
10	Introduction to the consequence assessment
11	Investigates the phenomena of mixing of leaked refrigerant within the passenger cabin, determines the refrigerant concentration profile and potential consequences
12	As section 11, for leaks in the engine bay
13	Identification of leak scenarios requiring risk assessment, based on the results of the consequence assessment
Part V	***Frequency Analysis and Risk Assessment***
14	Summary of the frequencies assigned to each event subject to risk assessment
15	Description of the risk assessment that has been performed
16	Presents risk management recommendations made to Boral Energy
Part VI	***Appendices***
1	Material Safety Data Sheet for ER12
2-4, 14-15	Appendices relating to Hazard Identification including the FMEA, HAZID, Study Assumptions, results of consultations and surveys are given
5-8	Detailed calculations relating to the consequence modelling of refrigerant releases into the passenger cabin and engine bay
9-10	Reports of experimental work conducted by Granherne on automobile ventilation rates, and tracer gas / ER12 leakage and mixing
11	Investigation of potential ignition sources in an automobile. This work was performed in conjunction with Unisearch
12-13	Frequency data for refrigerant leaks, collected from surveys and published literature
16	Detailed event trees used in the risk assessment. Results of "sensitivity" studies for the risk assessment
17	Granherne company background and resumes of the Granherne engineers involved in the work

1.4 Links to Issues Raised in Consultations

During the course of the 14 month long investigation, consultations were held with various government and industry stakeholders. The purpose of these consultations was to identify issues and concerns that should be addressed in the Safety Study.

Granherne has compiled these issues into **Table 1.2** and the appropriate cross-references to the report are provided for ease of identification.

TABLE 1.2
ISSUES RAISED IN CONSULTATION REQUIRED TO BE ADDRESSED IN STUDY

Topic	Issue Raised By	Description of Issue	Safety Report Section
Hazard Identification	Qld DME	Assessment of hazard and risk in all phases of life cycle of the refrigerant	Sections 8-15 and Appendices 2-13 and 15
	Qld DME	Systematic hazard identification using HAZOP and FMEA	Section 8 and Appendix 2
	Qld DME	Determine, where appropriate, of modifications that can be made to improve the intrinsic safety of the system	Sections 16
	RAA	Assessment should include the risk resulting from a leak into the passenger cabin when the vehicle is parked overnight	Sections 9,11 and 15 and Appendices 5-7, 11 and 15
Study Assumptions	Qld DME	All claims or assumptions that are made need to be substantiated	Section 7 and Appendix 4
Study Criteria	Qld DME	Define a criteria for a 'safe' system. Demonstrate that the proposal meets the criteria **Note:** A criteria for fatality is not defined as this Safety Report found that fatality consequence would not occur for the scenarios analysed (Sections 11 and 12). Frequency of injury consequence has been compared against the risk of serious injury or fatality from vehicle accidents. (Section16, Appendix 16)	Sections 11, 12 and 16 and Appendix 16
Compatibility of ER12 Refrigerant	Qld DME RAA	Effect of safety and reliability of system and components for change of refrigerant	Sections 4 and 14 and Appendices 2, 12, 13
Consequence Analysis	Qld DME	Good mixing of all gaseous components assumed by Dr Maclaine-Cross is questioned on the basis that testing of carbon dioxide concentration gas as it decays has not been adequately investigated. **Note:** This Safety Report has undertaken independent tracer gas experiments, and has measured the decay curve. Reproducible data has been obtained under planned experimental conditions. Good mixing is confirmed. (Appendix 10)	Section 11 and Appendix 10

TABLE 1.2
ISSUES RAISED IN CONSULTATION REQUIRED TO BE ADDRESSED IN STUDY

Topic	Issue Raised By	Description of Issue	Safety Report Section
Consequence Analysis	WA DOE RAA RAC	The release and mixing characteristics following a leak into the passenger cabin and to be clearly detailed	Section 11 and Appendix 10
	Qld DME	Assessment of the vulnerability of people who could be affected by an incident involving the refrigerant or air-conditioning system	Sections 11 and 12 and Appendices 7, 8 and 15
Ignition Potential	Qld DME WA DOE	Review of all electrical components have been stated to be ignition sources and determine potential ignition sources	Section 14 and Appendix 11
Frequency Assessment	Qld DME	Frequency of release should reflect AC usage and Australian conditions **Note**: Extensive Australian data has been collected in this Safety Report through surveys and interviews, as well as a parts count of the release sources in the refrigeration system. Appendix 12 and Sections 8 and 14	Sections 8 and 14 and Appendices 12-14
Risk Assessment	Qld DME	Secondary fires as a result of a flashfire/ jet fire in the passenger cabin should be considered, along with the potential for an accident initiated by the gas leak and ignition	Section 11 and Appendix 7
	RAA	Determine risk to motorist arising from flammability issues involving refrigerant product	Section 11 and Appendix 7
	WA DOE	Determine if the risk to the public from the use of the product is acceptable	Sections 11, 12 and 16 and Appendix 15
	Qld DME	Risk Assessment using Fault Tree or Event Tree Analysis	Sections 16 and Appendix 15
	Qld DME	Analysis of hazards in terms of their consequences and likelihood of occurrence	Sections 8-16 and Appendices 6, 7, 8 and 15
	Qld DME	Assessment and qualification of risk for each life cycle phase	Sections 5, 8 and 15 and Appendix 16

TABLE 1.2

ISSUES RAISED IN CONSULTATION REQUIRED TO BE ADDRESSED IN STUDY

Topic	Issue Raised By	Description of Issue	Safety Report Section
Risk Management	Qld DME	Compliance with relevant codes and standards	Section 15
	Qld DME RAA RAC	Training for workers in the use of gases in refrigeration or air-conditioning	Section 16
	Qld DME RAA RAC	Safe operation of refrigerant or air-conditioning workshops in which the gases are used	Sections 5, 6 and 15
	Qld DME	Signs, Safety Notices and Certification that must be displayed	Section 16
	Qld DME	Consideration of controls and other factors that could be implemented to mitigate the hazard and risk to all phases of life cycle	Section 16
General	Qld DME	The document prepared by Arthur D Little (Ref.3) does not satisfy the requirements of Section 4(c) as it is only a preliminary report **Note**: This Safety Report has undertaken a more systematic identification of life cycle hazards, more comprehensive assessment of risk for various parameters involved, and has supported the data used by independent experiments and surveys. Ref.3, however, has been used as a benchmarking reference for comparison	Sections 14 and 15 and Appendices 11 and 16
	Qld DME	The validity of papers by Dr Maclaine-Cross has been questioned as they have not peer reviewed **Note**: The results from the papers of Dr Maclaine-Cross have not been directly used in this study for risk assessment, but have been used mainly for comparisons	Section 11 and Appendices 5 and 10
	Qld DME	Referencing of all information and data sources	Sections 1 and 17 and Appendix 14

PART I AUTOMOBILE AIR-CONDITIONING SYSTEMS AND ER12 REFRIGERANT

2. DESCRIPTION OF AUTOMOBILE AIR-CONDITIONING SYSTEM

2.1 Purpose of Section

The purpose of this section is to introduce:

- concept of refrigeration as it applies to automobiles;
- automobile air-conditioning refrigeration cycle; and
- components found in an automobile air-conditioning system.

2.2 Principles of Refrigeration

The purpose of refrigeration in an automobile is to remove heat from one place to another by mechanical means to sustain a suitable temperature (i.e. driver comfort) in the passenger cabin.

Refrigerants such as hydrofluorocarbon (HFC) or hydrocarbon (HC) are used to achieve this continuous heat removal. The properties of the refrigerant allow the absorption of heat at low temperature through the evaporation of the liquid such that at the pressure of evaporation, the boiling temperature is low. This is achieved by passing the high pressure liquid refrigerant through an expansion valve. The sudden expansion and let down in pressure ensures that the temperature of the fluid is reduced to significantly below ambient levels.

When the cabin air indirectly contacts the surface containing the low pressure/ low temperature refrigerant, the latter absorbs heat from the air and returns the cooling effect.

2.3 Refrigeration Cycle

The refrigeration cycle involves two pressures, high and low, to enable a recirculating process to produce a cooling effect (Ref.4).

- High pressure liquid refrigerant from the receiver flows through a thermal expansion valve referred to as the Tx valve. The pressure is suddenly reduced accompanied by a reduction in temperature. This sudden expansion results in cooling of the liquid (known as the Joule-Thompson effect).

- The cold low-pressure two phase liquid passes through an evaporator. When the air-conditioning fan is switched on, it increases the heat load conditions across the evaporator. Heat is absorbed from the surroundings and transfers this to the refrigerant. The refrigerant now leaves the evaporator as a low-pressure vapour.

- The low-pressure return vapour from the evaporator is compressed in a compressor to a higher pressure. This high pressure vapour is then passed through a condenser to allow the refrigerant to change its state to a liquid phase. The condenser is located in front of the automobile radiator to allow this heat exchange to ambient air. When the system is functioning correctly, the condenser is always hotter than the ambient air. Latent heat is transferred from the refrigerant to the air stream and the refrigerant is condensed. Air flow can be achieved by the movement of vehicle or be fan assisted.

- The high-pressure liquid is received in the drier to then complete the refrigeration cycle.

The refrigeration cycle is schematically shown in **Figure 2.1**, with typical pressures and temperatures. The pressure and temperature would vary considerably, depending on the ambient temperature.

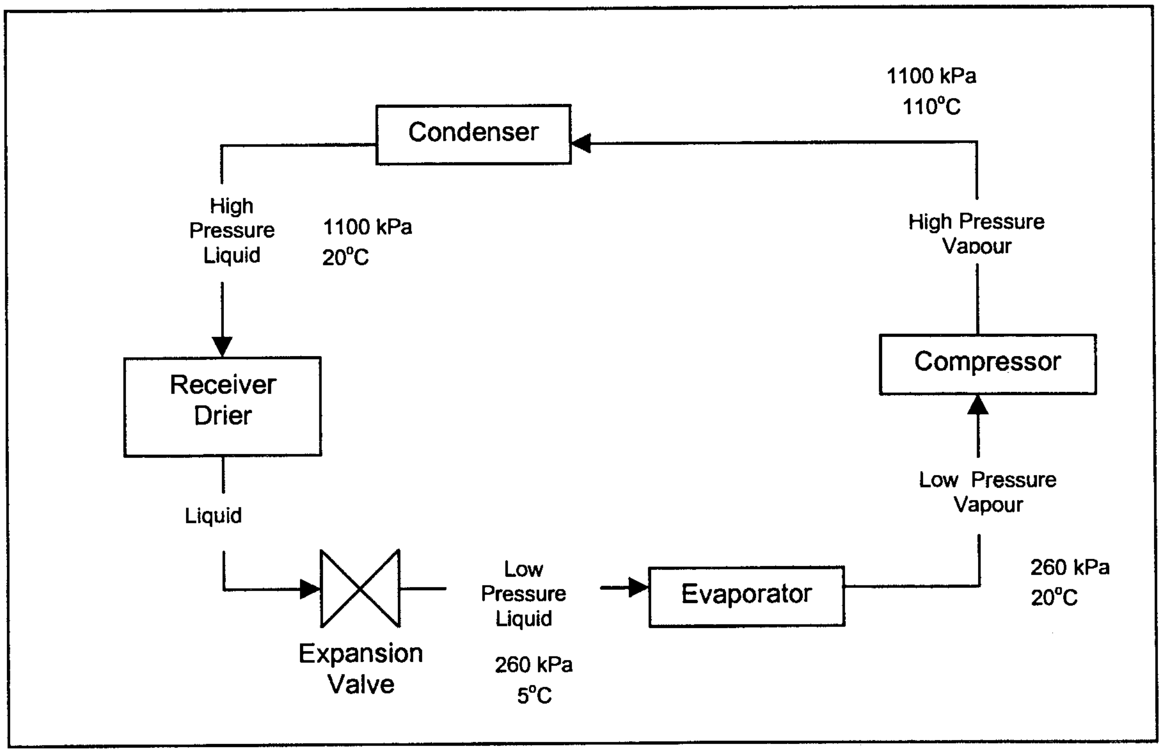


FIGURE 2.1
SCHEMATIC DIAGRAM OF REFRIGERATION CYCLE
(TYPICAL TEMPERATURES AND PRESSURES)

2.4 Components of Air-conditioning System

An automobile air-conditioning system utilises the principle of heat removal using the vapour compression refrigeration. The following components make up the air-conditioning system:

- thermal expansion (Tx) valve, a modulating device that regulates the refrigerant flow which reduces the pressure of the refrigerant and in turn reduces the temperature;
- evaporator, whose function is to remove the surrounding heat from the passenger cabin;
- compressor, to raise the pressure of the vapour to Tx valve inlet pressure and reconvert the saturated vapour into high compression vapour;
- condenser, to liquefy the compressed gas into the liquid form of the refrigerant; and
- receiver drier, where any moisture ingress is absorbed by a desiccant and the refrigerant liquid is stored and recycled into the system.

Figure 2.2 shows a typical vehicle refrigeration system, and **Figure 2.3** shows the schematic of the various components of the automobile air-conditioning unit. A "fire wall" separates the engine bay and the passenger compartment, with the majority of the components located in the engine bay. In all automobiles, the evaporator is located on the passenger side of the fire wall. The Tx valve may be situated either in the engine bay or on the passenger side of the fire wall, depending on the make and model of vehicle.

A detailed analysis of an automobile air-conditioning system has been conducted using a Failure Modes Effects Analysis (FMEA) and a summary of the findings are presented in **Part III** of the Safety Report. The FMEA workshop report and minutes are provided in **Appendix 2.**

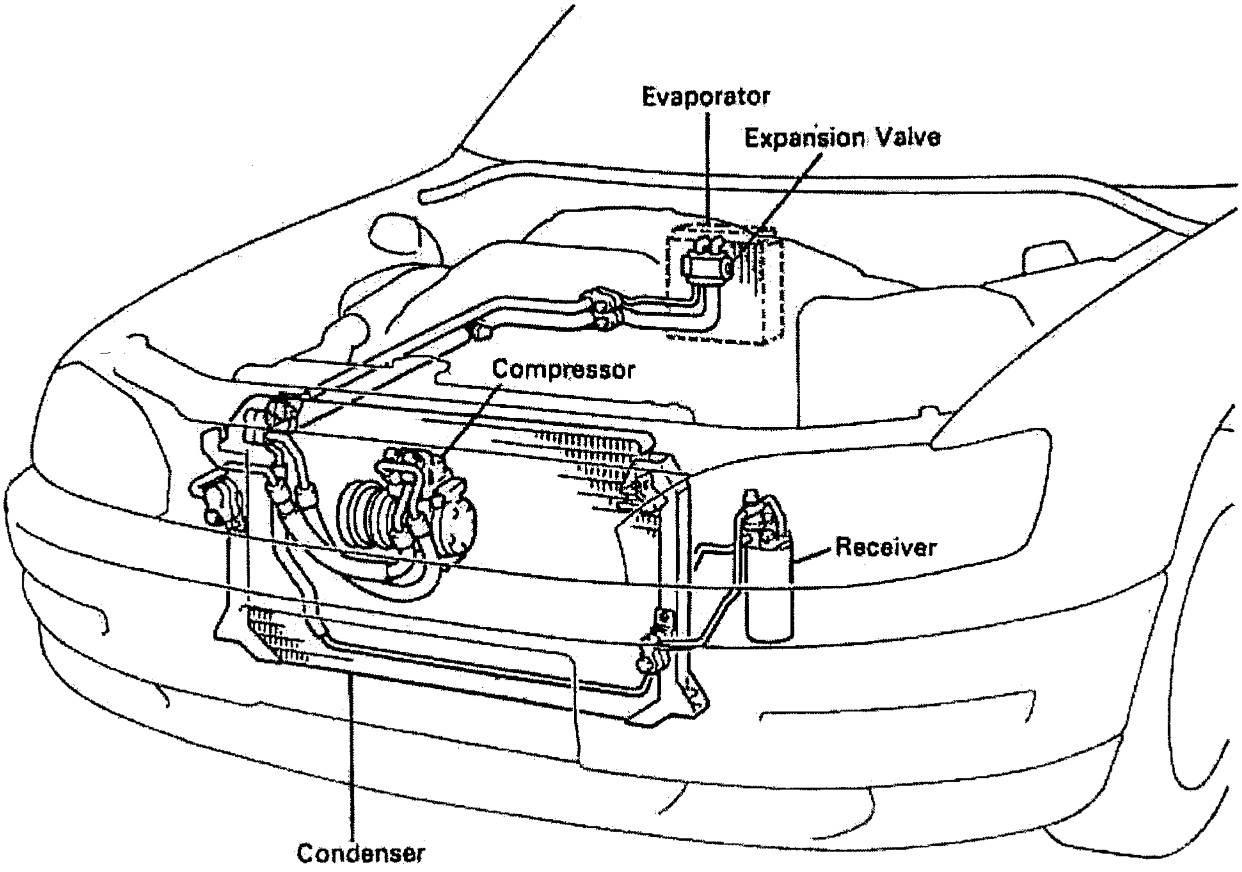


FIGURE 2.2
TYPICAL VEHICLE REFRIGERATION SYSTEM

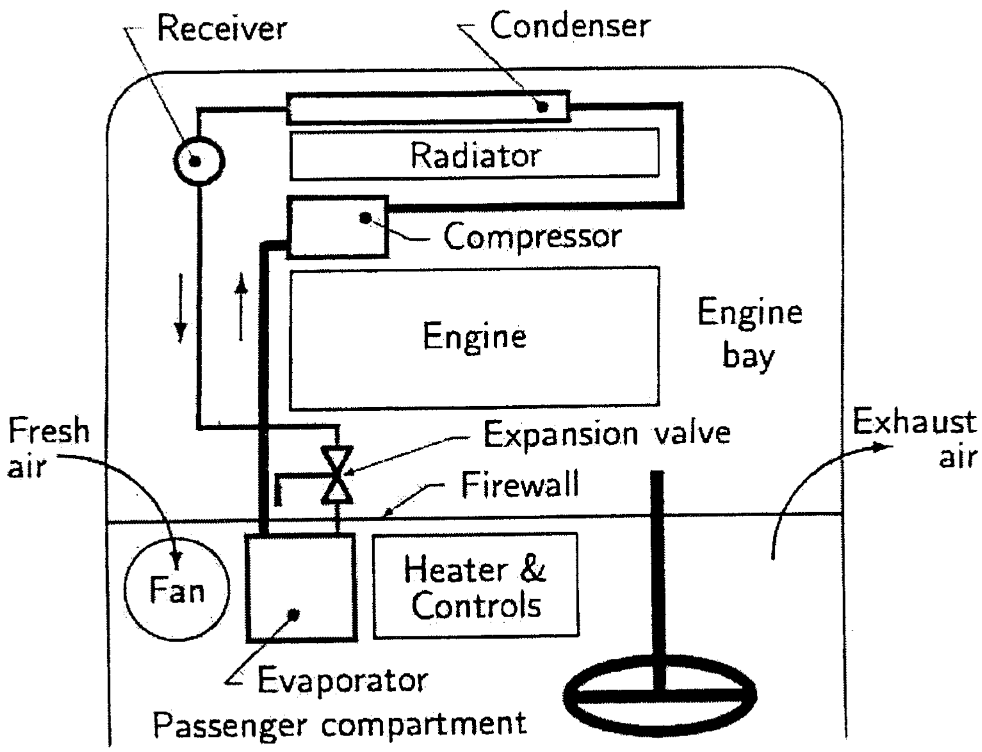


FIGURE 2.3
VEHICLE AIR-CONDITIONING SCHEMATIC

2.4.1 Compressor

The compressor is located in the engine compartment of the automobile. There are many different types of compressors in operation in automobiles, but all use similar operational principles. The refrigerant vapour is drawn into the compressor via the suction chamber through a valve plate and reconverted into a high compression gas where it is discharged into the condenser.

Lubrication of the compressor is achieved by lubrication oil stored in the crank case of the compressor. A carbon faced seal is provided with an ‘O’ ring to prevent leakage.

A thermostat is installed in the refrigeration system that operates a clutch to engage or disengage the compressor, in order to maintain optimum air-conditioning. Thus, depending on the ambient temperature, the compressor operation could be intermittent, controlled by the thermostat.

2.4.2 Condenser

There are several different types of condenser – tube and fin, modine and cross flow, for example. The condenser receives the superheated high pressure refrigerant vapour.

The air passing between the fins, being cooler than the refrigerant, readily receives the heat from the vapour. The refrigerant is then re-converted to a liquid.

The condenser is located in the engine compartment of the automobile, generally forward of the radiator fan so that it can receive the incoming ambient air.

2.4.3 Receiver Drier

The receiver drier collects refrigerant liquid after it leaves the condenser. Its function is to hold sufficient refrigerant to meet the system's varying requirements and whilst doing so, filter foreign matter from the refrigerant and remove any moisture. A desiccant (silica gel) is installed in the drier to provide the moisture removal function.

From the receiver drier, the high pressure refrigerant liquid passes to the Tx valve.

2.4.4 Tx Valve

The Tx valve receives high-pressure refrigerant liquid and automatically permits the required amount to spray into the evaporator coil at a lower pressure. The Tx valve may be located either on the engine side or the passenger side of the firewall, depending on the automobile design.

In general, for the purposes of this study, it was assumed that the Tx valve was on the passenger side of the vehicle for 60% of vehicles. This assumption was based on the available data that Ford and Holden vehicles generally have their Tx valves in the engine bay whereas other car types' Tx valves are in the passenger compartment. Data from VFACTS (Ref.5) indicates that approximately 40% of new vehicles bought in Australia in 1998 were Fords and Holdens, giving 60% of other car types.

2.4.5 Evaporator

The low-pressure refrigerant spray leaving the Tx valve passes through the evaporator coils and in doing so the spray removes the heat (from the fins and tubes) and turns to a vapour. The tubes of the evaporator are arranged to permit the air to be progressively cooled. The air temperature is reduced and the air is ready for distribution through the air vents. The tubing carrying the refrigerant vapour in the evaporator itself is seamless and has no welds.

Any moisture that condenses on the evaporator coils falls to the base of the evaporator housing and is then carried away from the tray via drain tubes to the underside of the vehicle in the engine bay.

The air is forced over the tubes by an electric fan capable of operating at variable speeds. These speeds are controlled by resistors. The compressor switch is interlocked to shut down when the ventilation fan switch is in the "off" position.

2.4.6 Fittings

There are various fitting in an automobile air-conditioning system that are either 'O' rings or flared as shown in **Figure 2.4**. For the purposes of the study, it was assumed that all fittings were 'O' rings and this made the study conservative. The location of these fittings is shown in **Figure 2.5** and described in **Table 2.1**.

If the Tx valve is located inside the passenger cabin, then there are at the most, two 'O' rings. Similarly, if the Tx valve is located in the engine bay, there are no 'O' rings in the passenger cabin.

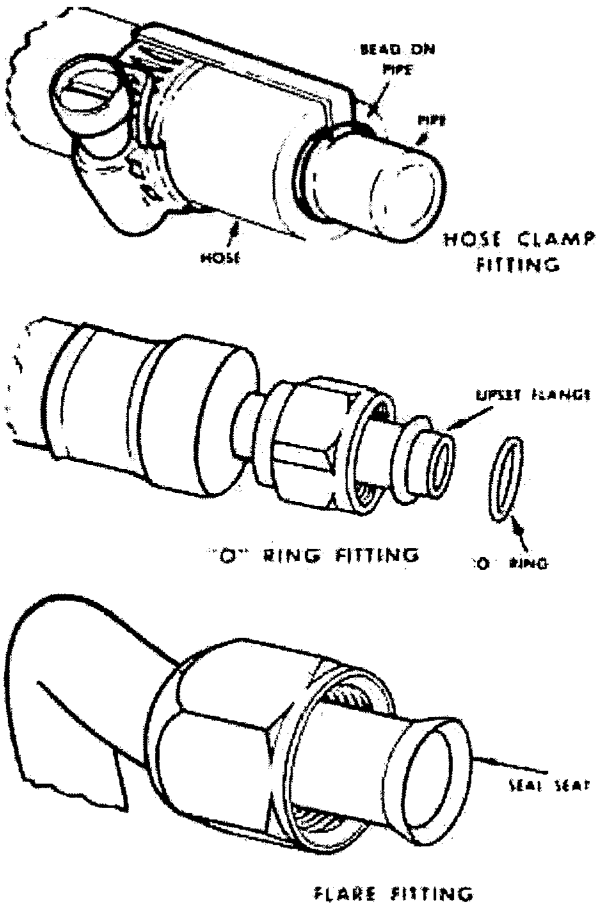


FIGURE 2.4
TYPICAL FITTINGS IN AN AIR-CONDITIONING SYSTEM

TABLE 2.1
PARTS COUNT OF FITTINGS IN A TYPICAL AIR-CONDITIONING SYSTEM

Air-conditioning System		Fitting Type	Number of Fittings	Ref. in Fig. 2.5
From	To			
Compressor	-	Seal on suction and discharge lines	2	A, B
Compressor	Condenser	'O' ring seal and screwed fitting	2	C, D
Condenser	-	None – seamless with no welded elbows	n/a	
Condenser	Receiver/ Drier	'O' ring seal and screwed fitting	1	E
Receiver/ Drier	Expansion valve	'O' ring seal and screwed fitting	1	F
Expansion valve	-	'O' ring seal and screwed fitting (or flared joint) upstream and downstream	2	G, H
Expansion valve	Evaporator	None – seamless with no welded elbows	n/a	
Evaporator	Compressor	'O' ring seal and screwed fitting	2	I, J

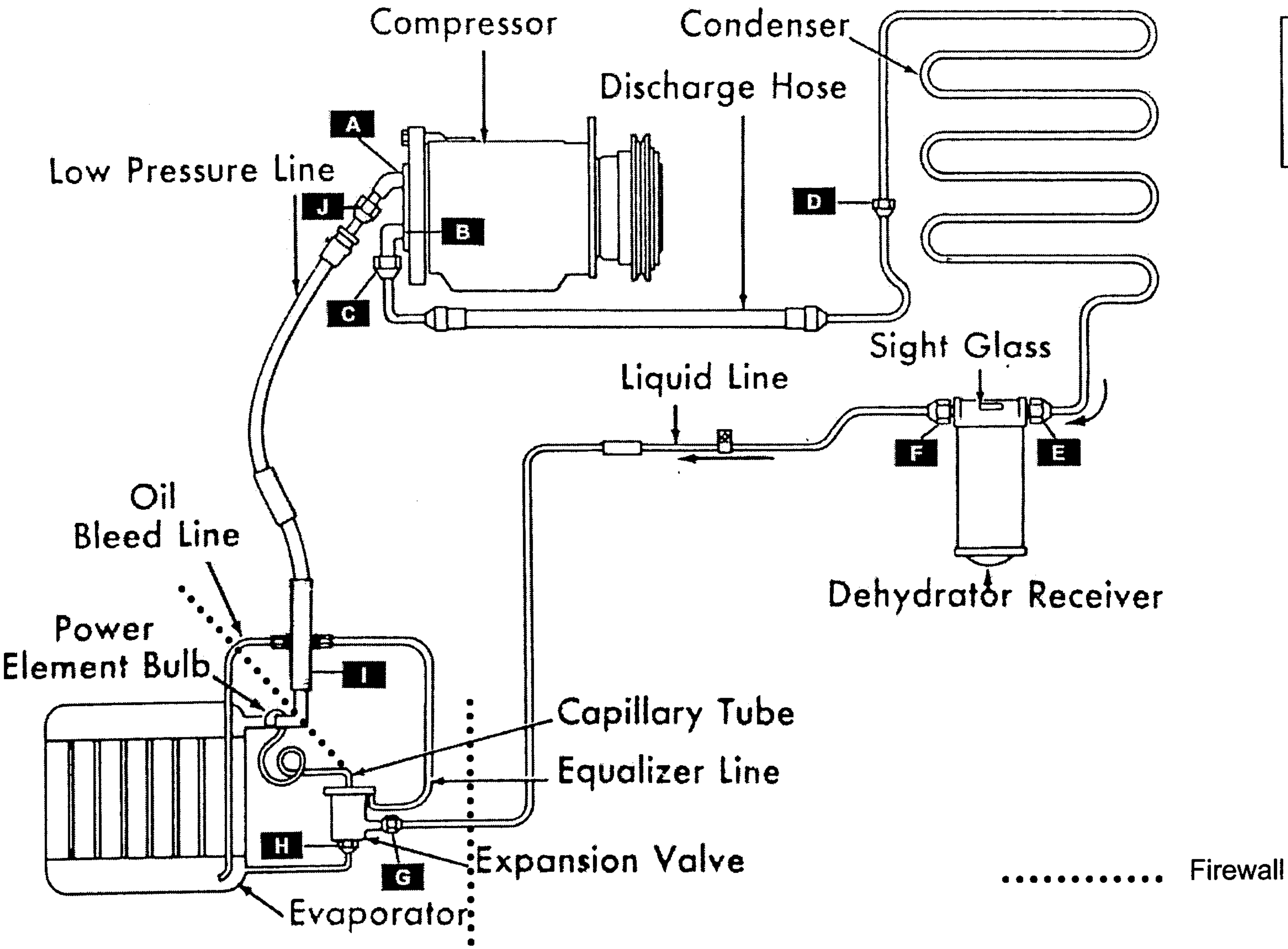


FIGURE 2.5
SCHEMATIC OF TYPICAL VEHICLE REFRIGERATION SYSTEM

3. DESCRIPTION OF ER12 REFRIGERANT

3.1 Purpose of Section

The purpose of this section is to provide descriptions on:

- background to Boral Energy who formulate and market the ER12 product;
- use of hydrocarbon refrigerants in industry;
- description of the ER12 refrigerant product; and
- benefits of using hydrocarbon refrigerants.

3.2 Company Background

Boral is an Australian company operating in over 20 countries globally. The company employs around 22,000 people with annual sales of approximately A$5 billion. Boral has two primary divisions:

- Boral Building and Construction products; and
- Boral Energy.

Boral Energy has over 40 terminals in Australia and is the only integrated national explorer, producer, distributor and retailer of gas products. The manufacture and marketing of ER12 refrigerant is handled by Boral Energy.

3.3 Use of Hydrocarbon Refrigerant in Industry

Hydrocarbon refrigerants are used in many parts of the world for both refrigeration and air-conditioning applications in the following systems (Ref.6):

- vehicle air-conditioning;
- refrigerated containers and transports;
- domestic refrigerators and freezers;
- drink dispensers;
- supermarket cool units and displays;
- industrial cool rooms and freezers;
- agricultural chillers and vats; and
- domestic and commercial air-conditioning systems.

3.4 Benefits of Using Hydrocarbon Refrigerants

The benefits of using hydrocarbon refrigerant as an alternative to the traditional refrigerants of CFC and HCFC may be broken down into two categories of:

- performance (in terms of heat removal and cooling), and
- environmental (in terms of global warming and ozone depletion).

The former is detailed in **Section 4** of the Safety Study whilst the environmental implications are now discussed. The Australian Institute of Refrigeration Air-conditioning and Heating (AIRAH) in its Refrigeration Selection Guide (1998) that hydrocarbon refrigerant has the following benefits:

- zero Ozone Depletion Potential,
- very low Global Warming Potential, and
- short estimated atmospheric life.

A comparison of hydrocarbon refrigerant against the traditional refrigerants of CFC and HCFC are shown in **Table 3.1**.

TABLE 3.1
COMPARISON OF ENVIRONMENTAL ASPECTS OF REFRIGERANTS

Refrigerant	Formula	Ozone Depletion Potential (ODP)[1]	Global Warming Potential (GWP)[2]
R290 (propane)	C_3H_8	0.0	3 (note 3)
R600a (iso-butane)	C_4H_{10}	0.0	3 (note 3)
ER12 (blend of propane and iso-butane)	C_3H_8/ C_4H_{10}	0.0	<4 (note 4)
R12 (CFC)	CCl_2F_2	0.95	4,500 (note 4)
R22 (HCFC)	$CHClF_2$	0.055	510 (note 4)
R134a (HFC)	CH_2F_4	0	420 (note 4)

Notes:

1. ODP relative to R11 (values taken from AIRAH).
2. GWP is relative to carbon dioxide over 500 year basis.
3. Values supplied by Boral Energy. AIRAH reports corresponding values of 8500 years for R12 and 1,700 years for R22.

3.5 Properties of ER12 Refrigerant

3.5.1 Physical Properties of ER12

ER12 is manufactured from a blend of purified R290 and R600a (propane and iso-butane). At ambient temperatures and atmospheric pressure, ER12 is a gas. It is kept liquefied in certain parts of the air-conditioning system under pressure.

On release from containment due to leakage etc, the material would vaporise immediately. The gas is odourised with ethyl mercaptan in accordance with AS 1677.1-1998 (Ref. 7). The odourant concentration is 25 parts per million (ppm). The material has a rotten-cabbage-like odour, and hence can be readily detected by smell in the event of a leak.

3.5.2 Physical Properties of ER12

The physical properties of ER12 refrigerant are listed in **Table 3.2**. It is a flammable gas with Lower Flammability Limit (LFL) of less than 3.5%. Therefore, it is classified as group A3 refrigerant under AS 1677, Part 1 (Ref.7).

TABLE 3.2
SELECTED PHYSICAL PROPERTIES OF ER12

Property	Value
Vapour Specific Gravity	1.5 to 2.0 (air = 1)
Lower Flammability Limit (LFL)	1.9% in air
Upper Flammability Limit (UFL)	9.5% in air
Vapour Pressure	490 kPag @ 20°C
Ratio of Specific Heats	1.116 @ 1atm, 30°C
Minimum Ignition Energy	0.25 milliJoules
Auto Ignition Temperature	400-450°C

A full list of the physical properties of ER12 is given in **Appendix 1** in the Material Safety Data Sheet.

The maximum temperatures and pressures reached by ER12 in an automobile air-conditioning system are shown in **Table 3.3**. The same variables are shown for R134a for comparison. The values in **Table 3.3** show that a system containing ER12 will operate in the same range as the other traditional refrigerants.

TABLE 3.3
MAXIMUM TEMPERATURE AND PRESSURES IN REFRIGERANT CYCLE

Refrigerant Class	Product	Temperature (°C)	Pressure (kPag)	Reference
HC	ER12	30	819	8
HFC	R134a	30	769	9
HCFC	R12	30	745	9

Note:
These values were measured by Boral laboratory (NATA certified) based in Melbourne.

3.5.3 Flammability Properties of ER12

ER12 consists of a mixture of propane and iso-butane. These gases are aliphatic hydrocarbons that are purified by passing the gas over molecular sieves to remove impurities prior to it being used a refrigerant.

The following properties of ER12 are relevant to this discussion (see **Appendix 1**).

1. Lower Flammability Limit (LFL): 1.9% volume in air. A hydrocarbon gas/ air mixture will not ignite if it is below the LFL, i.e. the mixture is too lean in fuel.

2. Upper Flammability Limit (UFL): 9.5% volume in air. A hydrocarbon gas/ air mixture will not ignite if it is above the UFL, i.e. the mixture is too rich in fuel.

3. Auto-ignition Temperature: 400-450°C (Ref.10). A hydrocarbon gas in air must be heated to its auto-ignition temperature before it will ignite without an external ignition source such as a spark or flame.

3.5.4 Amount of ER12 Required in Vehicle Air-conditioning Systems

The quantity of charge is approximately 30% of the original charge mass for HFC depending on the design of the automobile air-conditioning unit. Boral Energy supplies with each ER12 gas cylinder, charge cards for all popular vehicle makes.

For example, a Holden Commodore that is normally charged with approximately 900 grams of R134a, requires only 300 grams of ER12 refrigerant. By comparison, this is a smaller charge mass and is comparable to hydrocarbon used as a propellant in household products such as hairspray or flyspray.

4. COMPATIBILITY OF ER12 REFRIGERANT IN AUTOMOBILE AIR-CONDITIONING SYSTEM

4.1 Purpose of Section

The purpose of this section is to discuss the compatibility issues of the ER12 refrigerant in existing automobile air-conditioning systems.

The Australian Institute of Refrigeration Air-conditioning and Heating (AIRAH) in its Refrigeration Selection Guide (1998) states the following for hydrocarbon refrigerant as an alternative option to the CFC and HCFC refrigerants:

- compatible with common elastomer materials found in refrigerating systems, and
- soluble in conventional mineral oils.

In addition, AIRAH also state that since aliphatic hydrocarbons do not contain chloride or fluoride atoms in their chemical structure, they cannot undergo reaction with water (i.e. moisture in the system), and hence do not form the corresponding strong acids that can lead to leaks in the air-conditioning system.

4.2 Compatibility with Components

This section reviews the compatibility of ER12 with all equipment in the air-conditioning system. As given in **Table 3.3**, the pressures in the automobile air-conditioning system using hydrocarbon refrigerant are similar to those using CFC and HCFCs. It should be noted that the components of the automobile air-conditioning system (such as the compressor, evaporator) are able to withstand pressures greater than the working pressure of the refrigerant.

Granherne (see **Appendix 2**) conducted a Failure Modes Effects Analysis (FMEA) of each component of the air-conditioning unit, with reference to compatibility of hydrocarbon refrigerant and potential for leaks. This workshop was attended by industry representatives experienced in charging both hydrocarbon and non-hydrocarbon refrigerants into automobile air-conditioning systems. The issue of compatibility was addressed in this workshop.

4.2.1 Compressor

The compressor is alloy cast and is compatible with both hydrocarbon and non-hydrocarbon gases. The compressor has an 'O' ring seal which is made of neoprene rubber in the units that previously used CFC refrigerant, or nitro-butyl rubber (HBNR) for units that presently use R134a refrigerant.

Both the materials are compatible with ER12 refrigerant.

4.2.2 Flexible Hoses

Flexible hoses are made of elastomeric materials, and are designed to SAE J2064 (Ref.11), for R134a refrigerant. They are compatible with hydrocarbon refrigerants and cover the temperature range -30°C to 125°C. Further, the vapour pressure of hydrocarbon refrigerants (819kPa at 30°C for ER12), is only marginally higher than the corresponding vapour pressure of HFC refrigerant (769kPa at 30°C for R134a) and CFC refrigerant (749kPa at 30°C for R12) since the hose is designed to the high pressure switch cut out pressures (about 1700 kPa), overpressurisation of the hose is not possible.

Flexible hoses are only for the discharge and suction side of the compressor.

4.2.3 Condenser/ Evaporator

The condenser and evaporator are made of aluminium and are compatible with ER12.

4.2.4 Receiver Drier

The drier is metallic (steel) and is compatible with both hydrocarbon and HFC/ CFC refrigerants.

4.2.5 Tx Valve

The thermostatic expansion valve is cast bronze and is compatible with both hydrocarbon and HFC refrigerants.

4.3 Compatibility with Lubricants

The Material Safety Data Sheets (MSDS) on three different types of lubricants were reviewed (Refs.12,13,14). These were:

- Refined naphthenic oil (mineral oil);
- Polyalkylene glycol (P.A.G); and
- Synthetic esters and additives (i.e. Mobil EAL ARCTIC 22 CC).

All the MSDS list that the only materials incompatible with the oils are strong oxidising agents.

Since ER12 contains only aliphatic hydrocarbons and no oxidising substances, no incompatibility issues with the lubricants were identified.

In an extensive review of refrigeration lubricants, Short and Rajewski (Ref.15) have indicated that PAG lubricants have been used very successfully in hydrocarbon applications as they resist dilution by the refrigerant during compression, even at high pressures, and thus provide improved compression efficiency.

In fact, some lubricants such as mineral oil and alkyl benzenes are not compatible with HFCs, and hence PAG lubricants are extensively used with HFC refrigerants. Thus, the lubricants currently used for HFC systems are also compatible with hydrocarbon refrigerants.

5. LIFE CYCLE OF ER12 REFRIGERANT

5.1 Purpose

The purpose of this section is to outline the life cycle of the ER12 refrigerant from:

- Manufacture of ER12;
- Handling of ER12 in Workshops;
- Use of ER12 in Automobile Air-conditioning System; and
- Disposal of ER12.

5.2 Manufacture of ER12 Refrigerant

5.2.1 Formulation Plants

The formulation of the ER12 refrigerant product is conducted in the following locations:

- Cavan Terminal, Adelaide, South Australia (operated by Boral Energy); and
- Gas Technology, Melbourne, Victoria (under contract to Boral Energy).

5.2.2 Formulation Process

The formulation of ER12 refrigerant consists of the following steps:

- purification of propane;
- purification of iso-butane;
- metering the components to required proportions;
- bottling the product into 9kg cylinders.

Propane and iso-butane are stored in two separate storage tanks. The tanks are $8m^3$ and $15m^3$ in capacity. In Victoria, the propane tank is above ground, and the iso-butane tank is underground. In South Australia, both tanks are above ground in the open. Propane is odourised and iso-butane is unodourised.

Metering pumps deliver the two products to preset quantities via dedicated molecular sieves into a blending tank of $8m^3$ capacity. The molecular sieves remove any trace impurities in the commercial propane and butane raw materials. The propane molecular sieve does not remove the odourant, and hence the product in the blending tank remains odourised.

5.2.3 Quality Testing and Packaging

Prior to blending, samples of the propane and butane feedstock are taken and measured against their relative standards.

Once a batch is prepared in the blending tank, samples are taken for laboratory tests to meet the quality requirements for ER12. Once the quality check is passed, the product is decanted into 9kg cylinders, dedicated to the use of ER12.

Random sampling of the final product is also done and all samples are coded against their batch number for easy identification.

Cylinders may be reused. These cylinders are vacuumed down, cleaned by air purging and refilled with ER12 product. Each cylinder is clearly labelled with an ER12 label.

5.2.4 Safety Management Systems

The tank installations (propane, butane and ER12 product tank) comply with AS 1596 (Ref.16) and are licensed by the respective government agencies in these states.

Manufacture is carried out batch-wise, and the operations are carried out only during weekdays, in daylight hours. A trained operator is in attendance.

Boral Energy has a corporate Safety Management System (SMS) for all its gas installations and the ER12 manufacture is covered by these procedures. At Gas Technology, all procedures relating to the formulation and handling of ER12 are NATA and SAA certified.

5.3 Handling of ER12 in Workshops

5.3.1 Handling Aspects

With the exception of formulation, exposure to ER12 refrigerant is the greatest in the workshop situation when an automobile is either:

- serviced for repairs, or
- ER12 is charged into the air-conditioning system (both first time and re-gassing).

Consultation with Boral Energy and surveys of workshops in Victoria, South Australian and West Australia were conducted to address the issue of charging. It was found that the existing charging procedure for HFC refrigerant may be applied directly for hydrocarbon.

5.3.2 Charging Procedure

The following procedure generally applies for charging of ER12 refrigerant into an automobile:

1. When re-charging a vehicle with refrigerant, if the old refrigerant is a HFC or CFC, then the refrigerant is recovered into a cylinder dedicated to HFC or CFC only, which is later sent for disposal to an approved disposal agency. If the old refrigerant is a hydrocarbon, there is no statutory requirement for recovery and it is simply vented in a controlled manner to atmosphere. (Note: Hydrocarbon refrigerant has a lower Global Warming Potential than HFC and HCFC – see **Section 3.4**).

2. An accredited automotive air-conditioning mechanic conducts any identified repairs on the automobile air-conditioning system.

3. The high and low pressure sides of the air-conditioning unit are connected to a vacuum pump and the system is evacuated down to about 10 kPa absolute, before it is isolated. This step ensures that there is no moisture or non condensables left in the system.

4. The system is left under vacuum for some time to ensure that the vacuum holds and that there are no leaks (air ingress). If air ingress is detected by rising pressure, it must be rectified before gas can be charged into the system. The HC is connected to a 9kg cylinder, placed on a weigh scale, calibrated to show the weight of gas charged into the system (i.e. initial weight minus current weight at any point in time).

5. The vacuum is then disconnected, and a small quantity of HC liquid is charged first. Checks are made for any leak before continuing the charging. The quantity of charge is approximately 30% of the original charge mass for HFC, depending upon the design of the air-conditioning system. The charge mass can be preset for automatic cut-out at the end of the charge, or it can be manually isolated by watching the reading on the weigh scale, which is located within readable distance from the operator.

6. Once the cylinder is isolated, the engine is run with air-conditioning on to check that actual pressures achieved at the high and low pressure side of the system are within acceptable limits. Alternatively a dial a charge unit would be used.

7. Finally, the compressor itself is used to drain residual HC liquid in the hoses back into the cylinder, prior to disconnecting the cylinder and the gauges.

Procedures have been developed for this purpose, and Boral Energy runs training seminars for the dealers. This aspect is further discussed in **Section 16**. The procedures are similar to HFC refrigerants, indeed for the most part identical.

The charging equipment connected to an automobile is depicted in **Figure 5.1**.

FIGURE 5.1
GAS CHARGING EQUIPMENT

5.4 Use of ER12 in Automobile Air-conditioning System

The normal operation of a vehicle air-conditioning system uses the ER12 refrigerant as described in **Section 2.2**. The air-conditioner is a sealed system, and generally needs little or no servicing during its operational life.

The focus of the Safety Report has been identifying and evaluating incidents involving ER12 refrigerant in automobiles under driving and stationary conditions that could effect the occupants.

5.5 Disposal of ER12

The final phase of the life cycle of the ER12 refrigerant is disposal through either:

- natural losses from the automobile air-conditioning system;
- vent down to atmosphere of remaining charge in the automobile air-conditioning system for re-charging;
- vent down to atmosphere of hydrocarbon charge when the automobile is destroyed.

As given in **Section 3.4** of the report, hydrocarbon refrigerants when compared to HFC and HCFC refrigerants have a considerably lower global warming potential effect. In addition, hydrocarbon refrigerants do not have any effect on the ozone layer. As such there is no statutory requirement to reclaim hydrocarbon refrigerant and can be discharged to atmosphere.

Granherne has identified risk management issues relating to the safe discharge of ER12 refrigerant in the workshop and car wrecker yard. These recommendations deal with training issues and are detailed in **Section 16** of the Safety Study.

PART II STUDY METHODOLOGY

6. STUDY APPROACH

6.1 Outline of Study Approach

The purpose of this section is to:

- outline the methodology adopted in the safety assessment of ER12 refrigerant;
- detail the impairment criteria used in the safety assessment;
- outline the risk assessment approach in terms of the advantages and limitations.

The study may be divided into four distinct phases:

- Phase I Hazard Identification.
- Phase 2 Consequence Assessment.
- Phase 3 Frequency Assessment.
- Phase 4 Risk Assessment and Risk Management.

A graphical representation of the methodology used in the study is presented in **Figure 6.1**. Discussions of the critical parts of the study are discussed in the following sections.

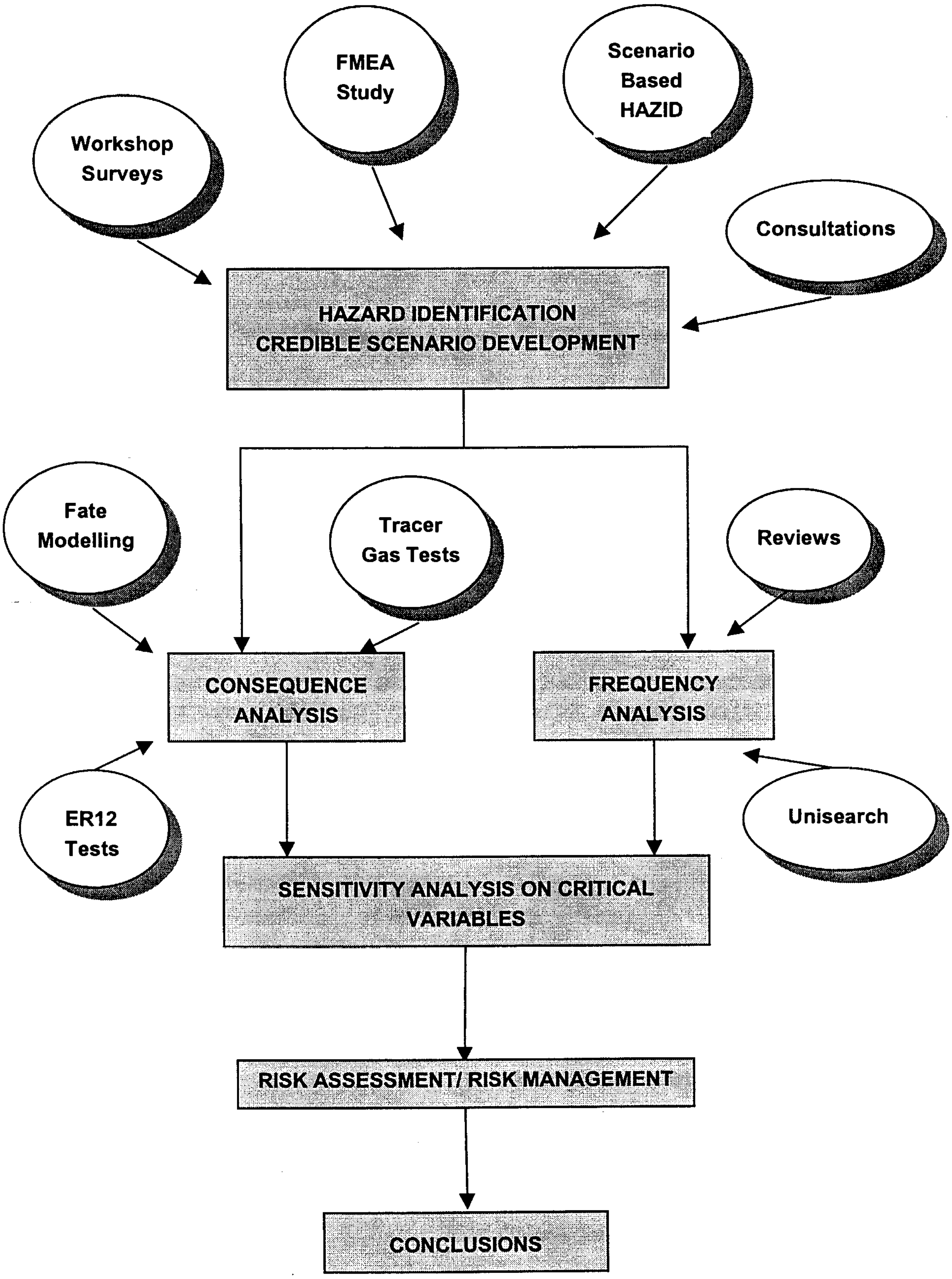


FIGURE 6.1
OVERVIEW OF STUDY METHODOLOGY

6.1.1 Hazard Identification

The objective of the hazard identification was to develop for each life cycle phase of the ER12 refrigerant, credible scenarios that may affect people. This was accomplished through:

- Failure Modes Effect Analysis (FMEA);
- scenario based hazard identification;
- consultations with government, industry and motorist association bodies;
- surveys of workshop and garages that are involved with automobile air-conditioning; and
- physical inspection of air-conditioning components with accredited air-conditioning mechanics.

Details of the consultations are provided in **Part III** of the Safety Report and summarised in **Appendix 14**.

Note: It was found that the FMEA approach is more appropriate for the given situation than a Hazard and Operability Study (HAZOP). The FMEA study considers each component of the automobile air-conditioning system and identifies the potential for release of refrigerant from containment).

6.1.2 Consequence Assessment

In this section of the study each of the scenarios developed in the hazard identification for the passenger cabin and engine bay was analysed to determine the outcomes of a refrigerant leak. The analysis determined firstly if a flammable mixture could be formed under the conditions identified, and secondly, the potential effects if a flammable mixture was ignited.

This was accomplished through:

- Conduct of leak tests using ER12 refrigerant;
- Tracer gas studies of motor vehicles;
- Fate and transport modelling.

6.1.3 Frequency Assessment

The objective of this section was to determine base line failure frequency data and assign frequencies to the identified release events. Failure data was derived in the following way:

- surveys of workshop and garages (done in Queensland, South Australia, Victoria and Western Australia) that are involved with automobile air-conditioning;
- detailed parts count of an automobile air-conditioning system;
- review of statistical data supplied by agencies;
- electrical testing by Unisearch of identified electrical components commonly found in automobiles; and
- review of published literature and past studies on automobile air-conditioning systems.

6.1.4 Risk Assessment and Risk Management

The final phase of the study was the determination of the risk associated with each incident forwarded for assessment. Event tree analysis was conducted to logically determine the potential outcomes for each identified initiating event.

The risk assessment was then subjected to a sensitivity analysis on critical variables and the overall risk compared with published voluntary risk values.

Based upon the risk assessment, the Safety Report then presented its conclusions and forwarded risk management recommendations.

6.2 Study Parameters

Some of the key parameters of the safety study were:

- passenger cabin volume;
- charge mass of refrigerant;
- refrigerant physical properties;
- cabin ventilation rates; and
- automobile groups.

Comments on these parameters are provided in the following sections.

6.2.1 Passenger Cabin Volume

The volume of the passenger vehicle determines, to some degree, the concentration of hydrocarbon in the cabin in the event of a release into the passenger compartment. The volume of the vehicle passenger compartment was used in calculations to determine the concentration of refrigerant vapour in the vehicle. The volumes were calculated from measurements of vehicle dimensions. The details of calculations and method are provided in **Appendix 5**.

6.2.2 Charge Mass of Refrigerant

Charge mass was defined as the mass of ER12 refrigerant used in the vehicle air-conditioning system. It was used in calculations to determine the time for which a release would occur. Charge masses were taken from charge charts supplied by Boral Energy for vehicles in Australia. In general, the charge mass for ER12 is one third of that required for R134a. For example, a large car such as a Holden Commodore will be charged with approximately 300 grams of ER12 (or 900 grams of R134a).

6.2.3 Refrigerant Physical Properties

For this study, the physical properties of the refrigerant have been based on ER12. The properties are listed in **Section 3.5**.

6.2.4 Ventilation Rates

The number of air changes per hour (ACH) represents the ventilation rates in a vehicle passenger cabin. The ventilation rate is a critical parameter in the analysis as it influences the rate of accumulation of a refrigerant release in the passenger cabin, and hence the concentration of hydrocarbon.

Manufacturers' data on ventilation fan capacities in automobiles was not available. Granherne contacted equipment manufacturers for information. However, ventilation fan manufacturers refused to provide the information without the approval of vehicle manufacturers. Australian vehicle manufacturers were than contacted, and they refused to provide any information in this regard. A limited amount of data was obtained through private communication between Boral Energy and General Motors Holden. This data is given in **Appendix 12**.

Maclaine-Cross (Ref.17) from the University of New South Wales has published information on passenger cabin volumes and ventilation rates for ten different vehicle types. These values come from the work of Razmovski (Ref.18) and Rajeskariah (Ref.19). A review of these papers found that the ventilation rates were highly variable and not consistent. The results were not able to be verified because there was no information on the reproducibility of experiments done by the students (Ref.18 and 19).

Fletcher and Saunders from the Health and Safety Executive in the United Kingdom (Ref.20) measured air change rates in a range of vehicles under different conditions (windows open, windows closed, moving vehicle, stationary vehicle in the open) and under various wind speed conditions, and have correlated number of air changes per hour (ACH) against wind speed. This is the most reliable data available in the literature and was used in this study.

In addition, Granherne conducted a series of tracer gas studies to determine the ACH values for a variety of automobiles under still wind and winter conditions. These studies focused on determining the ACH for vehicles parked either in the open or in an enclosure (i.e. garage). The experimental protocol was based upon previous tracer gas work conducted by Granherne. The experimental report is provided in **Appendix 10**.

6.2.5 Automobile Groups

The vehicles that were measured for passenger cabin volume calculation were classified into three groups according to the volume calculated:

- large (volume > 5m^3). Vehicles such as Holden Commodore Wagons are included in this category;
- medium (volume 4-5m^3). Vehicles such as Holden Commodore Sedans and Mitsubishi Magnas etc are included in this category;
- small (volume < 4m^3). Vehicles such as Ford Lasers, Holden Astra, Holden Barina, Toyota Corolla etc are included in this category.

6.3 Impairment Criteria Used in Study

The primary hazard involving the use of hydrocarbon refrigerant in an automobile is flammability. Therefore the Safety Study focussed for each credible release event, if a flammable mixture could be formed, especially in the passenger cabin. The impairment criteria used in the Safety Study are presented in **Table 6.1**.

TABLE 6.1
IMPAIRMENT CRITERIA USED IN SAFETY STUDY

Parameter	Flammability Limit	Value (kg/m^3)	Comment
Flammable concentration in passenger cabin	LFL	0.04	Lower flammability limit for ER12. Ignition would occur if a source was present
	50% LFL	0.02	If the average concentration reached 50% LFL, it is possible for LFL concentrations to be present in pockets of incomplete mixing. The peak to mean concentration ratio is taken as 2:1 (Ref.21). (See **Appendix 4**)
	20% LFL	0.008	Suggested practical limit of Class A3 refrigerants is one fifth of LFL from AS 1677.1 (Ref.7)

6.4 Risk Criteria

Numerical risk targets in terms of probability of occurrence of accident events resulting in injury or fatality to the public from industrial facilities have been set by regulatory authorities in various countries of the world, including Australia. No numerical targets or criteria have been set for risk to people from the use of a consumer product. Therefore, it is left to the product supplier to demonstrate that the risk to people has been reduced to tolerable levels.

During the course of the Safety Study, findings suggested that fatalities would not result from potential leaks of ER12 refrigerant in an automobile air-conditioning system. Therefore, it was considered that the use of fatality risk criteria was not relevant or appropriate.

Attention was focused on finding a reasonable risk criteria for injury risks. Two methods were identified:

(a) Estimate the historical risk of injury from automobile accidents using available statistical data for Australian conditions.

If the risk of injury from the use of ER12 is “significantly” lower than the accident injury risk, then the risk may be considered tolerable. The world “significantly” is subjective, but one to two orders of magnitude is considered reasonable.

(b) A criteria for risk of minor injury from fires and explosions to public from major hazard facilities has been set in New South Wales as $5x10^{-5}$ per installation-year, or 1 chance in 20,000 per year (Ref.22). This value has bee generally adopted by other Australian States. Formal criteria for fatality only, but not injury, have been published by other States (Victoria and Western Australia).

If the risk of injury from the use of ER12 is shown to be of the same order as 1 chance in 20,000 per vehicle-year or less, then the risk may be considered tolerable.

It should be noted that Granherne has adopted the approach of ‘risk tolerability’, after applying necessary safety controls, rather than the approach of ‘risk acceptability’, in line with the approach adopted by the UK Health and Safety Executive (Refs.23 and 24).

Some historical risk data are shown in **Table 6.2**.

TABLE 6.2
FATALITY RISK ARISING FROM VOLUNTARY ACTIVITIES

Activity	Chances of Fatality Per Million Person Years
Travelling by motor vehicle	145
Travelling by aeroplane	10
Pedestrian struck by motor vehicle	35
Smoking (20 cigarettes per day – all effects)	5000

The application of risk criteria for risk tolerability is discussed in **Section 15**.

6.5 Benefits and Limitations of Quantitative Risk Assessment

As outlined in this section, the Safety Report has utilised a risk assessment approach incorporating Quantitative Risk Analysis (QRA). This technique is currently being used extensively across the world, for quantifying and ranking risks and to develop specific mitigation measures where required.

The purpose of this section is to outline to the reader the benefits and limitations of the technique.

6.5.1 Uncertainties in Risk Assessment

In the safety system approach to risk management, decisions have to be made on risk assessed on probabilistic estimates of incident likelihood. One of the important questions that arises in relation to risk assessment is:

"How much reliance can one place on the probability estimates, especially for incidents that may not have occurred, but have a potential to occur, under specific circumstances, none of which are yet known?"

Uncertainty is essentially the absence of sufficient information to make an informed decision. This makes risk an abstract concept, and the assessment results are relative. Risk analysis is largely concerned with estimation of uncertainty, qualitative or quantitative, using the concept of probability. Even though risk results may sometimes be expressed in absolute numbers, the results of a risk assessment must be considered relative to other risks, in order to make meaningful interpretations.

If the above fact is ignored, there is the pitfall of looking for "zero" risk, based on perceptions arising from inadequate information, or information not validated by scientific means.

The important points to remember in judging risk results are:

- Have all possible adverse outcomes been identified?
- What assumptions have been made in estimating the likelihood of an adverse outcome, and how valid are these assumptions, given the relative paucity of data?
- Have sufficient measures been developed to prevent an unwanted outcome and/ or mitigate its adverse effects?

In the present Safety Study of ER12 refrigerant, every attempt has been made to minimise uncertainty in the risk assessment.

6.5.2 Benefits and Limitations

The most important benefit of the risk assessment technique is that it provides a basis making management and engineering decisions that may not be possible without some form of quantification. The reason for this is that QRA combines two separate dimensions of risk, namely the consequential effects of all identified potentially hazardous events, and the likelihood of the events that may affect people.

The only way these two dimensions can be combined into a single risk index is through quantification of both to obtain the cumulative risk.

There are, however, certain limitations to the approach and these should be borne in mind when interpreting risk results. These limitations are set out below:

(a) Failure Scenarios:

The scenarios postulated for loss of containment of hydrocarbon refrigerant are hypothetical. For this study, the assumptions made are as realistic as possible, and are based on observed phenomena in developing credible release scenarios.

(b) Failure Rate Data:

The frequency of failure of major component or pipework is generally estimated from historical data collected from surveys and questionnaires and contains the judgement of the operators answering the questionnaire. Some frequency data has been used from generic databases. However, frequency data has also been derived from surveys of accredited automobile refrigeration mechanics.

(c) Mathematical Models:

The mathematical models used to represent the physical behaviour of hazardous incidents contain idealised approximations. This is a necessary part of modelling, but does introduce some uncertainties in calculating hazard impacts for fire and explosion effects.

(d) Human Error and Management System Failures:

A risk analysis study only partially includes incidents caused by human error and safety management system failures and hence the risk estimated could be optimistic. In order to account for this, sensitivity analysis on the assumptions has been undertaken to identify the impact on risk by varying critical parameters relating to human error.

7. ASSUMPTIONS MADE IN STUDY

7.1 Purpose of Section

The purpose of this section is to outline the assumptions made in the Safety Study of the ER12 refrigerant product. Justification for each assumption is provided in **Appendix 4**.

7.2 Assumptions Made in Study

7.2.1 Hazard Identification

Assumption 1

The hazard identification process was used to segregate potential incidents involving ER12 into different categories of:

- manufacture;
- storage and distribution;
- workshop; and
- end use of product.

Assumption 2

For the incident involving an accidental overcharging of the vehicle air-conditioning system, analysis was conducted only for the case of moving vehicle.

7.2.2 Leak Rate Calculations

Assumption 3

Release rates were evaluated for two cases that best represented typical Australian conditions at:

- average ambient temperature of 20°C; and
- average ambient temperature of 40°C.

Assumption 4

Release locations were divided into two distinct groupings:

- Engine bay; and
- Passenger cabin.

Assumption 5

It was assumed that for vehicles manufactured by General Motors Holden and Ford Australia, the thermal expansion (Tx) valve was located in the engine bay. For all other vehicles, the Tx valve was assumed to be located in the passenger cabin (**Appendix 6**).

Assumption 6

The leak size rule sets shown in **Table 7.1** were used in the analyses.

TABLE 7.1
LEAK SIZE RULE SET

Location	Leak Category	Equivalent Hole Size
Engine Bay	Pinhole	0.1mm
	Large	1.0mm
	Catastrophic	vapour – 12mm
		liquid – 8mm
Passenger Cabin	Pinhole	0.01mm
	Large	0.1mm
	Catastrophic	> 1mm

Assumption 7

A sudden and complete loss of ER12 charge from an air-conditioning system was assumed to occur following a collision.

Assumption 8

The leak rate from a pinhole (0.01mm) was treated as a semi-continuous release.

Assumption 9

For releases from large and catastrophic sized holes, the release rate versus time depressuring profile was calculated based upon the system pressure and ER12 charge.

Assumption 10

For release rate calculations, discharge coefficient value of 0.8 was used.

Assumption 11

The time to vent (excluding vacuum) of ER12 refrigerant from a vehicle air-conditioning system was taken to be on average 90 seconds.

7.2.3 Release Modelling

Assumption 12

For the purposes of calculations, the estimation of a vehicle volume was based around a series of "boxes".

Assumption 13

For the purposes of the analyses, passenger vehicles were divided into three categories of large, medium, small on the basis of volume.

Assumption 14

The associated ER12 charge mass was based upon the average of those vehicles in that category and these were:

- Large sized vehicles (300 grams);
- Medium sized vehicles (228 grams);
- Small and micro sized vehicles (216 grams);
- Micro sized vehicles (210 grams).

Assumption 15

The concentration in the passenger cabin following a release of ER12 refrigerant is well mixed.

Assumption 16

It was assumed that stationary vehicle had all vents in the closed position to limit the associated air exchange rate.

Assumption 17

The air exchange rates (ACH) values shown in **Table 7.2** were used in the assessment.

TABLE 7.2
ACH VALUES USED IN SAFETY STUDY

Situation	Car Type	Minimum ACH Value (h^{-1})	Comment
Vehicle parked in enclosure (winter day and evening)	Late Model	0.3	Experimental
	Early Model	0.3	Experimental
Vehicle parked in open area (winter day and evening)	All models	1.0	Experimental / HSE
	Late Model	0.7	Experimental / HSE
	Early Model	1.1	Experimental / HSE
Vehicle Moving	All Models	10	HSE

Assumption 18

The physical state of release from the leak sizes considered in the study were:

- Pinhole (vapour phase).
- Large (vapour phase).
- Catastrophic (two phase initially followed by vapour phase).

Assumption 19

Incidents that displayed a peak concentration at or above 50% LFL were carried forward for further analysis.

Assumption 20

A full rupture of the air-conditioning system when the vehicle was stationary (for example, parked in a garage) was not feasible.

Assumption 21

An accidental overcharge of ER12 into a vehicle air-conditioning system would be detected by the workshop mechanic during post-charging inspections. Hence a human error probability of 0.09 was assigned.

Assumption 22

The ACH values could be estimated using a first order decay equation.

Assumption 23

The ACH values used in the present assessment for stationary vehicles were derived for Sydney winter conditions.

Assumption 24

It was assumed that all of the refrigerant leak from the evaporator or Tx valve would go into the passenger compartment.

Assumption 25

The volume occupied by the seats in the passenger cabin was not subtracted from the total volume measured to obtain the free volume.

Assumption 26

The charge masses used in calculations for an overcharged system were as follows:

- large car: 400g (133% of nominal charge of 300g);
- medium and small car: 300g (nominal charge 220g).

Assumption 27

For engine bay calculations, the free volume of the engine bay was assumed to be 20% of the total volume of the area.

7.2.4 Frequency and Risk Analysis

Assumption 28

The data results obtained from the workshop surveys was used to represent failures of vehicle air-conditioning systems.

Assumption 29

It was assumed that at least 52% of passenger vehicles in Australia are fitted with air-conditioning systems.

Assumption 30

In a typical motor vehicle air-conditioning system and assuming the Tx valve is located inside the passenger cabin, there are 2 'O' rings representing 25% of the total 'O' rings present in the system.

Assumption 31

Sixty percent of passenger vehicles in Australia have the Tx valve located inside the passenger cabin.

Assumption 32

On average, a driver spends approximately 1.8 hours in a vehicle per day.

Assumption 33

It was assumed that a passenger vehicle is parked equally in the open (i.e. carpark or street) or in an enclosure (i.e. probability value of 0.5).

Assumption 34

In assessing the minimum ignition current using the methodology of AS 2380.7 (Ref. 25), circuits were assumed to be resistive if the measured inductance was less than 1 milliHenry.

Assumption 35

The minimum ignition current was determined assuming a battery voltage of 16V.

PART III HAZARD IDENTIFICATION AND LEAK RATE CALCULATION

8. HAZARD IDENTIFICATION

8.1 Purpose of Section

The purpose of this Section is as follows:

- to describe the life cycle hazard identification process adopted for the use of ER12 refrigerant in automobile air-conditioning;
- to summarise the list of hazards identified from workshops, surveys and consultations with government and industry bodies;
- to develop incident scenarios of potentially hazardous events;
- to apply a screening process to screen out events that would have no significant adverse impact; and
- to develop a list of scenarios that can be carried forward for more detailed assessment in this study.

8.2 Hazard Identification Process

8.2.1 Introduction

Comprehensive hazard identification was undertaken in order to identify possible leak scenarios for the study. The results of these analyses are presented in this section of the report. A range of techniques were used in the hazard identification process:

- Failure Modes and Effects Analysis (FMEA);
- Scenario based hazard identification (HAZID);
- surveys of a number of workshops handling both hydrocarbon and non-hydrocarbon refrigerants; and
- consultations with industry and government bodies.

The main hazard presented by the hydrocarbon refrigerant is its flammability under certain conditions. Hazardous events therefore relate to loss of containment of the refrigerant.

8.2.2 FMEA Workshops

FMEA is a tabulation of each piece of equipment, identification of its failure modes, and the effects of such failures in terms of safety and operability of the unit. The emphasis is on failure of the hardware.

The FMEA workshop was carried out in Melbourne in September 1998 with a representative group of personnel. The participants are listed in **Table 8.1**.

TABLE 8.1
PARTICIPANTS IN THE FMEA WORKSHOP

Participant	Organisation
Ross Bradshaw	Esanty Refrigerants
Barry Duckworth	Boral Energy
Jan Goedhardt	Newtek Pty Ltd
Paul Kesley (part time)	Environment Protection Authority (Federal)
Graham Nathan	Henron Automotive
Colin Spencer	Esanty Refrigerants
Steve Sylvester	Granherne (Study Leader)

The FMEA minutes are provided in **Appendix 2**.

The purpose of the study was to identify the failure modes of the vehicle air-conditioning system and thus identify leak scenarios for further analysis. Some survey results available in the briefing document published by the NSW Motor Vehicles Repair Industry Association (Ref.26) were also used.

Failure Modes

Clodic (Ref.27) identifies four types of emissions from the vehicle air-conditioning system:

1. Fugitive emissions.
2. Release from fittings and components.
3. Losses due to accidents.

Fugitive Emissions

This is the most common cause of refrigerant leak. These are emissions whose source cannot be precisely located. Sometimes they can be detected only under a pressure test in the workshop. These emissions occur over a long period of time, sometimes several weeks to months.

Release from Fittings and Components

Refrigerant releases could occur from fittings and components, but these are exceptional. If we discount material incompatibility, as HC refrigerant is compatible with all the materials in the automobile air-conditioning system, the main causes of such release are:

- overstressing on piping;
- external corrosion; and
- overtightening bolts or flanges.

Human error in maintenance is probably the main cause of component failure. These failures are generally avoided through the use of good assembly methods and procedures in the workshop, if the unit requires dismantling for maintenance. Work is undertaken only by accredited automotive mechanics.

Motor Vehicle Accidents

Release of the full inventory of refrigerant could occur in the event of motor vehicle accidents.

8.2.3 Scenario Based HAZID

The scenario based hazard identification process involves a brainstorming session of technical personnel to produce a list of risk-related issues for the life cycle of the refrigerants. Working though the issues, a list of event scenarios are developed, with identification of potential consequences, and safeguards to prevent or mitigate the event.

The issues were identified in the workshop, with participants listed in **Table 8.1**. The issues list was further updated after the survey results and consultations.

The results were recorded in tabular form showing the event scenario, its causes, potential consequences and safeguards provided. Full details are provided in **Appendix 3**.

8.2.4 Consultations with Government and Industry Bodies

Consultation was held with the following bodies, either through face-to-face meetings or through correspondence.

The following bodies were consulted:

- ER12 refrigerant distributors (Victoria and South Australia);

- South Australian Royal Automobile Association (Adelaide Head Office);
- Royal Automobile Club of Western Australia (Perth Head Office);
- WA Department of Energy (Perth office);
- Trans Adelaide (St Agnes Depot); and
- Department of Mines and Energy (Chief Gas Examiner, Queensland).

Concerns and issues raised were gathered from interviews held, and were included in the hazard identification considerations.

Details of the issues raised in consultations are given in **Appendix 14**.

8.2.5 Workshop Surveys

A survey questionnaire was prepared for obtaining data on historical experience in the industry on the type of leaks, size, location and frequency.

Data was obtained through survey workshops of operators in Queensland, South Australia, Victoria and Western Australia, that undertake maintenance and repairs on automobile air-conditioning units.

The workshops in Victoria and South Australia used either R134a and ER12, depending on the customer choice. The workshops in Queensland and Western Australia were using R134a only at this time in automobile air-conditioning systems. The survey data is present in **Appendix 12**.

8.3 Findings from FMEA

The following findings were made from the FMEA study:

8.3.1 Vehicle Operation

1. No material incompatibility was found for air-conditioning systems currently using R134a to change the use to ER12.

2. Equipment failure scenarios would not result in a hazardous event, but only cause operability problems, unless release of refrigerant was involved.

3. Leaks identified were very small pinhole leaks in the automobile air-conditioning systems using R134a.

8.3.2 Passenger Cabin

4. The only two release events that may result in refrigerant in the vehicle's passenger cabin were:

- a leak from the Tx valve (for those models where Tx valve is on the passenger side of firewall); and
- a leak from the evaporator coil.

5. If a significant leak of ER12 in the passenger cabin were to occur, it can be readily detected if the vehicle is occupied, as the gas is odourised.

8.3.3 Engine Bay

6. Loss of significant refrigerant inventory into the engine bay could occur from:
    - vehicle accidents;
    - fatigue failure of aluminium bend; and
    - failure of flexible hose on compressor suction or discharge lines.

7. The potential for ignition for small leaks into the engine bay is very low when the engine is running due to significant dilution from air flow generated by the radiator fan, dispersing the hydrocarbon to atmosphere.

8. Refrigerant release in the workshop could occur from failure of the flexible hose connecting the bottle to the air-conditioning, but the release rate is limited due to the small hose size (3mm diameter), and the quantity released can be minimised by operator presence to shut off flow from the cylinder.

9. To ensure that correct procedures are adopted, training needs were identified for operator charging gas as well as for repairers/ workers dismantling the unit, in a professional manner.

8.4 Findings from Consultations

The following issues were identified in the consultations (see **Appendix 14** for details):

Dealers

- ER12 product has been used in automobile air-conditioning systems since October 1995 in Victoria, and since October 1998 in South Australia. There are no known cases of leaking units, and no known cases of fire.
- There are no reported incidents from workshops using ER12 products.

Automobile Associations/ Motor Traders Association

- The automobile associations required the following issues to be address in this Safety Report:

  - risk involved with the flammability of the product, and acceptability of risk to public;
  - safety of handling HC refrigerant at workshop level;
  - level of training provided to workshops on product handling and use;
  - situation of vehicle parked overnight;
  - use of HC refrigerant in existing vehicle air-conditioning systems; and
  - mixing of refrigerant in the passenger cabin following a leak.

- The automobile associations recognised that ER12 product is more environmentally friendly than current refrigerants, and wanted the performance characteristics of the product to be highlighted in the Safety Report. This has not been done in this report as it is considered outside the scope of the Safety Report, which focused only on safety issues.

- There were no known fire incidents associated with the use of ER12 in automobile air-conditioning systems.

Government Bodies

- The following issues were raised by the government bodies consulted:
  - risk to public from the use of product;
  - investigate potential ignition sources; and
  - how a refrigerant leak is dissipated.

- Assessment of hazard and risk in all phases of life cycle of the refrigerant.

- Effect of safety and reliability of system and components for change of refrigerant.

- Systematic hazard identification using HAZOP, FMEA, Fault Tree or Event Tree Analysis.

- Analysis of hazards in terms of their consequences and likelihood of occurrence.

- Assessment of the vulnerability of people who could be affected by an incident involving the refrigerant or air-conditioning system.

- Consideration of controls and other factors that could be implemented to mitigate the hazard and risk to all phases of life cycle.

- Assessment and qualification of risk for each life cycle phase.
- Referencing of all information and data sources.
- Compliance with relevant codes and standards.
- Training for workers in the use of gases in refrigeration or air-conditioning.
- Safe operation of refrigerant or air-conditioning workshops in which the gases are used.
- Signs, Safety Notices and Certification that must be displayed.
- Define a criteria for a 'safe' system. Demonstrate that the proposal meets the criteria.
- Identification and adoption, where appropriate, of modifications that can be made to improve the intrinsic safety of the system.
- All claims or assumptions that are made need to be substantiated.
- Frequency of release should reflect air-conditioning usage and Australian conditions.
- Secondary fires as a result of a flashfire/ jet fire in the passenger cabin should be considered, along with the potential for an accident initiated by the gas leak and ignition.
- There are no known instances of fires with HC refrigerant in automobile air-conditions.
- Maintenance downtime in buses had decreased significantly from the use of HC product.

8.5 Findings from Workshops Surveys

The new data obtained from a total 68 surveys in Queensland, south Australia and Victoria were processed into statistically useable data, in the form of the following:

- Proportion of total vehicles serviced that have air-conditioning;
- Leak size distribution; and
- Leak location distribution.

The following comments are made with regards to the above results:

- All survey locations provided consistent values in terms of leak sizes.
- Survey results for Brisbane displayed a higher tendency for leaks arising from condensers followed by hoses and dryers. All these components are located in the engine bay.
- Approximately 52% of all vehicles are fitted with sir-conditioning systems. This value compares favourably with a statistic published by NSW Motor Vehicle Repair Industry Association of 50% (Ref.26).
- The majority of leaks fell between the leak classification of "pinhole" and "large".
- 44% of all leaks were defined as "pinhole". A pinhole leak was defined by the workshop mechanics as a leak that occurs over "a period of 3-6 months".
- 52% of all leaks were defined as "large". A large leak typically occurs in the engine bay where air-conditioning system components are typically moving or exposed to vibration and corrosion.
- Of the vehicles fitted with air-conditioning and assuming that the thermal expansion (Tx) valve is located on the passenger side of the firewall, a leak inside the cabin resulted in approximately 14% of the cases.
- In one instance in May 1999, involving a collision accident of a vehicle using ER12 in the air-conditioner in Victoria, the condenser was ruptured. Total loss of refrigerant occurred, and dispersed as a white cloud without ignition.

8.6 Scenarios Carried Forward for Quantitative Assessment

A list of scenarios considered for quantitative modelling is listed in **Table 8.2**. This list is a subset of all scenarios evaluated in **Appendix 3**.

TABLE 8.2
SCENARIOS CARRIED FORWARD FOR QUANTITATIVE ANALYSIS

HAZID No.	**Scenario**	**Status of Vehicle**	**Leak Location**		**Status of Air-conditioning System**	
			Cabin	**Engine Bay**	**On (Operational)**	**Off (Static)**
N-1	Leak under driving conditions	moving	■		X	
N-2	Leak under driving conditions	moving		■	X	
N-3	Total release of refrigerant	collision		■		
N-4	Leak when car is parked [1]	stationary	■			X
N-5	Leak when car is parked [1]	stationary		■		X
N-6	Leak under driving conditions	moving		■		X
N-7	Leak under driving conditions	moving	■			X
N-8	Leak from overcharged system	-	■	■		
W-1	Release of refrigerant in workshop	-				

Notes:

1. Denotes when car is either parked in a structure (i.e. garage) or outside (i.e. street).
2. "X" denotes applicable situation.

9. DEVELOPMENT OF LEAK SCENARIOS AND LEAK RATES

9.1 Purpose of Section

The purpose of this Section is to:

- develop a set of potential leak scenarios for ER12 release in the engine bay and passenger compartment;
- describe the basis for selection of the scenarios;
- postulate a rule set of representative leak sizes;
- list the operating parameters considered for release modelling;
- calculate the release rates and release duration, taking into account the depressuring of the system as the leak continues.

9.2 Release Scenarios

9.2.1 Basis for Release Scenarios

The FMEA workshops and the survey data showed that the component failures from which a release of refrigerant could occur as follows:

- compressor shaft and ‘O’ ring seals (vapour);
- Tx valve seal failure (2-phase);
- Evaporator (vapour – very small);
- Leaks at screwed fittings (2-phase release or vapour, depending on location in the engine bay or passenger cabin); and
- Hose failures (full bore vapour for hose lines at suction and discharge of compressor).

The leak size would depend on the following factors:

- size of gap in seal or ‘O’ ring;
- gap in screwed fittings; and
- potential for abrasion/ vibration, resulting in pipework/ component failure.

The above failures would result in a range of release sizes, varying from small pinhole leak/ hairline crack to full bore failure of hose connections. In risk analysis, it is normal practice to cover the range of release sizes by three representative hole sizes. In this study, the hole sizes selected were described as small, large and catastrophic. The term "catastrophic" is defined in this context as follows:

- instantaneous release of the entire refrigerant inventory in the engine bay from a collision accident or hose rupture; or
- release of entire inventory as a liquid in the engine bay in less than a minute; or
- release of entire inventory as a vapour in the engine bay or passenger cabin in about 10 minutes.

The FMEA workshops and the survey results identified that most leaks of refrigerants were of such low magnitude, that only a dye test or a pressure test could detect the leak. In most cases, the refrigerant inventory would leak out over days or weeks, rather than hours. These represent small leaks.

For hose failures, the leak sizes were taken as the equivalent hose diameter. These releases could occur only in the engine bay and not in the passenger cabin, as the hoses are connected to the suction and discharge of the compressor.

9.2.2 Experiments to Determine Release Characteristics of ER12

Prior to postulating specific hole sizes for the analysis, some experiments were conducted with ER12 refrigerant. The focus was on the Tx valve and evaporator and associated piping and joints, as these have the potential to release the refrigerant into the passenger cabin.

An automotive air-conditioning system known as the " test rig" was used for the experiments. In the test rig, Schrader valves had been welded in an automobile air-conditioning system at different locations. This allowed copper tubing of 0.1 and 1mm diameter to be attached to these valves. By opening the valve, ER12 was released to atmosphere from the test rig, and this enabled visual observation of leaks. The tests were conducted in open air to assist the safe dispersion of ER12 into the atmosphere. Details of the experiments are provided in **Appendix 9**.

In addition, Granherne also physically inspected components of automobile air-conditioning systems that were faulty (i.e.leaking). Consultations were held with accredited automotive air-conditioning mechanics in this regard.

The observation results on the release characteristics of ER12 are shown in **Table 9.1**.

TABLE 9.1
PHYSICAL RELEASE CHARACTERISTICS OF ER12

Location of Test Points in Air-conditioning System		**Observations**	
		Leak Size Category	**Phase**
		Air-conditioning System On	
A	upstream of Tx valve	catastrophic (1mm) major (0.1mm)	liquid/ two phase vapour
B	downstream of Tx valve	catastrophic (1mm) major (0.1mm)	vapour vapour
C	downstream of evaporator	catastrophic (1mm) major (0.1mm)	vapour vapour
		Air-conditioning System Off	
A	upstream of Tx valve	catastrophic (1mm) major (0.1mm)	liquid (<5sec)/ vapour vapour
B	downstream of Tx valve	catastrophic (1mm) major (0.1mm)	vapour vapour
C	downstream of evaporator	catastrophic (1mm) major (0.1mm)	vapour vapour

The following observations were made as a result of the tests:

- With the exception of a catastrophic release upstream of the Tx valve, a leak in the air-conditioning system when it is running will result in a vapour release. A liquid/ two phase release was observed for a 1mm leak upstream of the Tx valve, but only vapour release was observed downstream of the Tx valve.
- All releases from the air-conditioning system when it was static were observed to be vapour phase. For the 1mm release upstream of the Tx valve, there was an initial release of liquid (< 5 seconds) followed by a vapour release.
- The physical state of released refrigerant into the vehicle cabin was observed to be vapour phase. This was verified by the application of a leak detection solution around the cracked joint (during the beginning and conclusion of each experiment) and observing the formation of bubbles.

Photographs of the releases are shown in **Appendix 9**.

9.3 Development of Leak Size Rule Sets

Based on the FMEA workshops, survey data and visual observations of release of ER12 from small orifices in experiments, the hole sizes were selected for the three categories of releases. Details are given in **Appendix 6**.

9.3.1 Engine Bay

The hole size rule set for releases in the engine bay is listed in **Table 9.2**.

TABLE 9.2
ENGINE BAY RELEASE RULE SET

Leak Category	Equivalent Hole Size
Small	0.1mm
Large	1.0mm
Catastrophic	vapour – 12mm
	liquid – 8mm

Note: A full rupture of the system in the engine bay is possible in a vehicle collision.

9.3.2 Passenger Cabin

The air-conditioning components located within the passenger compartment of the vehicle are hard piped and there are no moving parts. This leads to the pinhole leak size of 0.01mm being the most likely due to a material failure which is often undetectable in the workshop. The hole size rule set for releases into the passenger cabin is listed in **Table 9.3**.

TABLE 9.3
PASSENGER CABIN RELEASE RULE SET

Leak Category	Equivalent Hole Size
Small	0.01mm
Large	0.1mm
Catastrophic	1mm

9.4 Case Studies Considered

The following cases were considered to cover the full operating range of the refrigerant, by varying the ambient conditions:

1. Base Case — Ambient temperature of 20°C. This is a typical ambient temperature used for engineering estimates in the southern parts of Australia.
2. Case 1 — High ambient temperature of 40°C. Temperatures in this range are experienced in the northern tropical regions of Australia and under extreme summer conditions in other parts of the country.

9.5 Summary of Release Rates

The calculated release rates for the various release scenarios postulated are listed in **Table 9.4**. The system pressure and temperature and type of release (vapour, liquid or 2-phase) are also shown in **Table 9.4**. The calculation methodology is provided in **Appendix 6**.

The values shown in **Table 9.4** are initial release rates when the leak commences. In reality, the leak rate would reduce following the initial leak due to depressuring of the system charge, especially for large leaks. This depressuring phenomenon also determines the leak duration for refrigerant charge to leak out. This is discussed in **Section 9.6**.

TABLE 9.4
LEAK RATES OF REFRIGERANT FROM AUTOMOBILE AIR-CONDITIONING SYSTEMS

Study	Passenger Compartment			Engine Bay		
	Phase	**Hole Size (mm)**	**Leak Rate (kg/s)**	**Phase**	**Hole Size (mm)**	**Leak Rate (kg/s)**
Air-conditioning System Operating (AC on)						
Base Case (typical)	Vapour	0.01	6.54E-08	Vapour	0.1	6.54E-06
	P= 260 kPag	0.1	6.54E-06	P= 260 kPag	1	6.53E-04
	T= 20°C	1	6.54E-04	T= 20°C	12	0.095
	2 phase	0.01	2.56E-07	Liquid	0.1	2.05E-04
	P= 260 kPag	0.1	2.56E-05	P= 1100 kPag	1	2.05E-02
	T= 5°C	1	2.56E-03	T= 48°C	8	1.31*
Case 1 (high ambient temperature)	Vapour	0.01	7.56E-08	Vapour	0.1	7.56E-06
	P= 331 kPag	0.1	7.56E-06	P= 331 kPag	1	7.54E-04
	T= 40°C	1	7.54E-04	T= 40°C	12	0.11
	2 phase	0.01	2.86E-07	Liquid	0.1	2.44E-04
	P= 331 kPag	0.1	2.86E-05	P= 1655 kPag	1	2.44E-02
	T= 10°C	1	2.86E-03	T= 64°C	8	1.56*
Air-conditioning System Static (AC off)						
Base Case	Vapour	0.01	1.03E-07	Vapour	0.1	1.03E-05
	P= 465 kPag	0.1	1.03E-05	P=465 kPag	1	1.02E-03
	T= 20°C	1	1.03E-03	T= 20°C	12	0.15
				Liquid	0.1	1.39E-04
				P=465 kPag	1	1.39E-02
				T= 20°C		
Case 1 (high ambient temperature)	Vapour	0.01	1.64E-07	Vapour	0.1	1.64E-05
	P= 836 kPag	0.1	1.64E-05	P= 836 kPag	1	1.64E-03
	T= 40°C	1	1.63E-03	T= 40°C	12	0.24
				Liquid	0.1	1.81E-04
				P= 836 kPag	1	1.81E-02
				T= 40°C		

* This is greater than the inventory, indicating instantaneous release of full inventory of 220-300 grams.

9.6 Release Duration from System Depressuring

Depressuring calculations were undertaken to estimate the release rate - time history and the duration of release. The calculations were performed using the software TNO EFFECTS 2.1, developed by the TNO organisation in the Netherlands. The calculations covered the following conditions:

- Vapour leak into passenger cabin: 0.1mm and 1mm leaks. The 0.01mm leak rate was too small to be of any significance, and was assumed conservatively to be constant.
- Refrigerant mass of 300 grams (large car) and 220 grams (medium and small cars). It was found that the total release duration was dependent on the initial mass of refrigerant in the air-conditioning system.
- Both cases of air-conditioning system running and air-conditioning system off.
- Two ambient temperature cases of 20°C and 40°C.

The depressuring curves for releases in the passenger cabin, namely at the evaporator and Tx valve are shown in **Appendix 6**. The following observations can be made from the results:

- It was found that the release rates for the two ambient temperature cases differed only by about 16%, with the higher ambient temperature obviously giving the higher release rate.
- The release duration for inventory depletion was essentially independent of the initial temperature, but dependent mainly on the total refrigerant inventory in the system.
- The release rates were approximately 30% higher in the case of air-conditioning off, than in the case of air-conditioning being operational. This is due to the fact that while the air-conditioning is operating, evaporator pressure and hence leak rate remains low. When the air-conditioning is turned off, there is pressure equilibration across the Tx valve over a period of time, and the evaporator pressure ultimately reaches the vapour pressure of the refrigerant at the ambient temperature.
- The release duration for the air-conditioning off condition was approximately 30% less than that for air-conditioning operational, reflecting the higher release rates.
- In the case of a liquid hose failure (8mm leak), the inventory depletion was nearly instantaneous, similar to a collision situation.

- Liquid leaks of 0.1mm would result in loss of inventory in 30-35 minutes (large leak).

The main purpose of generating the depressuring curves is that they form an input into the next step in the consequence analysis, namely estimation of ER12 concentration in the passenger cabin under various conditions. This is described in **Sections 10** and **11**.

PART IV HAZARD CONSEQUENCE ASSESSMENT

10. CONSEQUENCE ASSESSMENT

10.1 Purpose of this Section

The hazard consequence analysis forms one of the core sections of the Safety Report. The purpose of this Section is as follows:

- to present the steps involved in consequence assessment of postulated leaks of ER12 refrigerant;
- to provide an outline on the physical effects of the release of ER12, either into the engine bay or into the passenger cabin in terms of mixing, estimation of gas concentration, evaluation of ignition potential of released gas, and the impact of ensuing fire and/ or explosion, as appropriate;
- to outline the evaluation of the vulnerability of the consequences of ignition of a release, in terms of effect on people; and
- to summarise the structure of the consequence analysis described in detail in **Appendices 6** to **10**.

10.2 Structure of Consequence Analysis

The structure of consequence analysis is shown in **Figure 10.1**. It covers the following aspects:

- modelling of gas mixing in passenger cabin and development of concentration profiles for a range of parameters;
- modelling of potential ignition of gas in passenger cabin with resulting flashfire or explosion;
- modelling of fire/explosion in the engine bay; and
- estimation of the impact on people in the event of realisation of the hazard.

Where it was found that the consequences of specific incidents would have no adverse effect on people, these were screened out and were not carried forward for frequency analysis and risk assessment. Only those events that could adversely impact on people were carried forward.

This section is essentially a summary of the detailed analysis presented in **Appendices 6** to **10**.

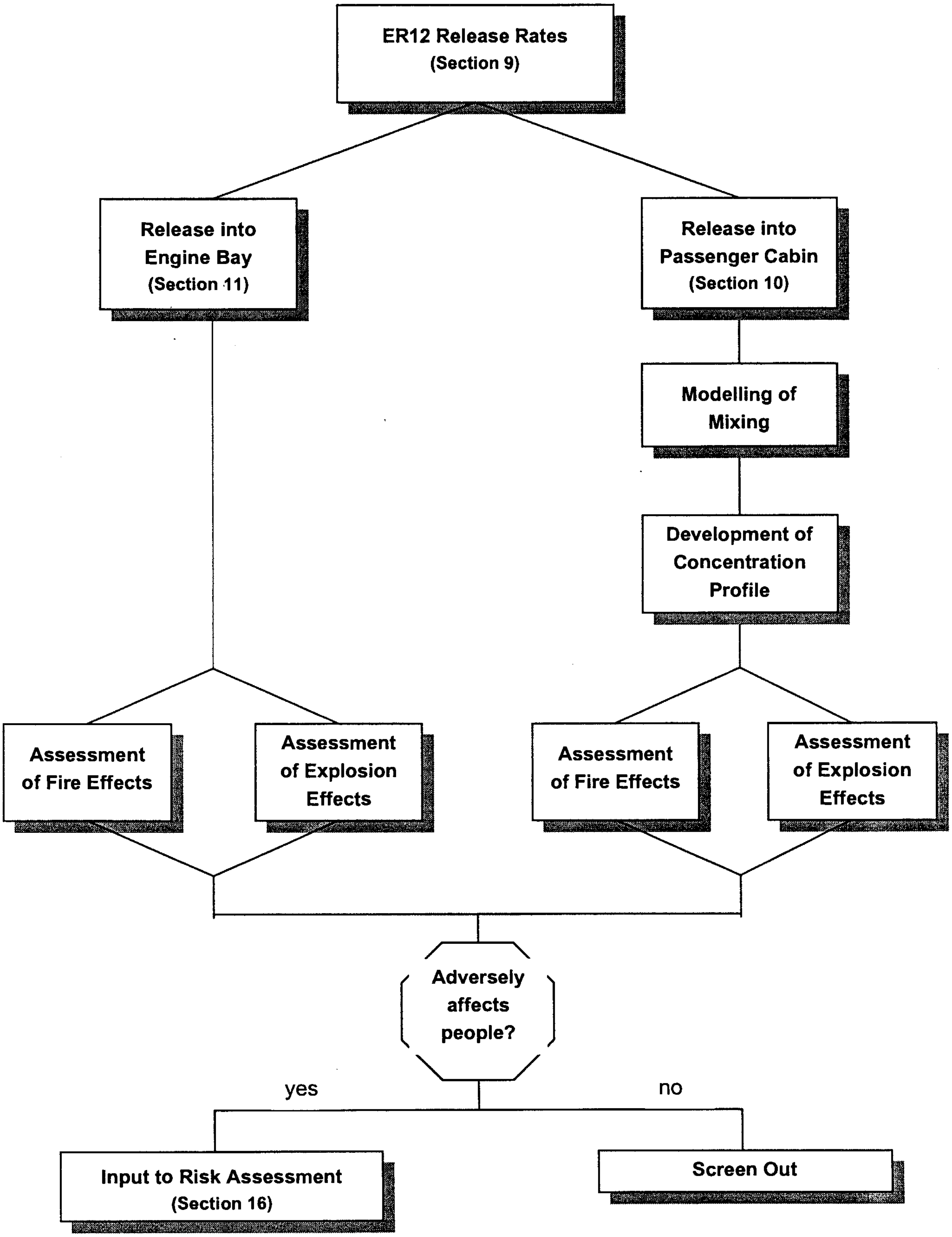


FIGURE 10.1
OVERVIEW OF CONSEQUENCE ANALYSIS

10.3 Parameters Modelled in Passenger Cabin

There are a number of variables involved in the study, all of which have to be modelled to cover possible release scenarios in the passenger cabin. The following variables were modelled:

- Size of car (large, medium and small);
- ER12 charge mass (based on air-conditioning system design);
- Vehicle in motion;
    - air-conditioning on or off,
    - Ventilation on fresh air or recirculated air;
- Vehicle parked;
    - In the open,
    - Within an enclosure (garage);
- Leak rate (depends on hole size, 0.01, 0.1 and 1mm).

11. ANALYSIS OF FIRE AND EXPLOSION POTENTIAL IN PASSENGER CABIN

11.1 Release Characteristics

In order to determine the characteristics of a hydrocarbon refrigerant release under pressure, it was necessary to conduct dispersion modelling. The results of this analysis formed a direct input into the development of the concentration profile models.

Since the refrigerant vapour is heavier than air, one would expect that a release would slump to the floor. However, a vapour release under pressure results in a turbulent momentum jet with significant air entrainment and mixing. The mixing profile is best determined by actual field experiments using a tracer gas density similar to the ER12 vapour.

A series of experiments involving ER12 and with a tracer gas (carbon dioxide) was undertaken to investigate the mixing characteristics. The main purpose was to determine the following:

- whether upon release the hydrocarbon refrigerant would be either uniformly distributed (concept of "well mixing") or slump to the floor in the vehicle's passenger cabin; and
- to measure typical gas concentrations as a function of time.

Details are given in **Appendices 9** and **10**.

The following observations were made as a result of the experiments:

- The experimental results showed that for a "typical leak" within the passenger cabin, the refrigerant concentration would be well below the LFL. This supports the claims by workshop personnel that refrigerant leaks are typically very small and cannot be detected.
- For a "large leak" of refrigerant vapour, the concentration within the cabin would be lower than the LFL and could be detected by smell.
- The results also showed that the concentration in the vehicle would reach a peak steady state value even if it was parked overnight in a garage.
- The tracer gas experiments have clearly shown the atmosphere in the passenger cabin will be well mixed within 2 to 20 minutes, even if the released gas is heavier than air.

The overwhelming conclusion of the experiments was that near uniform mixing occurs within the passenger cabin, without stratification. This was mainly attributed to turbulent momentum jet effects of the released vapour in entraining the surrounding air, as well as the small release rates. The mixing characteristics were also confirmed by jet dispersion modelling, using a free turbulent jet dispersion software TECJET. Details of jet dimensions are provided in **Appendix 7**.

11.2 Concentration Profile in the Passenger Cabin

11.2.1 Air Exchange Rates in Passenger Cabin

The ventilation rate or Air Exchange rate per Hour (ACH) is a measure of the leak paths in the vehicle body. A vehicle will exhibit a low ACH if all vents are closed and the vehicle stationary. Conversely, a vehicle in motion would have a high exchange rate, especially if it were drawing through the fresh air vents.

There has been some research conducted by universities and government agencies such as the UK Health and Safety Executive (UK HSE) into quantifying and developing correlations of ACH (Ref.20). This is a comprehensive study and has been conducted under controlled conditions to obtain reliable results.

The measurements indicated that for all air vents in a closed position, the ACH increased with increasing speed of the vehicle, the ACH varying from 15 at 54 kph to 35 at 108 kph.

For the present study, an ACH of 10 was used to cover low speeds in built-up areas, as a conservative measure.

For parked vehicles, the HSE correlation as well as Granherne's field experiments (**Appendix 10**) were used to estimate the ACH. The values used in the study are summarised in **Table 11.1**.

TABLE 11.1
ACH VALUES TO USE IN SAFETY STUDY

Situation	Car Type[1.]	Minimum ACH Value (h^{-1})	Comment	Ref.
Vehicle parked in enclosure (winter day and evening)	Late Model	0.3	Experimental	App.10
	Early Model	0.3	Experimental	App.10
Vehicle parked in open area (winter day and evening)	All models	1.0	Experimental / HSE	App.10/ Ref.20
	Late Model	0.7	Experimental / HSE	App.10/ Ref.20
	Early Model	1.1	Experimental / HSE	App.10/ Ref.20
Vehicle Moving	All Models	10	HSE	Ref.20

Note: 1. Early model is defined as pre-1988; late model as post 1988.

11.2.2 Estimation of Concentration Profiles in Passenger Cabin

The concentration profiles were estimated by a mathematical model, subject to the following assumptions:

- uniform mixing in passenger cabin – this assumption is supported by experiments;
- time-variant release into the cabin as a result of system depressuring over time; and
- ventilation rates for vehicles from **Table 11.1** above.

The mass balance constitutive equation for ER12 was integrated to obtain an analytical expression for concentration-time history. Details are provided in **Appendix 7**.

11.2.3 Conclusions from Gas Mixing Modelling

11.2.3.1 Concentration Levels Analysed

The analysis focused on ER12 concentration at three levels:

1 Lower Flammability Limit (LFL). This corresponds to a concentration of 0.04 kg/m^3 in air. It is normally considered that below this concentration, ignition is not possible.

2 50% of LFL. This corresponds to a concentration of 0.02 kg/m^3. Since there are fluctuations in gas concentration associated with turbulent mixing in the

passenger cabin, a value of one-half LFL is also used in practice to estimate ignition potential.

3 20% of LFL (0.008 kg/m^3). This value is the practical limit of Class A3 refrigerants, suggested by AS/ NZS 1677.1 – 1998 (Ref.7).

The analysis was conducted in two different ways:

1. For the various postulated releases, the minimum ACH required limit gas concentration to a specific level was estimated. This ACH was then compared with the available ACH data to determine whether or not a specific concentration would be exceeded. This method was used for the case of vehicle in motion.

2. For the measured ACH in stationary vehicles the concentration-time profile in the passenger cabin was calculated, using the time dependent release rates for the various release scenarios. This profile was reviewed to determine if LFL or 50% LFL concentration would be reached, for ignition potential.

11.2.3.2 Vehicle in Motion with Air-conditioning On or Off

For vehicle in motion the conclusions were the same regardless of whether the air-conditioning was on or off. The following conclusions were reached:

- For all leak sizes, the concentration in the passenger cabin would not reach LFL.
- For large releases (0.1mm hole size), the concentrations within the passenger cabin were less than 1% of the LFL for all car types.
- For catastrophic leak size of 1mm (i.e. entire refrigerant inventory leaks in less than 10 minutes), and vents open, the concentration in the passenger cabin would exceed 20% LFL, but would be less than 50% LFL.
- While the air-conditioning is on, the maximum concentration of vapour in the passenger cabin from a potential release would not reach a level that could ignite.
- For the case of vents closed (recirculated air), and for catastrophic releases (1mm hole size), and low speed travel, the concentrations within the passenger cabin could reach 50% LFL for small cars for air-conditioning on or off, and for medium sized cars when the air-conditioning is off.

11.2.3.3 Vehicle Parked in the Open or in the Garage

For the vehicle parked, catastrophic leak has been discounted as non-credible. Only the typical and large leak scenarios have been analysed. The following findings were made:

- The concentration within the vehicle rose steadily to a maximum until the refrigerant was fully released, and then gradually declined as the refrigerant leak had stopped due to inventory depletion.
- The peak concentration in the cabin was highest for the larger leak size and if the vehicle is parked in an enclosure.
- The peak concentration did not reach LFL levels at any time.
- The peak concentration for large and medium sized cars did not reach 50% LFL concentration at any time, for cars parked in a garage.
- For cars parked in the open, 50% LFL concentration was not reached even for large leaks, for all car types.
- The peak concentration for small cars reached 60% LFL after 3.2 hours, but dropped to 26% of LFL after 6 hours, and 8% of LFL after 10 hours.
- For typical leak of 0.01mm hole size, the maximum concentration was less than 1% LFL for all car types, whether in the open or inside a garage.

An LFL concentration could be reached in the cabin of a stationary vehicle, only in the unlikely event that a rupture of the air-conditioning system occurred on the passenger side of the firewall (i.e. from an accident). This event is considered remote given that the vehicle is stationary (i.e. engine not running) and the air-conditioning system is not operating. Further, the components of the air-conditioning system located on the passenger side of the firewall (i.e. evaporator and Tx valve depending on design) are static with no moving parts.

11.3 Results of Explosion Analysis in Passenger Cabin

11.3.1 Mechanism of Combustion and Pressure Rise

In order to determine the explosion potential of a hydrocarbon refrigerant vapour-air mixture in the passenger cabin, it is necessary to understand the phenomenon of combustion and pressure buildup, that ultimately results in an explosion. The following summary has been extracted from Ref.28.

When a flammable vapour-air mixture is ignited by a weak ignition source (i.e. a spark or a hot surface), the flame starts as a laminar flame. The laminar flame propagates at a relatively slow speed. However, two factors could cause a pressure buildup. These are:

- fast flame propagation due to obstacles in the flame front resulting in enhanced turbulence; and
- burning in a confined volume.

In addition, the consequences and probability of occurrence of gas explosions depend on a number of parameters. Typical of these are:

- type of fuel. A stoichiometric mixture of fuel will give rise to explosion overpressure in the following order: Hydrogen > Acetylene > Ethylene > Ethane > Propane > Methane. Butane falls into the same category as propane and methane.
- concentration of fuel in the hydrocarbon-air mixture. When the gas concentration in the mixture is near the flammability limit, the burning rate will be very low. However, in a confined situation, there is potential for an increase in pressure.
- For single fuels, the maximum explosion pressure is normally observed at stoichiometric or slightly richer mixtures. In other words, for mixtures close to LFL, there may not be a pressure rise at all, depending on the system geometry (confinement and obstacles to flame front).
- Mixtures that ignite at the edge tend to have lower pressure rise than those ignited in the middle of the cloud.
- In an experiment conducted at the Christian Michelsen Research in Norway (Ref.28), mixtures of ethane and propylene at various concentrations were ignited, and the resulting explosion pressure rise measured in a 1m wedge shaped vessel. The results are shown in **Figure 11.1**.

It was observed that the maximum pressure rise occurred at stoichiometric compositions (5.6% for ethane and 4.4% for propylene). Further, pressure rise occurred in a narrower range compared to the flammability limits. For instance, the pressure rise range was between 3% and 8.5% for propylene, whereas the LFL and UFL are 2.4% and 10.3% respectively. Similar results were obtained for ethane. It was concluded that the concentration range for significant explosion overpressure was dependent on the system geometry.

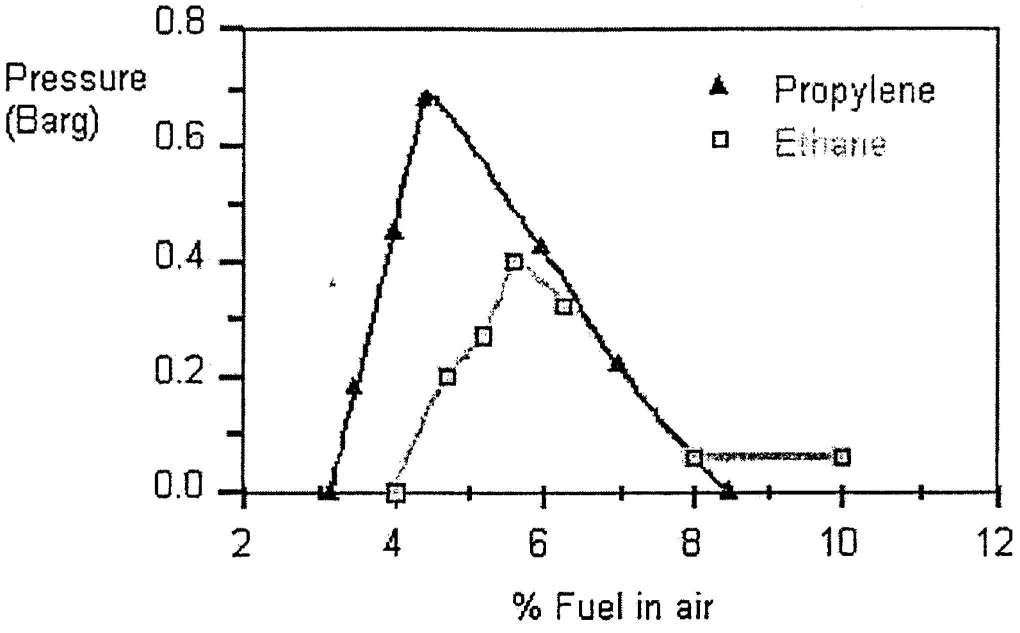


FIGURE 11.1
PEAK PRESSURE VERSES FUEL CONCENTRATION (%vol) IN AIR

11.3.2 Estimation of Explosion Pressure Rise

The estimation of gas concentration in the previous sections indicated that only in a few instances a value of 50% LFL was exceeded and that in no instance, an average concentration of LFL was reached in the passenger cabin. This is a significant finding.

If we utilise the experimental results in **Figure 11.1** as an indication, the following observations may be made:

- Since the minimum concentration at which pressure rise begins to occur is higher than LFL, then for the conditions predicted in the motor vehicle, where average LFL is not reached, there would be no explosion at all, but rather a flashfire would result, if ignited.
- Even if the pressure rise begins at LFL concentration due to high degree of confinement and obstacles in the system geometry, the pressure rise would be significantly lower than that at stoichiometric concentration, with pressure rises of the order of 0.1 bar.
- This conclusion is also supported by the study in Ref.29, who has stated that the maximum overpressure for a 3m^3 cabin volume, with all the windows closed, was 0.14 bar (14 kPa). The concentration of the gas mixture for this experiment has not been stated.

It may be concluded that the potential for realising an overpressure from an explosion is very low, with mainly the likelihood of a flashfire. Even if an overpressure of about 0.1 bar (10 kPa) were realised, this is insufficient to result in fatality to the person opening the vehicle door (Ref.30). An injury is, however, possible.

11.4 Fire Analysis in Passenger Cabin

11.4.1 Methodology

Flashfire calculations were carried out for a potential flashfire of released refrigerant vapour in the passenger cabin. Details are given in **Appendix 7**. The methodology adopted was as follows:

- calculate the flame temperature from combustion characteristics of the vapour content in the cabin.
- calculate the incident heat flux on the passenger from flame temperature and emissivity.
- estimate the flashfire duration from established correlations for hydrocarbon fireballs (Ref.31).
- Calculate the thermal load using the method of Hymes et al. (Ref.32) to assess injury potential. A thermal load of 1060 s.(kW/m^2)$^{4/3}$ is equivalent to 1% chance of fatality.
- Use the probit method for calculating the potential for fatality, 2nd degree burns and 1st degree burns (Ref.31).
- Sensitivity analysis calculations were carried out for the following two cases, for a typical passenger vehicle volume of 4 m^3.
  - average concentrations in the passenger cabin at 50% LFL; and
  - average concentration in the passenger cabin at 100% LFL. This case covered those situations where the vapour concentration exceeds 50% LFL, but does not reach 100% LFL.

11.4.2 Results of Fire Analysis

The following findings were made from the flashfire calculations:

- The duration of the flashfire for the 50% LFL and 100% LFL cases were 0.44 and 0.53 seconds respectively. Smaller passenger cabin volumes would give lower duration due to correspondingly lower hydrocarbon content in the cloud.

This means that the flashfire would be virtually instantaneous and the vapour would burn out.

- There is no risk of fatality for such short duration exposures for both cases, as the thermal load calculated was one order of magnitude less than that required to result in 1% chance of fatality.
- There is no risk of 2nd degree burn injury for both cases.
- There is no risk of 1st degree burn injury for the 50% LFL case, but there is approximately 80% chance of first degree burns if the vapour concentration reached 100% LFL.

11.5 Conclusions

The following conclusions were reached as a result of the analysis of fire and explosion potential in the passenger cabin:

- since the maximum concentration of vapour for all conditions would not reach LFL concentrations, the potential for ignition is very low;
- it has been conservatively assessed that should a source exist, ignition is possible if the vapour concentration is at or above 50% LFL. This presupposes a peak to mean ratio of 2, a value recommended in practice (Ref.21);
- since stoichiometric concentration is never reached, the potential for significant pressure rise from the ignition of a vapour-air mixture of about 50% LFL is low. Peak pressures are estimated to be about 0.1 bar (10 kPa). The outcome is more likely to be a flashfire;
- at these overpressures, there is little chance of fatality, but injury to exposed people is possible; and
- the duration of a flashfire was estimated to be about 0.4-0.5 seconds. Since the duration of exposure is extremely short, the thermal load is 5-10 times lower than that required for 1% chance of fatality. Therefore, the consequence is expected to be first degree burns to exposed people rather than fatality, or second degree burns.

12. ANALYSIS OF EXPLOSION AND FIRE POTENTIAL IN ENGINE BAY

12.1 Release Characteristics

The engine compartment is open to the ground. Therefore, there are always air changes occurring, that would dilute a release and disperse the vapour. Since there is a high degree of congestion in the engine compartment, a jet release would impinge on equipment and lose its momentum, forming a vapour cloud. However, close to the source of release, considerable dilution would occur from momentum jet effects.

If the engine were running, a significant amount of air is being drawn into the engine compartment through the radiator fan. This is expected to dilute the release below the lower flammability limit. Since there are ignition sources within the engine compartment, should a release ignite before being diluted, a flashfire would occur. If there is insufficient venting of the combustion gases, then there would be pressure rise with corresponding explosion effects.

A large release in the engine compartment, capable of causing a full inventory release instantaneously, could occur from a traffic accident. It is less likely to occur from a full bore hose failure, which is robustly fitted to the suction and discharge of the compressor.

12.2 Results of Fire Modelling in Engine Bay

The release rate for a 1mm leak in the engine bay was calculated as 1.63 g/s. The leak duration would last about 2 minutes (see **Appendix 6**).

At a leak rate of 1.63 g/s, if ignition occurred, the jet fire would be localised, would last for less than 2 minutes and hence any damage potential is very low. Such a fire would have no adverse impact on the passengers. Gas dispersion calculations showed that the distance to LFL concentration was only 0.4m.

An instantaneous release following a collision is more likely to occur from a condenser/ receiver rupture. This would generally disperse as a white vapour cloud. There has been one reported incident of an accident involving a vehicle with ER12 refrigerant in the air-conditioning system. On impact, the refrigerant was released as a vapour cloud and dispersed without ignition.

If the vapour cloud ignited in a collision incident, it would burn as a flashfire in the open. The total fire duration of the flash fire is estimated to be 0.3 seconds (Ref.33). No damage or adverse effects to personnel would occur from this incident.

12.3 Results of Explosion Analysis in Engine Bay

As mentioned above, if the vapour is well mixed in the engine bay and finds an ignition source, a vented explosion would occur. By vented explosion is meant the potential for the expanding combustion gases to escape through openings in the compartment, i.e. to the ground.

There are many correlations for predicting pressure rise in vented explosions (Ref.34). The predicted results can vary up to one order of magnitude. Therefore, the normal practice is to use more than one method and select a pessimistic value for conservatism.

In this study, the explosion pressure rise was predicted by two different methods. Details are given in **Appendix 8**.

The maximum pressure rise predicted by the two methods gave value of 0.042 kPa and 0.11 kPa respectively. Since the explosion venting models do not allow for obstacles in the vent path, and that there are significant obstacles from the top of the engine bay to the floor, it is expected that the pressure rise would be much higher, perhaps up to 10-fold.

The Arthur D. Little study (Ref.29) predicted a value of 2.7 kPa. The method of calculation has not been given.

These values indicate that the combustion products would be vented through the gap between the engine bay and the ground, preventing any damage from explosion effects. A pressure rise of the order of 3 kPa, would cause window breakages (Ref.35) in conventional buildings, and would not significantly affect robust metallic equipment in the engine bay. In any case, there would be no adverse impact on passengers.

12.4 Conclusions

The following conclusions were arrived at from the analysis of potential fire and explosion in the engine bay.

- When the engine is running, there is significant air ingress into the engine bay from the radiator fan. This would tend to dilute a refrigerant release and hence the potential for ignition is very low.
- When the engine is not running, a potential refrigerant leak would tend to dilute and disperse through natural air changes in the engine bay, due to the open area present at the floor of the engine bay.
- Should an ignition occur near the source, the maximum jet flame length would be less than 0.4m, and the fire duration would be a maximum of 2 minutes. This fire

could cause localised damage, but would have no adverse impact on the passengers.

- Should a vapour cloud form in the engine bay and ignite, the pressure rise from combustion gases would be vented through the opening at the floor of the engine bay, and hence the expected pressure rise would be low. Not only the damage effect is predicted to be minimal, but there would be no adverse effects on the passengers either.

Since there is no risk to people from an incident in the engine bay, this scenario was not carried forward for frequency analysis and risk quantification.

13. INCIDENTS CARRIED FORWARD FOR FREQUENCY ASSESSMENT

Based on the consequence analysis, it was only necessary to carry forward those events that could potentially result in a 50% LFL concentration for frequency analysis. The other events do not have an adverse impact on the passenger and hence would not contribute to overall risk to passenger.

A summary of the consequence analysis is given in **Table 13.1**. Incidents carried forward for frequency analysis are shaded in grey.

TABLE 13.1
PASSENGER CABIN INCIDENTS CARRIED FORWARD FOR FURTHER ANALYSIS

No.	HAZID Grouping	Vehicle Status	Car Type	Fresh/ Recirc.	AC Status	Hole Size (mm)	Concn > 50% LFL
1	N-1	Moving	All	Fresh	On	0.01, 0.1, 1	No
2	N-7	Moving	All	Fresh	Off	0.01, 0.1, 1	No
3	N-1	Moving	Large	Recirc.	On	0.01, 0.1, 1	No
4	N-1	Moving	Medium	Recirc.	On	0.01, 0.1, 1	No
5	N-1	Moving	Small	Recirc.	On	0.01, 0.1	No
6	N-1	Moving	Small	Recirc.	On	1	Yes
7	N-7	Moving	All	Recirc.	Off	0.01, 0.1	No
8	N-7	Moving	All	Recirc.	Off	1	Yes
9	N-4	Stationary (inside)	Large	Recirc.	Off	0.01, 0.1	No
10	N-4	Stationary (inside)	Medium	Recirc.	Off	0.01, 0.1	No
11	N-4	Stationary (inside)	Small	Recirc.	Off	0.01	No
12	N-4	Stationary (inside)	Small	Recirc.	Off	0.1, 1	Yes
13	N-4	Stationary (outside)	All	Recirc.	Off	0.01, 0.1	No
14	N-8	Overcharged	Large	Recirc.	On/ Off	0.01, 0.1, 1	No
15	N-8	Overcharged	Medium	Recirc.	On	0.01, 0.1, 1	No
16	N-8	Overcharged	Medium	Recirc.	Off	0.01, 0.1	No
17	N-8	Overcharged	Small	Recirc.	On/ Off	0.01, 0.1	No
18	N-8	Overcharged	Medium	Recirc.	Off	1	Yes
19	N-8	Overcharged	Small	Recirc.	On/ Off	1	Yes
20	N-3	Collision	All	-	-	-	Yes

Note:
1. No loss of refrigerant incidents in the engine bay were found to affect the passenger compartment.
2. For those cases where 50% LFL is reached, it remains at this level only for a limited duration as concentration decay continues due to air changes.
3. It should be noted that the 50% LFL cutoff was not on a strictly 'yes' or 'no' basis, but based on judgement. In other words, situations where concentration had been marginally less than 50% have been included in the 50% category.

PART V FREQUENCY ANALYSIS AND RISK ASSESSMENT

14. FREQUENCY ANALYSIS

14.1 Introduction

In this study, frequency analysis involves estimation of the likelihood of occurrence of refrigerant leak events and the likelihood of various impacts following these events. The first requirement is to determine the frequency with which a certain emission rate could occur.

The fundamental data required for frequency analysis is the failure rate of each item of equipment. A considerable amount of information is available in the literature on automobile air-conditioning systems. However, the focus of this literature has been under the broad headings of air-conditioning systems, refrigerant replacements to CFC, and retrofitting components associated with air-conditioning.

Little or no data was available in the public arena on parameters useful for a safety assessment, such as quantification of leak frequency from air-conditioning systems. Car makers and air-conditioning equipment manufacturers were contacted, but no information was made available to Granherne due to confidentiality reasons.

It was therefore necessary to obtain the required data for the Safety Report directly from the field in the form of surveys. **Appendix 12** outlines the survey results and their interpretation as well as the data analysis performed to obtain the required frequency values.

14.2 Failure Rate Data Used in this Study

14.2.1 Field Surveys

Field surveys were carried out in Melbourne, Perth, Adelaide, and Brisbane of motor vehicle repairers to collect data for frequency analysis in this report. The survey took the form of a questionnaire that was filled in during face-to-face interviews with accredited automotive refrigeration mechanics in their workshop areas. A total 68 surveys were conducted to provide a reasonable sample size for statistical analysis.

The surveys included workshops that serviced only R134a (Brisbane), and both ER12 and R134a (Melbourne, Perth and Adelaide).

A summary of the survey results is shown in **Figures 14.1** to **14.3**.

FIGURE 14.1
LEAK SIZE DISTRIBUTION IN ENTIRE AIR-CONDITIONING SYSTEM
(ENGINE BAY AND PASSENGER CABIN)

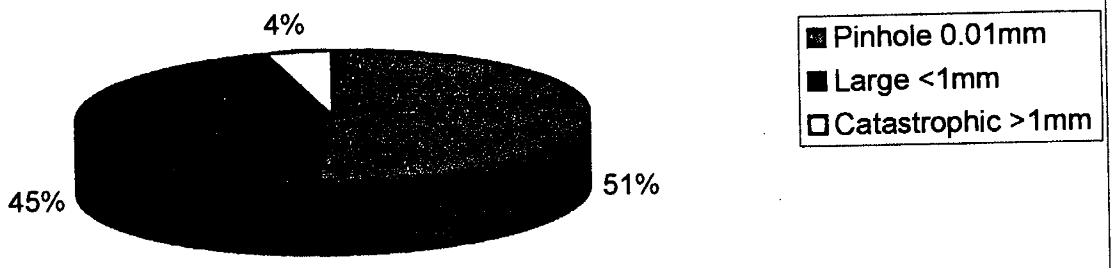


FIGURE 14.2
DISTRIBUTION OF LEAK LOCATIONS IN ENTIRE AIR-CONDITIONING SYSTEM

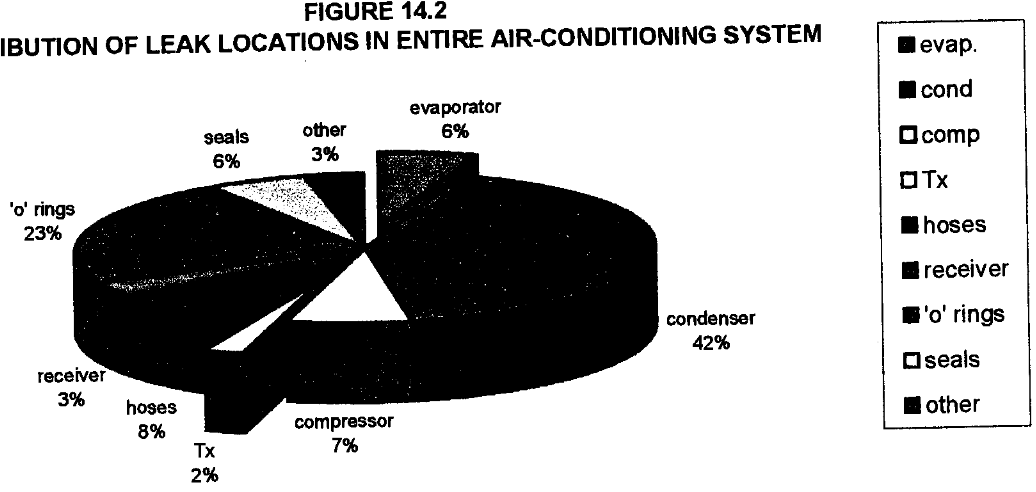
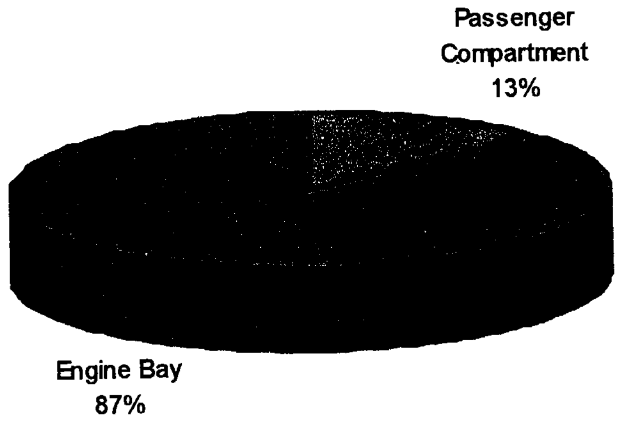


FIGURE 14.3
DISTRIBUTION OF LEAK SOURCES IN ENGINE BAY AND PASSENGER CABIN



The following comments are made with regards to the above results:

- All survey locations provided consistent values in terms of leak sizes.
- Survey results for Brisbane displayed a higher tendency for leaks arising from condensers followed by hoses and driers. All these components are located in the engine bay.
- Approximately 52% of all vehicles are fitted with air-conditioning systems. This value compares favourably with a statistic published by NSW Motor Vehicle Repair Industry Association of 50% (Ref.26).
- The majority of leaks fell between the leak classification of "pinhole" and "large".
- 44% of all leaks (including engine bay and passenger cabin) were defined as "pinhole". As given in **Appendix 12**, a pinhole leak was defined by the workshop mechanics as a leak that occurs over "a period of 3-6 months". The majority of leaks in the passenger cabin were pin hole leaks.
- 52% of all leaks were defined as "large". These included leaks in engine bay and passenger cabin, but predominantly the passenger cabin.
- Of the vehicles fitted with air-conditioning and assuming that the thermal expansion (Tx) valve is located inside the firewall, approximately 14% have exhibited a leak inside the passenger cabin.
- There were no "catastrophic" leak incidents identified inside the passenger cabin. Leaks of this category occurred in the engine bay, and mainly from motor vehicle accident events.

14.2.2 Estimation of Leak Sources by Parts Count

The total frequency was obtained by multiplying an individual component leak frequency by the number of component parts. A detailed parts count is given in **Appendix 12**.

The drawings of the basic components of the air-conditioning system are shown in **Figures 2.1** and **2.2**. The location of the various components of the air-conditioning system may be conveniently divided between the engine bay and passenger cabin. These two areas are separated by the firewall.

The distribution of the fittings within the vehicle were obtained as shown in **Table 14.1**.

TABLE 14.1
DISTRIBUTION OF 'O' RING FITTINGS

Location	Number of 'O' Ring Fittings	% of Total
Engine Bay	6	75
Cabin	2	25
Total	8	100

14.2.3 Estimation of Base Frequencies

Only evaporator and Tx valve base failure frequencies were calculated as they are the only two components that can fail and cause a leak into the passenger compartment of a car. The base frequencies are shown in **Table 14.2**. Details of derivation of the frequencies are shown in **Appendix 12**.

TABLE 14.2
BASE FREQUENCY VALUES

Component	Base Frequency Value
Evaporator	0.00191 evaporator failures /car-year
Tx valve fittings	0.043 Tx valve failures /car-year

A leak frequency for each leak category (typical, large, catastrophic) was required for use in the risk calculations. These values were calculated by allocating the following distribution to the base frequencies given in **Table 14.2** as follows:

Typical (0.01mm)	90% base frequency
Large (0.1mm)	9% base frequency
Catastrophic (1mm)	1% base frequency

Since there has not been a catastrophic leak inside the passenger cabin in a total of 46,950 car-years surveyed, a hypothetical failure frequency was derived using a binomial distribution, for a 50% confidence limit. This gave a value of 0.8% of the base frequency. Therefore, a value of 1% was ascribed. The 90/9 split of the remaining value is based on a pessimistic assumption, as the survey indicated that the potential for a "large" leak in the evaporator is extremely low.

14.2.4 Refrigerant Release Frequencies

The calculated refrigerant leak frequencies are shown in **Table 14.3**. Details of calculation are shown in **Appendix 12**.

TABLE 14.3
LEAK FREQUENCY DISTRIBUTION

Component	Leak Category	Leak Size (mm)	Leak Frequency (/ car-year)
Intrinsic			
Evaporator	Typical	0.01	1.72E-03
	Large	0.1	1.72E-04
	Catastrophic	1	1.91E-05
Tx valve	Typical	0.01	3.87E-02
	Large	0.1	3.87E-03
	Catastrophic	1	4.3E-04
Collision			
AC system	Catastrophic	1	1.78E-03 (Ref.27).

Note: 1.72E-03 denotes on average 1 car in 600 car-years.

14.2.5 Event Frequencies

From the base frequencies in **Table 14.3**, the event frequencies were derived using the probabilities listed in **Table 14.4**. Details of the derivation are given in **Appendix 12**.

TABLE 14.4
PROBABILITIES USED IN ASSESSMENT

Probability Description	Value
Tx valve inside passenger cabin	0.6
Overcharged system with refrigerant	0.09
Moving car	0.075
Stationary car	0.925
Parked inside	0.5
Large Car	0.4
Medium sized car	0.1
Small car	0.5
Fresh air vents closed	0.5
AC on	0.4
AC off	0.6
Leak in engine bay due to collision	0.99
Leak in cabin due to collision	0.01

The probabilities shown in **Table 14.4** are based on the following information:

- number of new cars sold in Australia in 1998 (Ref.36) for large, medium and small car distribution;
- total cars registered in Australia (1995-1999) from Australian Bureau of Statistics (Ref.36);
- vehicle accident data resulting in serious injury/ fatality from Federal Office of Road Safety (FORS) (Ref.37);
- risk assessment report for use of hydrocarbon refrigerants in motor vehicles in Ref.29.

The event frequencies calculated are summarised in **Table 14.5.**

TABLE 14.5
INITIATING EVENT FREQUENCIES FOR RISK ASSESSMENT

Event Numbers	Event Description	Initiating Frequency /vehicle-year
6, 8, 12	Small car, 1mm leak	2.25E-05
8	Medium/ large car, 1mm leak	2.25E-05
12	Small car, 0.1mm leak	2.02E-04
18	Medium car, 1mm leak	4.49E-06
19	Small car, 1mm leak	2.25E-05
20	Collision	8.90E-05

Note: 2.25E-05 denotes on average 1 in 44,000 car-years.

14.3 Estimation of Ignition Probability

14.3.1 Potential Ignition Sources

A review of car passenger vehicle electrical systems was undertaken to identify areas where a potential ignition source existed. It is expected that the most likely source of ignition is operation of electrical switches and relays on closing and opening. Another possible source is electrical motors fitted with carbon bushes which have the potential for spark generation. The report by Arthur D Little for the US Department Energy (Ref.3) contains the results of a series of experiments conducted with ignition of non-inert refrigerants. it was found that only high energy ignition sources could cause ignition and not lit cigarettes or in-car cigarette lighters.

The potential for spark generation is dependent on the following factors:

- the size of current running through the component;

- the amount of inductance in the system. High inductance circuits (such as relay coils, motor windings) can generate high voltages at contacts when switches are operated, which can in turn lead to arcing;
- the degree of sealing of electrical contacts from the atmosphere; and
- the amount of corrosion on components which can reduce the voltage at which arcing can occur.

Arcing can also occur as a result of failures such as electrical shorting. The probability of igniting a leak would depend on the likelihood of a short occurring, and the vapour is still in the flammable range.

14.3.2 Hot Surfaces

Hot surfaces such as engine manifold can be a potential ignition source in the engine bay. The autoignition temperature of ER12 is 550°C (see MSDS in **Appendix 1**). This is the lowest surface temperature at which combustion can be observed over the entire flammable range of an air-vapour mixture of ER12. A study by the Gas Research Institute in the USA (Ref.38) for liquefied natural gas vapour clouds has shown that the hot surface temperature required to ignite methane was significantly higher than the auto-ignition temperature.

In a study on non-inert refrigerants for automotive applications for the US Department of Energy (Ref.3), it was estimated that a minimum surface temperature of 800°C would be required to ignite a propane-air mixture. This rules out all the engine bay hot surfaces except perhaps an overheated exhaust pipe.

There are no hot surface ignition sources in the passenger cabin.

14.3.3 Screening of Electrical Ignition Sources

Appendix 11 provides a full list of electrical components in an automobile. It consists of the following categories:

- resistive circuits (relays and switches); and
- inductive circuits (motors).

The methodology used for screening out a potential source was as follows:

For resistive circuits:

1. For the given maximum voltage (taken as 16 volts for a fully charged battery), from Figure A.1 provided in AS 2380.7 "Intrinsic Safety i"(Ref.), determine the

minimum ignition current to ignite a mixture of propane and air (Group IIA material).

2. Measure the current across the selected resistive circuit. This was carried out by a licensed auto-electrician in a range of cars.

3. If the measured current in Step 2 is less than the minimum ignition current required as calculated in Step 1, then screen out the component as a potential ignition source.

For inductive circuits:

3. Measure the inductance of the selected component. This was carried out by Unisearch Limited, the consulting arm of the University of NSW.

4. For the rated current of the component, obtain the inductance that would provide the minimum ignition energy for Group IIA material, from Figure A.5 of AS 2380.7 I (Ref.25) This is given for a 24V supply. Adjust this inductance value for a 16V supply, to give the same ignition energy, using the relationship $E=0.5\ LI^2$. This step assumes constant resistance and hence uses the relationship $I = V/R$.

5. If the measured current in Step 2 is less than the minimum ignition current required as calculated in Step 1, screen out the component as a potential ignition source.

6. If the inductance measured in Step 3 is less than that calculated in Step 5, then screen out the component as a potential ignition source.

Calculation details are given in **Appendix 11**. It was found that none of the resistive circuits (i.e. switches) had sufficient current to exceed the minimum ignition current, and hence were ruled out as potential ignition sources.

Many of the inductive sources (motors) had sufficient stored energy to be potential ignition sources. In the passenger compartment, these included the following:

- Ventilation fan motor. However, when the ventilation fan motor is operational, the vehicle engine would normally be running, and under these conditions, no flammable mixture forms from a refrigerant leak.

- Power window winder motor. However, accumulated gas in the stationary vehicle would escape when the vehicle door is opened. If the vehicle is in motion, any leak in the passenger cabin would only result in a gas mixture of less than 20% LFL and hence there is no ignition potential even if the power windows were operated.

- Central locking mechanism.

Therefore, when the vehicle is parked, the central locking mechanism was found to be the only source with sufficient ignition energy, coincident with a potential for refrigerant vapour reaching above 50% LFL. However, the probability of ignition is still very low as the mechanism is located in a covered unit behind the upholstery panel in the door cavity, and is not exposed.

14.3.4 Probability of Ignition

The Arthur D. Little study for the US Department of Energy study on non-inert refrigerant for automotive applications (Ref.3) has evaluated the potential for ignition of propane-air mixtures and concluded that low amperage electrical circuits such as relay points, open/close contact sparking ignition wires, lit cigarettes and in-car cigarette lighters would not ignite the gas mixture.

Only high energy electrical sparks from circuits directly wired to the battery (100 amp circuits), fixed spark gaps in the ignition circuit, or very hot exhaust components were included as definite ignition sources. While high energy electrical sparks could occur in the engine bay from the coil, the resistive-inductive circuits in the passenger cabin do not have this energy.

In **Section 8.3.3**, some inductive circuits (motors) were shown to have the stored energy that exceeded the minimum ignition energy for ER12. However, these circuits are essentially in covered units and, even though not electrically sealed, are not directly exposed to the vapour-air mixture, unless the unit was damaged, or shorting occurred at the time of operation, releasing a high-energy ignition source. The probability of such occurrence is considered very low, as damage to these electrical components could only occur in a collision accident.

There has been one experimental work on estimating ignition potential of a flammable gas-air mixture by automobile electrical components, in a Gas Research Institute Report (Ref.38). The study was conducted only with natural gas-air mixtures at 7% concentration (close to stoichiometric composition). It was found that only a struck match could ignite the mixture, indicating that a high-energy ignition source is required. Ignition probabilities were derived from the tests and analysis. While the minimum ignition energy required to ignite propane is lower than natural gas (0.25 mJ compared to 0.29 mJ), the probabilistic approach can still be used to estimate an ignition probability for hydrocarbon refrigerant. Arthur D Little has done this evaluation in their risk assessment study on flammable refrigerants in automobile applications (Ref.29). A value of 0.03 for immediate ignition and 0.01 for delayed ignition was used in Ref.29. This includes all potential electrical ignition sources.

In this study, a value of 0.01 has been adopted for immediate as well as delayed ignition in the passenger compartment, for moving vehicles. For stationary vehicles, a value of 0.001 was used as there is only a single potential ignition source (i.e. the central door locking mechanism). This value is considered pessimistic due to the following reasons:

- The energy source available for ignition is considered low, and needs a fault condition.
- The door locking mechanism is normally placed behind the upholstery panel in the door cavity on both front doors, and the potential direct contact of refrigerant vapour-air mixture with the mechanism is very low.
- While the mean concentration for fully mixed conditions is above 50% LFL, the maximum concentration could exceed LFL only in pockets of poor mixing, and the probability of LFL concentration contacting the ignition source is considered low.
- A stoichiometric composition of refrigerant and air is never present in all the release scenarios analysed, under several parametric variations.
- The values used are for the passenger compartment only, whereas in Ref.29, the value has been used for all events, including the engine compartment, where there are additional sources of ignition.

15. RISK ASSESSMENT

15.1 Introduction

This section summarises the risk assessment carried out in the study. As mentioned elsewhere, the risk assessment consists of both qualitative and quantitative components. ER12 formulation, gas charging, maintenance on AC equipment in workshops and disposal were covered qualitatively. Normal operational life of the AC unit with ER12 were covered quantitatively.

For the scenarios carried forward for quantitative risk analysis, the results of the consequence and frequency analysis were combined for each outcome of each individual event, to obtain a measure of risk associated with each outcome. The individual contributions to risk from similar outcomes can be summed to provide an overall estimate of risk.

15.2 Risk Association with Manufacture of ER12 Formulation Risks

As described in **Section 5.2**, the manufacture of ER12 is carried out in two installations, in Melbourne and Adelaide. The raw materials (propane and iso-butane) and product (ER12) storage and handling are licensed by the respective government agencies.

The pressurised storage and handling of liquefied hydrocarbon gases has been a well established practice throughout Australia, covering storage terminals, automotive retail outlets, and industrial facilities. The main governing code is AS 1596-1997 LP Gas Code (Ref.16)

The main hazard associated with these installations are loss of containment, ignition and fire or vapour cloud explosion.

The following safeguards are provided in the installation and operation of these facilities:

- design and installation to comply with AS 1596 (Ref.16), applicable at that time;
- hazardous area classification to AS 2430 (Ref.39) for tanks, pumps and molecular sieves;
- flammable gas detection and alarm near iso-butane pump as it is unodourised;
- remotely activated emergency shut off valves on the outlet of all these tanks;
- tanks, pumps and decanting area in the open and well ventilated;
- cathodic protection for underground tank;

- installation within security fenced area;
- fire protection to meet the requirements of AS 1596 (Ref.16);
- operations conducted by trained operators only;
- external inspection of cylinders each time they are fitted;
- procedure for full inspection and pressure testing every 10 years in accordance with the Code;
- procedure for six monthly pressure testing of cylinder filling hoses;
- Boral Energy's corporate Safety Management System (SMS) applies to the installations. These include:
  - standard operating procedures;
  - control of ignition sources;
  - permit to work system including;
    - hot work permits, and
    - operator training;
  - incident reporting and investigation;
  - emergency procedures; and
  - annual corporate audits.

The Melbourne facility has been in operation since 1995 and the Adelaide facility since 1997. There have been no reported incidents of major gas leaks or fire.

Since the design, installation and procedures are the same as well managed LPG facilities, a quantitative risk assessment of the manufacturing facility was not considered necessary in this context.

15.3 Risk Associated with Use of ER12 in Automobile Air-Conditioning

In **Appendix 3**, a total of nine (9) scenarios were identified in relation to handling of ER12. Some of these were not safety related and were screened out. The remaining were clustered into two scenarios for further investigation.

W-1: Release of refrigerant in workshop during gas charging.

W-2: Workshop unaware that the AC system is charged with HC refrigerant.

A release of refrigerant could occur from the cylinder during gas charging if there is a hose failure. The following safeguards are in place:

- cylinders and hose visually inspected prior to use;
- no smoking in workshop;
- no hot work in workshop while gas charging occurred or air-conditioning system is worked on;
- any leak is immediately detected by odour;
- operator is present all the time, and can shut off the flow immediately.

The leak rate from a cylinder hose failure was calculated as 0.01 kg/s. The gas jet dispersion model gave distances to LFL and 50% LFL of 0.4m, and 1m respectively.

The training and procedures should ensure that there are no ignition sources within a distance of 3m to ensure safe dispersion.

The risk mitigation measures in the form a Safety Management System for the workshops and training of operators are addressed in **Section 17**.

In order to recognise that the air-conditioning system contains ER12, it is recommended that a label sticker by placed near the unit. This would be similar to the system used to identify LPG powered motor vehicles.

15.4 Disposal

There are two potential locations of disposal of the refrigerant:

1. In the workshop, prior to repairs.
2. In the wrecking yard when the vehicle itself is disposed of.

In the workshop, the disposal is carried out by venting the vapour to the atmosphere, in a controlled manner, over a period of 5 to 15 minutes, depending on the location and ventilation. As discussed in the risk assessment in the workshop, the distance to LFL from such releases is 0.5m. Risk of ignition is minimised by the following measures:

- whenever possible venting should be carried out in the open to maximise dispersion;
- no ignition sources within 3m distance of vent location; and

the risk reduction measures in the SMS for the workshops in **Section 16** should be implemented. In the case of disposal in the wrecking yard, there could be a tendency to cut the air-conditioning equipment using a power saw. This may result in a flashfire, and could cause injury to the operator. To minimise this risk, the following measures are recommended:

- identification tag for HC refrigerant; and
- information on handling safety to wrecking yards. This should emphasise that venting shall be carried out prior to any cutting;
  - no cutting operations to occur while venting takes place; and
  - procedures for safe venting.

15.5 Normal Operations

15.5.1 Outcomes of Refrigerant Release Events

Each of these incidents was analysed separately to give the various outcome frequencies. The outcomes used in this study following a release of ER12 refrigerant were:

- Diffuse fire (due to immediate ignition of ER12 refrigerant). There is insufficient time for buildup of refrigerant vapour to flammable concentrations in the passenger compartment.
- Flashfire/ explosion (due to delayed ignition of ER12 refrigerant). It has been shown in **Section 7** that an explosion is not likely for gas concentrations close to LFL. Gas concentrations nearer the stoichiometric values would be required for significant explosion effect.
- No effect to passenger (due to safe dispersion of ER12 refrigerant). In this case, an ignition did not occur.

The individual event frequencies could then be summed for each car type (small, medium, large) and for each incident outcome (diffuse fire, explosion/ flashfire, no effect).

15.5.2 Event Tree Analysis

Event Tree Analysis (ETA) is applied when an incident scenario can result in a variety of consequences. For this Safety Study, ETA identifies and evaluates potential outcomes that might result following a leak of ER12 refrigerant, normally called an initiating event. ETA is an inducting reasoning technique, which is used to evaluate the frequency and consequences of final outcomes, working from cause to effect. Event trees are logic diagrams showing the alternative ways in which a system can fail after a given initial event.

Event trees were developed from the initiating event through to the consequences resulting from the circumstances or state of the vehicle at the time of the event.

The probabilities of stated conditions were obtained from survey data and past risk assessment studies, as outlined in **Appendix 12**.

A total of 6 event trees were developed. These are shown in **Appendix 16**. The event trees covered the initiating events listed in **Table 15.1**.

TABLE 15.1
LIST OF EVENT TREE INITIATING EVENTS ANALYSED

Event No.	Event Description
6	Small car, moving, vents closed, AC on, 1mm leak
8	All cars, moving, vents closed, AC off, 1mm leak
12	Small car, stationary, inside, 0.1 and 1mm leak
18	Medium car, overcharged, AC off, 1mm leak
19	Small car, overcharged, AC off, 1mm leak
20	Collision

The results of the Base Case Event Trees are shown in **Table 15.2**.

TABLE 15.2
BASE CASE RESULTS

Event No.	Event Description	Outcome (/car-year)								
		Diffuse Fire			Flashfire/ Explosion			No Effect/ Safe Dispersion		
		S	M	L	S	M	L	S	M	L
6	Small car, moving, vents closed, AC on, 1mm leak	3.4E-09	-	-	3.3E-09	-	-	6.7E-07	-	-
8	All cars, moving, vents closed, AC off, 1mm leak	5.1E-09	2.3E-08	9.0E-08	5.0E-09	2.2E-08	9.0E-08	1.0E-06	4.5E-06	1.8E-05
12	Small car, stationary, inside, 0.1 and 1mm leak	1.1E-07	-	-	1.1E-07	-	-	2.2E-04	-	-
18	Medium car, overcharged, AC off, 1mm leak	-	1.2E-09	-	-		-	-	4.0E-07	-
19	Small car, overcharged, AC off, 1mm leak	6.1E-09	-	-	6.0E-09	-	-	1.6E-06	-	-
Sub-Total		1.3E-07	2.4E-08	9.0E-08	1.3E-07	2.3E-08	9.0E-08	2.3E-04	4.9E-06	1.8E-05
20	Collision	2.7E-08			4.3E-09			8.9E-05		
Total		2.7E-07			2.4E-07			3.4E-04		

Note: S,M,L in the table refer to Small, Medium and Large vehicles.

15.5.3 Sensitivity Analysis

The probability values used in the event trees were derived from statistical data where available. Where no data was available, engineering judgement was used. In order to test the assumptions made in the engineering judgements, a sensitivity analysis was conducted by varying these parameters. The results of the sensitivity analysis showed the changes in calculated risk values to the parametric variations.

The sensitivity analysis covered the case listed in **Table 15.3**.

TABLE 15.3
CASE STUDIES INVESTIGATED IN SAFETY STUDY

Case Study	Description	Variable
Base Case	Risk values calculated based upon values given in **Appendices 12** and **13**	-
Sensitivity 1	Vehicle stationary (Incident 12)	The probability of a car being parked in the open was changed from 0.5 to 0.7
Sensitivity 2	Vehicle in motion (Incident 6, 8)	The probability that a vehicle would be in motion was changed from 0.075 to 0.25
Sensitivity 3	Vehicle in motion (Incident 6, 8)	The probability that the AC is on was changed from 0.4 to 0.6
Sensitivity 4	Vehicle stationary (Incident 12)	The probability of ignition was increased from 0.001 to 0.01, an increase in one order of magnitude. This is a pessimistic case.

The results of the sensitivity analysis can be summarised as follows:

- For Sensitivity Case 1, the risk of a flashfire/ explosion within the passenger compartment in the small car decreased from 1.1×10^{-7} p.a. (1 chance in 9.1 million car-years) to 6.7×10^{-8} p.a (1 chance in 14.9 million car-years), a reduction of 40%. This risk is directly proportional to the time a small car is parked within an enclosure.

- For Case 2, the total risk of fire/ explosion in the passenger compartment in all vehicles increased from 2.4×10^{-7} p.a. to 2.6×10^{-7} p.a, an rise of only 8%. This result indicated that the risk contribution from vehicle in motion is not that significant compared to stationary vehicle.

- For Case 3, the total risk of fire/ explosion in the passenger compartment in all vehicles remained virtually unchanged, indicating that the contribution from AC operation to overall risk is only marginal.
- For Case 4, the total risk of firel/explosion increased to 2.5x 10^{-6} per annum, in proportion to the increase in probability of ignition.

15.6 Summary of Risk Results

A summary of the risk results for the use of ER12 in automobile air-conditioning systems is provided in **Table 15.4**. The risk is presented as the sum of the frequencies of a flashfire and diffuse fire from **Table 15.2**. Since it has been shown in **Section 7** that there is no potential for fatality for the passenger from any of the incidents analysed, but there is only a potential for injury, the risk has been expressed as passenger injury potential per car-year.

TABLE 15.4
SUMMARY OF RISK OF PASSENGER INJURY FROM USE OF ER12 FOR NON-COLLISION EVENTS

Case	Car Type	Passenger Injury Risk per car-year
Base Case	Small	2.5E-07
	Medium	4.7E-08
	Large	1.8E-07
Sensitivity Case 1	Small	1.6E-07
	Medium	4.7E-08
	Large	1.8E-07
Sensitivity Case 2	Small	2.9E-07
	Medium	4.7E-08
	Large	1.8E-07
Sensitivity Case 3	Small	2.5E-07
	Medium	4.6E-08
	Large	1.8E-07
Sensitivity Case 4	Small	2.3E-06
	Medium	4.7E-08
	Large	1.8E-07

The following observations may be made from the risk results:

- The risk of injury to passenger is of the order of 1 chance in 4 million per car-year for the base case.

- The risk of evaporator failure and flashfire in the passenger cabin from a collision accident was estimated as 3.1 $x10^{-8}$ per car-year in **Appendix 16**. This risk is much lower than the injury risk from intrinsic non-collision failures, as given in **Table 15.4**.

15.7 Evaluation of Risk

As stated in **Section 6.4**, since the study found that there is no fatality potential for the vehicle occupants from a release of ER12 vapour into the passenger cabin, it was not necessary to establish a fatality risk criteria for risk tolerability. Therefore a comparison was made of the risk of injury estimated in this study with available data on risk to occupants from general motor vehicle accidents. This would allow a better perspective of the risks of ER12 use in automobile air-conditioning system.

The risk of first degree burn injury to the vehicle occupant from a release of ER12 into the passenger cabin and ignition was calculated to be 1 chance in 4-million car years. The calculations also showed that there would be no risk of 2nd degree burn injury.

Since statistical data on motor vehicle accidents mainly contained fatalities rather than injuries, the only comparison that can be made is with fatal accident statistics for motorists on Australian roads.

In **Table 6.2**, risks to people from voluntary activities such as driving are listed. The risk of fatality from motor vehicle accidents is 1.45×10^{-4} per person-year, or one fatality per 6900 person-years on average. If we multiply this figure by the average number of vehicles on Australian Roads of about 10 million, an annual fatality figure of 1450 is obtained, which is reasonably consistent with generally available Australian data of about 1200 fatalities per year.

Data from Federal Office of Road Safety (Ref.37), reproduced in Appendix 12, shows that on average during 1992-1996, there have been a total of 19120 road accidents in Australia, resulting in serious injury or fatality. This gives a ratio of about 12 fatalities for every serious injury sustained. The above data does not include non-serious injuries and hence the ratio of injury to fatality is rather low, compared to the US data (Ref.3) which gives a ratio of 56 to 1 between injuries and fatalities.

Taking the Australia data of 12 to 1 for serious injury versus fatality risks from normal motor vehicle accidents, the risk of serious injury from motor vehicle accidents in Australia becomes $1.74x10^{-3}$ per person-year, or one serious injury per 574 persons per year on average.

A comparison with the injury risk from ER12 indicates that the risk of injury from ER12 is approximately 7,160 times lower than the risk of injury from normal motor vehicle accidents.

The risk of minor injury from fire/ explosion events in major hazards fatalities has been set at 20,000 per year or 1 chance in $5x10^{-5}$ p.a. (Ref.22).

A comparison of the estimated injury risk of 1 chance in 4 million car-years for ER12 use with the above criteria shows that the risk of injury is 200 times lower than the criteria in Ref.22.

Even for the worst case sensitivity analysis (Case 4), the risk of injury was 700 times lower than the serious injury risk in vehicle accidents, and 25 times lower than the risk criteria for injury to public from major hazard installations.

The above arguments lead to the conclusion that the risk from the use of ER12 hydrocarbon refrigerant in automobile air-conditioning system is extremely low, and should be considered tolerable.

The findings of this study are consistent with the findings of independent studies in Refs.3 and 29.

15.8 Management of Safety

Good maintenance of the AC unit is essential to ensure that the potential for large leaks or catastrophic leaks from component failures is minimised. This requires a number of safeguards:

- training of workshop operators in the safe procedures of gas charging to ensure that the unit has been correctly charged;
- testing of the air-conditioning system thoroughly for leaks and operational performance prior to handover to vehicle owner;
- information/ induction to the vehicle owner on the hazards of hydrocarbon refrigerant, and the need to periodically conduct an external inspection of the hoses and connections; and
- a hard-wearing warning label on the air-conditioning system located in the engine bay adjacent to the AC components, to state that it contains hydrocarbon refrigerant and shall not be opened except by an accredited automotive mechanic.

The issues related to managing safety in the workshop environment are discussed in **Section 16.**

16. RISK MANAGEMENT MEASURES

16.1 Safety Management Systems

16.1.1 Introduction

The handling of ER12 in workshops requires management of safety in terms of control of hazards associated with hydrocarbon storage and handling.

A Safety Management System (SMS) consists of a comprehensive set of policies, procedures and practices designed to ensure that barriers to unwanted incidents are in place, in use, and are effective. The focus in the context of ER12 use is on management of technical safety.

Boral Energy has prepared an information booklet on the safe handling of ER12, which is distributed to all dealers. However, a more formalised system and training are considered necessary.

This section addresses the safety management issues involved, and the procedures and training required.

16.1.2 Safety Procedures Required

A need for procedures in the following areas was identified:

- storage of ER12 cylinder in the workshop;
- gas charging;
- maintenance of AC system; and
- disposal.

16.1.3 Storage of ER12 Cylinder

The average cylinder weighs 9kg. Generally only one cylinder is kept in the workshop. When the cylinder level is low, another cylinder is ordered.

The safe storage of the cylinder is governed by AS/NZS 1596-1997, the LP Gas Code (Ref.16). The storage of a single small cylinder comes under "minor storage" in accordance with Table 2.1 of Ref.16. The following requirements apply:

- There shall be no ignition sources within a distance of 1.5m of the cylinder.
- When not in use, the cylinder should be stored outside the workshop building whenever possible (Clause 6.4.1), but inside storage is permissible for minor

storage, provided the outlet valve of the cylinder is securely closed (Clauses 6.5, 6.6.3(a)).

- Cylinders should be stored in a vertical position.
- Any oxygen cylinder stored in the workshop for welding purposes shall be kept at a distance of at least 3m from the ER12 cylinder (Clause 6.6.1 (e)).

16.1.4 Gas Charging/ Maintenance

Section 10 of AS/NZS 1596-1997 (Ref.16) lists a number of operational safety requirements. The requirements for gas charging operation are compiled from the checklist in this Standard, and are listed below:

- A written operating procedure should be developed, describing the gas charging process step by step.
- The gas charging area shall be designated a non-smoking area, if smoking is permitted elsewhere in the workshop.
- The vehicle must be stationary and secured prior to connecting the cylinder.
- The workshop shall be well ventilated during gas charging, i.e. roller door fully open.
- The operator shall not leave the setup unattended while the cylinder is connected to the AC System.
- An emergency procedure shall be in place, covering the action to be taken in the event of a gas leak from the AC unit or from the cylinder, during charging.
- A formal training program shall be developed and the dealers/ workshop operators be trained in the safe operating and emergency procedures. The trades persons working with automobile AC units should be accredited under current regulation for handling HFC refrigerants. This training program would be a supplementary program to this accreditation to cover safe handling of ER12.
- Gas charging shall be carried out only by accredited automotive mechanics trained in the use of hydrocarbon refrigerants, and in managing the hazards associated with them.
- Any maintenance on the air-conditioning equipment should only be conducted by an accredited automotive mechanic, trained in the hazards of hydrocarbon refrigerants.

- If the AC System requires opening, the gas must be vented at a controlled rate safely and residual gas extracted out with vacuum before the unit can be opened.

16.1.5 Disposal

Two modes of disposal are possible:

1. Disposal of residual hydrocarbon in the AC system before dismantling, for repairs. This is carried out in an auto workshop.

   In this mode of disposal, the refrigerant is vented in a controlled manner safely, over a period of 5 minutes. Only accredited mechanics carry out the venting. The controlled venting is necessary to ensure that the lubricating oil in the system does not leak out with the refrigerant. This procedure is identical to the venting carried out before any maintenance on the AC components.

2. Disposal of the automobile in a wrecker's yard. The AC unit may be dismantled by the auto-wrecker for resale of parts.

Information must be provided to auto-wreckers on safe venting of the charge before cutting or dismantling. The charge can be recognised by the sticker.

16.2 Training

Boral Energy should develop the following systems as part of implementation of the safety management procedures for the use of ER12 in automobile air-conditioning:

- Develop an operating procedure manual for storage, handling, gas charging and maintenance of the AC unit, for ER12 application. The manual should also address emergency procedures.
- Develop a manual for training of dealers and operators in the safe storage and handling of ER12.
- Conduct formal training seminars for the dealers and operators.
- Periodically undertake an audit to ensure that the dealers have trained personnel in the workshops.
- Provide information to all wrecker yards that if the HC refrigerant label is stuck near the AC component in the engine bay, it should be vented to atmosphere in the open first before dismantling or cutting.
- The provisions of the following codes will apply:

- AS 2746 - Gas Vehicles Workshops Code;
- AS 1596 - LP Gas Code;
- AS 2430 - Classification of Hazardous Areas; and
- AS 1319 – Safety Signs for the Occupational Environment.

16.3 Potential for Hardware Modifications

A brief review was conducted to identify if any hardware modifications could be carried out that could reduce the risk further.

The Arthur D Little report to the US Department of Energy (Ref.3) has identified a few options. These modifications were specifically aimed at reducing the probability of engine bay fires following a collision accident, since the analysis of conventional vehicle configuration had indicated that the risk of passenger cabin fires is already very low.

In this study, for the passenger compartment, no hardware modification was identified to reduce the risk further, as the risk in a non-collision event was estimated to be extremely low. Since the residual risk was largely contributed by a leak into the passenger compartment of a parked vehicle, the potential for sealing the central locking mechanism can be explored in future cars to eliminate any ignition potential.

For leaks into passenger compartment from collision events, Ref.3 reviewed the potential for a liquid solenoid valve between the receiver and the Tx valve, that shuts off flow in the event of an impact. While this option is attractive in theory, the question of what activates the solenoid valve comes into question. It is possible that the mechanism that activates the air bag could also activate the solenoid valve. However, a wrecking yard survey conducted in Ref.3 had shown that even in a sideways collision, while deformation and dislocation of can occur without causing refrigerant leaks. Given that a collision event strong enough to damage the evaporator is likely to cause significant injury or fatality to the passenger, additional efforts to reduce a small risk to even smaller levels does not appear justified, for collision events.

Ref.3 has also reviewed the potential for minimising a fire risk in the engine compartment in the event of frontal collisions. In these incidents, the entire refrigerant inventory is expected to be released from the failure of condenser/ receiver. Since the release is instantaneous, and a flashfire would last less than 1-2 seconds, the main risk reduction options are to minimise ignition potential in the engine bay, and to minimise puncture potential of the condenser/ tubing. The following measures were reviewed:

(a) Increasing thickness of insulation of battery cables to prevent cable being cut in a collision, and become an ignition source.

(b) Reduce metal edges like the hood latch to minimise the potential for condenser puncture.

Both these above options were shown to reduce the risk of a fire in engine bay. Option (b) would require design changes to be made by motor vehicle manufacturers.

It should be noted that a release of hydrocarbon refrigerant in the engine bay following a collision accident would not adversely affect the occupants even in the event of a fire, and that the above measures have been aimed to minimising secondary damage, apart from the damage that had already occurred through the collision.

The above options are mainly for the consideration of motor vehicle manufacturers in their ongoing design improvements in future cars. No hardware change was identified that would need to be adopted by Boral Energy for the use of ER12 refrigerant as the estimated risk levels are very low.

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APPENDIX 1

MATERIAL SAFETY DATA SHEET

ESANTY Refrigerants ACN 006 083 263
Phone (03) 9872 3043
Suite 9, 602 Whitehorse Road Mitcham
Fax (03) 9873 5925
Emergency Phone Number (03) 9761 8788

MATERIAL SAFETY DATA SHEET

Date Issued: August 1997

IDENTIFICATION

PRODUCT NAME: ER12 Refrigerant Gas
Other Names: Hydrocarbon Blend
Dangerous Goods Class: 2.1
Emergency Procedures Guide: 2A2
Poisons Schedule: None Allocated

UN Number: 1075
Hazchem Code: 2WE
Subsidiary Risk: None
Manufacturers Code: ER12

USE: A flammable gas used as refrigerant, normally stored under pressure in liquid form.

PHYSICAL DESCRIPTION/PROPERTIES:

Appearance: Rapidly evaporating liquid or gas with rotten cabbage - like odour

Initial boiling point:	-30°C to 0°C	Vapour Pressure at 20° C:	490kPag
Melting Point:	Not Applicable	Flash Point:	-104 to 60° C
Density @ 15° C:	Approximately equal to 0.57	Solubility in Water:	Very slight
Lower Flammability Limit:	1.9% in air	Upper Flammability Limit:	9.5% in air

OTHER PROPERTIES:

Evaporation Rate:	Rapid	Vapour Density:	1.5 to 2.0 air = 1
Auto Ignition Point:	550° C	% Volatilise:	100%

INGREDIENTS:

Chemical Entity	CAS Number	Proportion
C_3H_8	74-98-6	0 to 50%
$CH(CH_3)_3$	75-28-5	0 to 50%

ER12 contains odourant ethyl mercaptan unless otherwise authorised. (recommended 25 mg/kg). This is detectable to 20% of its lower flammability limit.

HEALTH HAZARD INFORMATION

HEALTH HAZARDS

Inhaled: May cause irritation of the respiratory tract. May also cause headaches or dizziness at moderate exposures.
Asphyxiant: Causes unconsciousness and respiratory arrest at elevated exposures.
Eye: Irritating if the liquid gets into the eyes, with a possible hazard from freezing due to rapid evaporation. Vapours in high concentration may also be irritating.
Skin: Excessive prolonged contact to the liquid can cause skin irritation and frostbite due to rapid evaporation.
Swallowed: Unlikely to be a problem, owing to high evaporation rate.
Chronic: No effects reported from long term industrial exposure to this product.

FIRST AID

Inhaled: Avoid breathing vapours and fumes as much as possible. If someone is overcome by fumes, remove them to fresh air immediately. Rescuers should avoid becoming a casualty by wearing suitable respiratory protection. If the affected individual is not breathing, administer artificial respiration. Seek medical advice promptly in serious cases of over exposure.
Eye. Avoid contact with the product. Remove any contact lenses carefully. Hold eyelids open and flush eyes with tepid water for 15 minutes. Seek medical advice immediately for all eye contact.
Where significant splashing of ER12 liquid may occur, eyewash facilities stations should be installed.
Skin: Avoid skin contact with the liquid. Remove contaminated clothing and wash the exposed areas with plenty of soap and water. Seek medical advice if irritation or frostbite (see below) occurs.
Swallowed: Unlikely to be a problem, owing to high evaporation rate.
Frostbite: Obtain medical assistance. If medical advice is not available immediately, place casualty in a warm area as soon as possible and allow the injured area to warm gradually (further damage may occur if the area of injury warms too rapidly). DO NOT EXPOSE THE INJURED AREA TO EXCESS HEAT OR COLD (such as heat lamps, hot water, snow or ice). Gently cover or drape the injured area with clean material, such as dressing or sheet. To relieve pain, immerse the injured area in water which is near or at body temperature (35-40°C). If possible, get the casualty to exercise the injured area gradually. Give them something warm to drink, BUT NO ALCOHOL. Seek medical advice as soon as possible.

ADVICE TO DOCTOR

No specific treatment recommended. Treat symptomatically. Show a copy of this material safety data sheet to medical personnel dealing with cases of over exposure

PRECAUTIONS FOR USE

EXPOSURE STANDARDS

Worksafe Australia has established comments and exposure Standards for the following ingredients of this product:
R12: Simple asphyxiant 800ppm (1900 mg/m³) as an 8-hour Time Weighted Average.

ER12 is odourised before transport handling and is detectable to 20% of its LEL. If no stenching agent has been added, ER12 has a high odour threshold (in the order of 10-25 times the exposure standard). Therefore, unodourised ER12 does not have good warning properties.

NGINEERING CONTROLS

Ensure there is good ventilation of the area in which the product is used to keep concentrations below the exposure standard or lower explosive limit. While dilution by air may be sufficient in most cases, an exhaust ventilation may be required. In such cases use sparkproof equipment if possible. A ventilation locity of a least 0.3m/s is recommended.

PERSONAL PROTECTION

Avoid contact with eyes and skin. Overalls or a long sleeved shirt and closed in shoes or safety footwear should be worn as a general precaution.
e Protection: Eye protection is required (faceshield, chemical safety glasses or side shield glasses) where splashing is likely. Eye protection should nply with AS 1336/1337.
Gloves: Impervious oil and cold resistant gloves should be worn when using this product. Gloves made of PVC are preferred, although gloves made of nitrile and chloroprene should also be satisfactory. Any such gloves should comply with AS 2161.
spiratory Protection: If ventilation of the area is not sufficient, respiratory protection may be required. This should be at least approved air supplied or self ntained breathing apparatus where the exposure standard is likely to be exceeded or if work is required close to large gas leaks. Respiratory protection should comply with AS 1715/1716.

AMMABILITY

12 is gaseous and highly flammable at normal temperatures and pressures. The gas is normally stored under pressure in the liquid form. Release of pressure is associated with rapid cooling, the intensity of which is dependent on the rate of release. Containers of ER12 are explosive hazards, when exposed to excessive heat.

SAFE HANDLING

STORAGE AND TRANSPORT

ER12 is classified under the Australian Code for the Transportation of Dangerous Goods by Road and Rail as a FLAMMABLE GAS (Class 2.1).
rage: ER12 should be stored in approved areas only. Minimum conditions of storage include dry, cool, secure storage away from heat, sources of tion and oxidising substances. Keep containers closed and upright when not in use.
Transport: ER12 must be transported in accordance with the latest edition of ADG Code(April 1987). Large volumes must be transported in approved tankers, and smaller volumes in approved pressure containers.

ILLS AND DISPOSAL

Spills: Cut off source of leak. If the release is large, cut off all ignition sources and evacuate all non-essential personnel from the area. If possible, ventilate the area. If the incident is significant seek immediate assistance from local fire authorities and police. If possible, monitor the vapour concentration until d ipated.
osal: If possible allow to evaporate. Large volumes should be removed by tanker or by controlled burning. ER12 can be disposed of by approved incineration methods. Contact local supplier or fire brigade for further advice on disposal.

F E/EXPLOSION HAZARD

chem Code: 2WE
Extinguishers: Water spray or BC fire extinguisher.
Procedures: Stay out of gas or vapour. Use water to disperse unignited gas or vapour. Allow to burn out if possible.
cial Precautions: Fire-fighters should wear full protection and breathing apparatus.
2 is heavier than air, and vapours will tend to flow downwards and accumulate in low-lying areas such as drains and pits at ground level.
Containers: Cool fire exposed containers with water spray. If ignition has occurred and water is not available, tank metal may weaken from overheating.
Reactivity: Stable
mpatibilities: Oxidisers
bustion Products: Hazardous combustion products of carbon dioxide (carbon monoxide under poor conditions of combustion) and smoke may be uced.
Hazardous polymerisation will not occur.

NFPA Classification: Health: 1 Flammability: 3 Reactivity: 0

HER INFORMATION

ntact Name: Colin Spencer Title: Safety Officer Phone: (03) 9872 3043
NATURE: ______________________ Fax: (03) 9873 5925
of last review: 14 August 1997

APPENDIX 2

FAILURE MODES EFFECTS ANALYSIS REPORT

BORAL ENERGY

VEHICLE AIR-CONDITIONING RISK ASSESSMENT

FAILURE MODES EFFECTS ANALYSIS

DOCUMENT NO:	**J80065-BOR-RT-X-200**
REVISION:	**0**
DATE:	**5 September 1999**

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DOCUMENT REVISION RECORD

Rev.	Date	Description	Prepared	Checked	Approved
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A	05-08-99	Draft report for Client review	S.Sylvester	R.Raman	R.Raman
0	05-09-99	Formal Issue	S.Sylvester	R.Raman	R.Raman
			For 5.9.99	5\9\99	5\9\99

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Title: **Boral Energy** Automotive Air-conditioning System Failure Modes Effects Analysis		
QA Verified: J.Brini		**Date:** 5. 9. 99

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ABBREVIATIONS

Abbreviation	Explanation
CFC	Chloro Fluoro Carbon
FMEA	Failure Modes Effects Analysis
FSA	Formal Safety Assessment
ft	Feet
HC	Hydrocarbon
HCFC	Hydro Chloro Fluoro Carbon
HFC	Hydrofluorocarbon
kPa	kilo Pascals
LFL	Lower Flammable Limit
MIL	Military
STD	Standard
Tx	Thermostatic Expansion Valve
UV	Ultra Violet

1. INTRODUCTION

1.1 Background

As part of the Safety Report, an identification of the failure modes of the air-conditioning system in automobiles was undertaken to determine potential incidents that could lead to leaks of refrigerant from the air-conditioning system. This was conducted by Granherne as a Failure Modes effects Analysis (FMEA). This document reports on the objectives and scope of work, and results of the study.

1.2 Objectives

The objectives of the study were to:

- systematically examine the functions of an automotive air-conditioning system in order to identify potential failure modes and their effects;
- identify the most likely incident scenarios that would lead to a failure of the automotive air-conditioning system resulting in a leak of gas from the system; and
- document the results of the FMEA study and report on the findings.

1.3 Scope of Work

The scope of work for the FMEA of the automotive air-conditioning system included the following components and assemblies:

- The compressor, including drive components, belts pulleys, seals and bolted pipework connections;
- Pipework and flexible lines between the compressor and the condenser, including the crimped fitting on the flexible hoses;
- The condenser, including small bore pipework in the main cooling area of the unit;
- Pipework between the condenser and the drier;
- The drier, including the pressure switch, sight glass, desiccant, bolted or crimped pipework connections at the drier;
- Pipework and flexible lines between the drier and the thermostatic expansion (Tx) valve, including crimped connections on the flexible lines;

- The Tx valve, including the sensor bulb, capillary line and valve connections to the pipework;
- Pipework connection between the Tx valve and the evaporator, including connection to the evaporator unit;
- The evaporator unit including the small capillary tubes of the cooling section and the evaporator box unit in the vehicle dash;
- The pipework from the evaporator to the compressor, including the pressure switch and thermostat.

2. METHODOLOGY

2.1 General

The study was based on the FMEA methodology as described in US MIL-STD-1692 (Ref.1), Procedures for Performing Failure Modes Effects and Criticality Analysis.

The study involved the systematic assessment of an automotive air-conditioning system by a group of people who were directly involved in the maintenance, repair and reconditioning of the system and its various components. The study was conducted in a workshop format with representatives from various automotive air-conditioning installation, maintenance and repair companies. The inclusion of actual automotive air-conditioning repairers in the group brought a broad range of experience to the assessment and assisted in the understanding of potential failure modes and their effects.

The study was conducted at various automotive air-conditioning repair and maintenance facilities in the Melbourne (Victoria) area. The principal premises for the study was Henron Automotive, at 144-146 Chapel Street, St. Kilda, Victoria, 3186. The study workshop was conducted over 2 x 3 hour sessions on 28 August 1998. Other discussions and verification of the identified failure modes and effects were conducted at the following establishments:

Establishment	Manager	Date
Transmatic Air-conditioning and Transmission Specialists 7 Malan Street Ringwood Victoria 3134	Mr. David Russell	28 August 1998
Mr. Radiators Cave Hill Industrial Estate Cave Hill Road Lillydale Victoria 3140	Mr. Andrew Greig	28 August 1998
Nippon Air Parts 32-34 Clarice Rd. Box Hill Victoria 3128	Craig Pattison	28 August 1998

2.2 Study Participants

The following people participated in the FMEA study.

Name	Company	Position
Graham Nathan	Henron Automotive	Workshop Manager (Director)
Henry Nathan	Henron Automotive	Owner/ Director
Colin Spencer	Boral Energy	General Manager, Esanty
Ross Bradshaw	Boral Energy	Manager, Esanty
Barry Duckworth	Boral Energy	Manager LP Gas Eng. Services
Paul Kesby*	Dept. of Environment	Assistant Director - Ozone
Jan Goedhart	NEWTEK	Refrigeration & Air-conditioning Consultant
Steve Sylvester	Granherne	Senior Consultant (Facilitator)

*Paul Kesby attended part time on the morning of 27 August 1997.

The group was selected to provide a diverse and multi-disciplined team to assess the safety of the automotive air-conditioning system using HCFC and HC gases. Maintenance and repair representatives were included in the study to provide experienced input and to verify the types of failures experienced most during their day to day work on a broad range of vehicles.

2.3 FMEA Methodology

The methodology of assessment took the form of a workshop study conducted as a group assessment, drawing on the combined experience of the diverse members of the team. The study was facilitated by a Granherne risk engineer who led the sessions. The methodology of the study was as follows:

- Each session involved a detailed review of components of the automotive air-conditioning system. This commenced with a review of the system block diagram by the team. A copy of the diagram was placed on the wall where all participants could see the major system components. The maintenance repair representative explained the operation of the equipment to the team. The team then discussed the various operational issues and asked questions of the maintenance repair team members regarding clarification of particular issues relating to the safety features and other critical operational parameters.

- The FMEA was then conducted along the lines of "what if" scenario questioning. Each component of the system was identified and assessed in turn. The "what if" failure scenario was applied to each component to assess the effects on the whole system of individual failures. The aim was to identify potential failures and the possible consequences. The combined knowledge of the team provided wide-ranging experience and the ability to address and satisfy the many questions that arose.

As the workshop was held on the premises of an automotive air-conditioning system repair and maintenance facility, it was possible to view various components as they were discussed. Typical failure modes identified in the study were clearly evident on some of the components viewed during the study.

- The results of the study were recorded by tabulating the discussion points under the following headings:

1) Component	**2) Failure Mode**	**3) Effects**	**4) Safeguards**	**5) Remarks/ Action**

- On completion of the initial study at Henron Automotive, a number of repair and maintenance facilities were visited and discussions held to verify the failure modes and effects identified.

The minutes recorded during the initial study and the discussion points recorded at each of the maintenance/ repair facilities visited were typed and passed to each of the participants for comment. The minutes were updated for points of fact and a report written detailing the results of the study.

3. RESULTS

A full set of meeting minutes were recorded during the FMEA session. These are listed in **Appendix I**.

The points presented below are a brief discussion of the minutes points, including an expansion of the various issues raised during the FMEA sessions.

3.1 Compressor

FMEA Minute Number **FMEA Discussion**

1 **Belt Breakage** - This minute point was related to the potential for belt breakage and its impact on the air-conditioning system. The team agreed that a broken belt would only result in the compressor stopping and that there would be insufficient energy in the belt failure to result in any damage to the operating components in the system. Hence, there would be no release from this incident.

2 **Drive Belt and Pulleys** – The team identified that the drive belt and pulleys may fail in a number of ways, these are:

- Slipping belts, which may lead to overheating of the pulley, melting of the belt and eventual belt failure.
- Pulley bearing seizure, which may lead to the pulley jamming and belt slippage resulting in belt overheating and eventual belt failure.
- Compressor component seizure (i.e. clutch/ shaft/ pistons/ etc.), which will also lead to belt slippage, overheating and eventual failure.

Whilst belt failure problems are not a significant issue for the system, overheating of the pulley and bearing may lead to shaft overheating, which in turn melts the shaft seal resulting in gas release. Some mitigating factors in this incident are:

- For major overheating to occur, the team agreed that the vehicle engine revolutions must be high. Lower engine speeds will not generate significant heat of the order required to damage seals.
- When at higher revolutions, the higher heat generated will result in a major seal failure and rapid gas loss.
- At higher engine revolutions, there is a significant quantity of air moving in the engine bay, diluting any releases.

FMEA Minute Number	FMEA Discussion
	- The majority (if not all) of the gas would have escaped before the vehicle stops. Hence there is a low quantity of gas remaining to escape. - All releases are under the bonnet of the car and not in the cabin compartment. In general, the potential for major incident from this release is low due to the failure mechanisms and release location (i.e. under the bonnet when the vehicle is moving).
3	**Clutch Coil** – A failure of the clutch coil in open system was identified as a potential problem. This would only result in drive failure to the compressor. There would be no release of gas and no potential for a hazardous incident.
4	**Clutch Coil** – A short system of the power supply wire was identified as a potential problem. This would only result in a blown fuse or melted wire, causing a failure of the clutch with the same result as Minute 3.
5	**Clutch Coil** – Short system of the coil leading to high current. This would result in a blown fuse or melted wires. Similar effects to minute 4. The team did not know of any major short system incidents that have resulted in blown fuses or melted wires. The more common fault is open system as described in Minute 3 above.
6	**Shaft Seal** – Seal leak was identified as a credible failure scenario. However, historical evidence points to minor leaks that occur over a very long period. The release would occur in the engine compartment, however, it would not result in the formation of a gas cloud in the engine bay of the car. The team noted that leaks such as this are normally very difficult to detect as they are so small. However, the use of a dye added to the system aids in the detection of the leak (i.e. dye is ultra-violet (UV) light sensitive, hence when UV light is shone near the leak the dye is readily seen).
7	**Body Seal** – The team identified that body joints on the compressor (i.e. those seals between the pipework flanges and the compressor) are normally 'O' ring joints. Leaks at this location are very rare, unless the joint has been disturbed in some way. Resultant leaks are

FMEA Minute Number	FMEA Discussion
	generally very small occurring over days or even weeks. These Leaks are not readily detected and dye addition must be used (as per Minute 6 above). Leaks at this location occur in the engine bay and not inside the passenger compartment.
8	**Drive Shaft** – Failure of the drive shaft by catastrophic breakage was identified as a potential problem. However, the group agreed that during normal operation, it is highly unlikely that the shaft would fail before seal failure had occurred. Hence, all gas contents would have leaked from the system before the seal fails. One exception to this rule would be the impact accident causing significant front end damage. A broken shaft from this incident may cause immediate release of system refrigerant, however, this would be in the open, as significant damage to the vehicle would have occurred for the shaft on the compressor to be broken. All releases from this incident occur in the engine bay of the car.
9	**Compressor Internal Components** – Failure of a compressor internal component may lead to catastrophic failure of the compressure (i.e. seizure). Two events may result from this: - major compressor casing breach and gas release; or - no casing breach, no gas release. The team agreed that the compressor type plays an important role in the potential impact of a seized compressor. It was agreed that internal failure of scroll type compressors would not result in a major casing break. However, piston type compressors (TR70 & TR90) frequently fail resulting in compressor casing breach. This failure mode was supported in discussion with "Nippon Air Parts" during a visit to its facility in Box Hill, Vic. A failure of this kind would result in all gas contents being released in the engine bay of the car.
10	**Compressor Discharge Fitting** – failure of this fitting was identified to be a potential problem. A failed thread on the discharge fitting could lead to joint failure and subsequent release of gas. Gas in this section of the system contains a high content of oil, hence if released there is a potential for oil spray to contact hot engine components.

FMEA Minute Number	FMEA Discussion
	This may result in ignition and fire. This incident would be the same for HC and HFC gases, as it is not the gas that is a problem, but the fine oil mist created by the release (ie. lubricating oil for the compressor is carried in all refrigerants in the system). Should the incident occur, the impact would be in the engine bay.
11	**Discharge Fitting** – The potential for incompatible gas and seal material was identified as a problem. It was reported that this had occurred mainly with HFC's. Incompatible gas and seal materials have resulted in seal degradation and leaks in HFC's. Historically, degradation occurs over a long period and leaks commence as small releases occurring over days. Hydrocarbon blends are compatible with all seal materials used in air-conditioning systems, and material incompatibility leading to failure was not seen as a problem.
12	**Charge Ports** – the charge ports on the compressor suction side are fitted with a filling valve, known as a Schrader valve. A cap is placed over the charge port to prevent dust and other debris entering the valve. Leaks from this valve can occur and are usually small, occurring over a long period. The valve cap also aids in reducing the amount of gas released. In general, leaks from this source are very small.

3.2 Discharge Hose

FMEA Minute Number	FMEA Discussion
13	**Aluminium Bend** – The team identified that the aluminium bend has the potential to fatigue and crack resulting in gas release. There are two possible failure modes in this area, small crack releasing gas contents over a long period (days), or total fitting failure resulting in major gas release. The release of gas over a long period would not constitute a hazard as the gas would disperse before lower flammable limits could be reached. However, major release of gas may result in larger quantities of gas remaining in the engine bay before dispersion can occur.

FMEA Minute Number **FMEA Discussion**

The team estimated that about 50% of the gas would escape immediately, the low pressure switch would shutdown the compressor and the remainder of the gas would leak over a period of time. Determination of the exact quantity of gas released to be addressed in the consequence analysis.

14 **Crimp Connection on the Hose** – The team inspected a number of crimped connection hoses at the premises of Nathan Automotive and noticed that a number of hoses were loose at the connection point. Newer hoses had been glued at this point to reduce the chance of looseness and potential failure. However, it was also noted that major releases were not as a result of failure at the crimped connection. It was more likely that hoses fail due to overheating from contact with hot engine parts.

The team agreed that leaks from crimped connection looseness would result in minor releases over a period of days.

15 **Flexible Hose** – The use of incompatible gas with flexible hoses was identified as a potential problem. This has resulted in corrosive attack on the hoses which has led to catastrophic hose failure in the early days of HFC operation with previous CFC systems. HC blends are compatible with all hose types and materials, and hence failures of hoses from this source are not credible for HC refrigerants.

16 **Flexible Hose** – The team identified that failure of the condenser fan relay, a blown condenser fan fuse or loss of cooling over the condenser would lead to high pressure in the condenser and hoses.

Hoses have a maximum operating pressure of 3,500 kPa, hence it is unlikely that hoses will fail from excessive temperature under HC gas.

17,18 **Flexible Hose** – The team identified that there is a potential for overcharging of the system with gas that could lead to failure of the flexible hose. It was also noted that overcharging could lead to compressor failure.

The team identified that the high pressure switch would shut the compressor down, protecting against the potential for failure of the hoses or compressor.

FMEA Minute Number	FMEA Discussion
	It was also identified that the charge pressure would not normally exceed the design pressure of the system, even if the system were overcharged, which would only affect the system performance. Further, the charge mass of HC was only about 30% of the equivalent HFC mass. It was decided that an experiment would be conducted in a "test rig", where ER12 would be deliberately overcharged to observe the effects.
19	**Flexible Hose** – The team identified that there is a potential for hoses to be damaged by battery acid, exhaust heat, friction/ rubbing and oil impact over a long period. These impacts may lead to catastrophic failure of the hose resulting in major release under the bonnet of the car. Similar to 17 and 18 above, in the event this release occurs when the car is travelling, there would be significant dilution of the gas, well below the lower flammable limit of the gas/ air mixture. It was estimated that the major release would result in about 50% of the gas in the system being released immediately and the remainder over a period of time after the hose failure. It will be necessary to calculate the quantities released during such an incident.

3.3 Condenser

FMEA Minute Number	FMEA Discussion
20	**Condenser Shell** – It was identified that failures of the condenser shell have historically been due to corrosion, resulting in minor leaks that occur over a long period of time (i.e. days and weeks). It was noted that corrosion often occurs as a result of moisture in the system mixing with the gas and forming acidic compounds. This had occurred in the past with HFC blends and was not considered to be a problem with the HC refrigerants. The potential for leak from this source using HC refrigerants is very low, if not negligible.

FMEA Minute Number	FMEA Discussion
21	**Condenser Shell** – As the condenser is located at the front of the vehicle, it is most likely that accident impact resulting in vehicle deformation in the condenser area will cause condenser damage and breach. For most major accidents this will result in major release of gas. However, the condenser is outside the engine bay (i.e. in front of the radiator) and much of the release would disperse in the open.
22	**Condenser Body** – It was identified that welds on the condenser body may fail resulting in release. However, the team could not identify any historical evidence of major incident occurring from this source, for any of the refrigerants. Leaks from weld cracks release gas over a long period (days/ weeks), hence release rates are very small.
23	**Condenser Body** – Mounting failure was identified as a potential problem. Failure of the mountings could lead to the condenser resting on the rotating fan. This could lead to wear on the condenser tubes resulting initially in small leaks, then leading to large leaks. However, it is noted that by the time the leak becomes large enough to cause significant gas release, the majority of gas would have escaped. Further, with the fan operating, there is significant air movement under the bonnet of the car, leading to large dilution of the gas.
24	**Condenser Body** – Similar to Minute 23 above, the body of the condenser may rub against the chassis of the car, resulting in wear and eventual leak. However, leaks would start very small, growing to larger leaks over a period of time. By the time the leak grows to a point where a significant quantity of gas would be released, the majority of gas would have escaped. Like Minute 23 above, with the engine running, there would be significant quantities of diluting air under the bonnet of the car.

3.4 Pipe from Condenser to Dryer

FMEA Minute Number	FMEA Discussion
25	**'O' Ring Joint** – The team identified that an 'O' ring joint is fitted at the dryer pipe fittings. If the wrong refrigerant is used similar releases will occur to that described in minute No.11. However, as the 'O' rings

FMEA Minute Number	FMEA Discussion
	degrade over a period of time leaks commence as very small releases, occurring over a period of day or even weeks. By the time the 'O' ring has degraded sufficiently to cause a significant leak, the gas has already escaped. This release occurs in the engine bay of the car.
	It was noted that HC refrigerants are compatible with all 'O' ring seals.
26	**Aluminium Pipe** – The pipe from the condenser to the dryer is aluminium, it was identified that corrosive materials, formed within the system as a result of moisture ingress, may attack the pipe leading to leaks. As corrosion takes considerable time to attack the aluminium pipe, the eventual break through is small resulting in very small releases over days or even weeks. By the time the corrosion attack causes a significant leak the gas has already escaped. This release occurs in the engine bay of the vehicle.
	It is noted that this mechanism of failure may occur with non-hydrocarbon refrigerants, but not with HC refrigerants as the corrosive products do not form from moisture ingress.
27	**Aluminium Pipe** – Similar to Minute 21, the aluminium pipe is located at the front of the vehicle, it is most likely that accident impact resulting in deformation of the vehicle in the dryer area will cause aluminium pipe damage and breach. For most major accidents this will result in major release of gas. However, deformation of the vehicle to an extent where this pipe is damaged would certainly expose the engine bay by vehicle bonnet deformation. The resultant release would be well mixed with the air preventing a gas air mixture above LFL.

3.5 Dryer

FMEA Minute Number	FMEA Discussion
28	**Hose joint (inlet and outlet)** – The hose joint has been discussed in Minute 25. Degradation of hoses may occur due to incompatibility of gases with 'O' rings. This is not expected to occur with HCs.

FMEA Minute Number	FMEA Discussion
29	**Sight Glass** – The team identified that the sight glass has a potential to break releasing the full system contents. This would be a catastrophic leak with over 50% of the system contents being released immediately and the remainder being released over a period of time after the failure. However, it was noted that this event is extremely rare as the glass is moulded into the body of the dryer and the dryer is pressure tested after manufacture. Historically, leaks from this area are small, resulting in gas loss over days or weeks. The gas is released in the engine bay of the car. Releases can occur with both HC and HFC gases as corrosion is not the main cause in this location. It is more likely from manufacturing defects that may occur after the test.
30/ 31	**Pressure Switch** – The group discussed the potential for the pressure switch to fail operationally in the open position (ie. not operate when required). The switch design was reviewed and it was identified that the switch is a fail safe design which results in the switch failing closed in the event of operational failure. This incident would shut the compressor down. In both cases there would be no release issues. However, if failure of the switch occurred in the open position, high pressure in the system would not be detected and the compressor would not be shut down.
32	**Pressure Switch** – The team identified that the central pin through the switch casing has caused failures in the past. The failure mechanism results from looseness between the pin and the switch casing occurring over a period of time. This has resulted in minor gas releases in systems over a period of days. This failure mode can occur in both HF and HFC gases as it is a manufacturing fault and not a gas/ system compatibility issue.
33/ 34	**Dryer Casing** – The dryer casing is a robust unit manufactured as a steel cylindrical shell. The casing shell is thick enough so that corrosion will not breach the casing throughout the period of the vehicles life. The corrosive attack occurs more frequently in the aluminium components in the system. In addition, the robust nature of the shell reduces the potential for piercing of the casing during an accident. It is more likely that the casing will be dented but not breached. The magnitude of impact

FMEA Minute Number **FMEA Discussion**

resulting in a casing dent would severely damage other aluminium components resulting in leaks from these areas in preference to the dryer casing.

35 **Dryer Casing** – The team identified that the dryer casing is fitted with a desiccant which aids in removal of moisture droplets in the gas stream. In the event that the desiccant clogs, there is a potential for excessive pressure in the system, leading to failure of other system components. As the dryer is manufactured as a steel shell, it is more likely that other pressurised components such as flexible hoses and aluminium parts will fail before the dryer.

These failures are covered elsewhere in this study.

36 **Dryer Casing** – The potential for the desiccant in the dryer to become saturated was identified as a problem mainly with HFCs and CFCs. Saturated desiccant means that carry over of moisture would occur in the system, leading to the formation of acidic compounds. Corrosive attack on the aluminium components in the system would then result. Eventually, system breach would occur releasing system contents. As stated above, releases as a result of corrosive attack would start small, releasing contents over a number of days or week. By the time the release became significant, the majority of refrigerant system contents would have been released.

As HCs do not contain materials that have the potential to form acidic compounds, this failure mode does not result from the use of HCs. However, vehicle air-conditioning systems using HCs after HFCs and CFCs have been in the system for some time, may be released from HFC and CFC corrosive attack. Whilst the HCs will not add to the corrosion already formed from HFC and CFC gases, leaks may result from system weakness created by such corrosive attack from non-HC gases.

Notwithstanding this, as the HC gas will not add to the corrosive attack, the releases will be small occurring over days and weeks.

37 **Dryer to Tx Valve Pipeline** – Similar failure mechanisms will occur in this pipeline as to those described in Minutes 25, 26 & 27.

3.6 Thermostatic Expansion (Tx) Valve

In some vehicles this valve is located in the engine bay whilst in others it is located within the evaporator box under the dash board of the vehicle.

FMEA Minute Number	FMEA Discussion
38	**Pipe Joint (nut & tail joint)** – The team identified that this joint is metal to metal contact joint and leaks from this joint would be small, releasing over days or weeks. The team knew of no catastrophic failure of this joint.
39	**'O' Ring Joint (block valve type Tx valves)** – The team identified that failures at the 'O' ring would be similar to those described in Minutes 7 and 25.
40	**Equalising Tube in the Tx Valve** – The team identified that failure of the equalising tube in the Tx valve by breakage or blockage would lead to failure of temperature sensing. This would result in the evaporator icing up and no air flow over the evaporator. This may lead to liquid overflow into the compressor resulting in potential internal damage to the compressor. Whilst this was not identified as a release source, there could be significant damage to the system.
41	**Internal Components (Tx valve)** – The team identified that there is a potential for the Tx valve to jam in the open position, resulting in excessive flow of refrigerant into the evaporation. This would lead to similar scenario as Minute 40 above. Excessive cooling would lead to icing of the evaporator and liquid carry over into the compressor. Whilst it was not considered a release problem, internal compressor damage would be the result.
42	**Internal Components (Tx valve)** – The team identified that the Tx valve internal components may fail leading to seizure of the valve and loss of flow in the system. This in turn would lead to a low pressure at the suction side of the compressor resulting in activation of the low suction pressure switch and compressor shut down.

3.7 Evaporator

FMEA Minute Number **FMEA Discussion**

43 & 44 **Evaporator Shell and Tubes** – The evaporator shell and tubes are constructed from aluminium tubing arranged to allow a number of "passes" though the evaporator box. The internal holes within the "tubing" are extremely small, being about 1mm square. A cross section of the tubing is shown in **Figure 4.1**.

The team identified that aluminium tubing is susceptible to corrosive attack from acid compounds formed from moisture within the system. This occurs in a similar manner to those corrosion issues raised above. Leaks begin small, releasing refrigerant over a period of day or weeks. When the leak becomes significant, the majority of refrigerant has already escaped.

This mechanism of failure could occur with HFC and CFC refrigerants. HC refrigerants do not form acidic compounds when moisture ingress into the system occurs.

An additional failure mode was discussed relating to accident damage. As the evaporator is located under the dash board of the car, there would need to be significant damage to the vehicle before the evaporator was impacted. The team agreed that significant windscreen damage would occur before the evaporator was damaged to the extent where significant release occurred. This would mean that the vehicle cabin would be open to the atmosphere, preventing confinement of the gas.

The team identified that the construction of the tubes from aluminium with fine holes also assist in the prevention of major release when accident damage to the evaporator occurs. The deformation of the aluminium evaporator tubes tends to seal the tube ends, limiting the release to a slow escape of gas, much less than 1mm square.

45 **Evaporator Box Mounting Points** – The team identified that failure to effectively connect the evaporator box to the vehicle may lead to the weight of the evaporator resting on the inlet and outlet pipework through the firewall of the vehicle. As the firewall is sheet metal, there is a potential for rubbing to occur and wear on the pipework. This will eventually lead to pipework failure and release.

The team discussed the exact size of release and agreed that this

FMEA Minute Number	FMEA Discussion
	would be conditional on the road surface and jarring impact on the vehicle. Rough roads may lead to a major catastrophic failure as the impact is heavy over uneven road surface. Smooth roads would result in a gradual wear through the pipework, resulting in a small leak over a period of hours or days and finally leading to catastrophic failure. However, at this stage most of the contents of the system would have escaped.

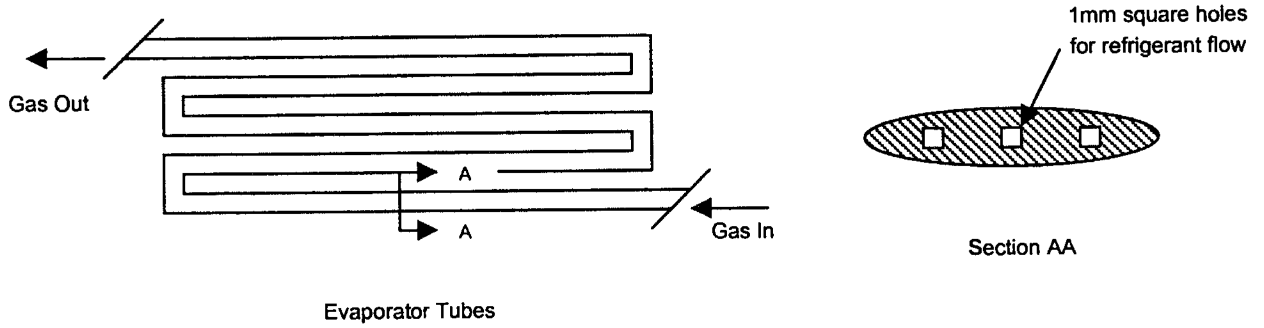

FIGURE 4.1
EVAPORATOR TUBE ARRANGEMENT AND TUBE CROSS SECTION

3.8 Thermostat Unit

FMEA Minute Number	FMEA Discussion
46	**Thermostat Unit** – Failure of the thermostat in the on position will lead to continued running of the compressor whilst the evaporator fan is running. This will lead to ice build up on the evaporator tubes and eventual liquid carry over to the compressor. Liquid in the compressor may lead to severe compressor damage internally, but there is little or no chance of major release.
47	**Thermostat Unit** – Failure of the thermostat in the off position would result in shut down of the compressor. There would be no potential for release from this failure mode.

3.9 Pipework from Evaporator to Compressor

FMEA Minute Number	FMEA Discussion
48	**Flexible Hoses** - The team identified failure modes similar to those discussed in **Section 4.2**. Consult this section for minor release scenarios.
49	**Flexible Hose** – The team identified that the flexible hose may fail catastrophically from contact with hot engine components (i.e. exhaust pipe). However, it was agreed that failure of this hose is unlikely due to the low pressure at this part of the system. In the event of failure, however, it was noted that the Tx valve sensor would immediately detect the low pressure and close within 1 to 2 seconds, isolating the leak. This occurs as a result of the low temperature on the discharge side of the evaporator. Major failures of the hose would result in a release in the engine bay only and would be equivalent to the full flow release for about 2 seconds.

3.10 Summary of Release Scenarios During Vehicle Operation

Release scenarios have been summarised by equipment and are listed in **Table 4.1**. This table gives a summary of the probable hole size from each failure mode as identified in the FMEA.

TABLE 4.1
SUMMARY OF RELEASE SCENARIOS DURING VEHICLE OPERATION

Component	Leak Magnitude (Hole Size)	Failure Mode
Compressor	Minor Leak	Shaft seal leak, body seal leak, discharge fitting, Schrader valves
	Major Leak (full bore)	Compressor seizes, discharge fitting
Discharge Hose	Minor Leaks	Crimp connection on hose
	Major Leak (full bore)	Overpressure of system, overheating of hose, battery acid, rubbing/ friction, aluminium bend failure, incompatible gas, excessive charge
Condenser	Minor Leak	Corrosion, weld failure, mounting failure, body wear (rubbing)
	Major Leak (full bore)	Impact from accident
Pipe (condenser to dryer)	Minor Leak	'O' ring joint, pipe corrosion
	Major Leak (full bore)	Impact from accident
Dryer	Minor Leaks	'O' ring joint, sight glass, pressure switch casing, corrosion, impact from accident (robust dryer is unlikely to result in major breach)
Thermostatic Expansion Valve	Minor Leak	Joint failure, 'O' ring failure
Evaporator	Minor Leak	Internal & external corrosion
	Major Leak (full bore)	Evaporator box mounting failure
Pipework (evaporator to compressor)	Minor Leak	Joint, crimped connections
	Major Leak (full bore)	Overpressure of system, overheating of hose, battery acid, rubbing/ friction, aluminium bend failure, incompatible gas, excessive charge

3.11 Air-conditioning System Charging

FMEA Minute Number	FMEA Discussion
50	**Filling Hoses** – The team identified that the hoses may be installed incorrectly and that the suction hose is fitted to the discharge and discharge to the suction. However, it was noted that the gas will not be charged to the system and there is no safety issue.
51	**Filling Hose** – A split hose during charging was identified as a potential problem. This would lead to gas release in the workshop. However, the release would be limited as the charging hose is only about 3mm diameter. Further, the charging operation is controlled by a workshop mechanic who is able to shut down the release within 5-10 seconds. The release quantity and potential effects (i.e. fire or explosion should be calculated during other studies in the assessment).
52 & 53	**Gauges and Scales** – The team identified that the gauges may be damaged or may be giving an incorrect reading. It was noted, however, that the gauges are not an extremely expensive item and would be replaced if damaged. Wrong reading may lead to slight overcharge of the system, however, scales are also used to determine the exact weight of the charge delivered to the system. This is normally the primary means of monitoring the charging. Gauges are used as a back-up check. The team did not see a significant problem with this failure mode as there are back up systems available.

3.12 Vehicle Disposal/ Panel Shop Work

FMEA Minute Number	FMEA Discussion
54 & 55	**Hoses/ Pipework** – The team identified that there is a potential for panel shop workers of wrecking yards to dismantle vehicles that are fitted with an air-conditioning system containing a full gas charge. Cutting and dismantling will start with engine components. Breach of the system would result in major release of gas inside the engine bay.

In many cases, ignition sources would be available as a result of the sparks generated during grinding or cutting, hence, it is likely ignition would occur.

The team noted that the potential for ignition would not be dependent on the type of gas used. Air-conditioning systems use lubricating oil as a system additive to aid in lubricating system components (i.e. Compressor). It is the rapid release of oil laden gas (as a spray) that leads to ignition and fire.

In the majority of cases, cutting into the system or removing a major component (hose, joint, etc.) would result in a major release. This would be in excess of 50% of the system contents, with the remainder of the gas escaping over a period of time.

3.13 Fire in the Vehicle

FMEA Minute Number	FMEA Discussion
56	**Hoses** – The team identified that a fire in the vehicle would take some time to affect the metal components of the air-conditioning system. However, flexible hoses would be quickly affected and would burn through resulting in major failure. This would release combustible materials (oil) into the fire area in vehicles using all refrigerants (i.e. CFCs, HFCs and HCs).
	In the HC case, flammable material would be released into the fire area. However, the quantity is extremely small (≈350grams). The team was of the opinion that there would be little additional effect as a result of the hydrocarbon release from a fire of sufficient magnitude to cause hose failure.

4. REFERENCE

1 MIL-STD-1692, Procedures for Performing a Failure Modes, Effects and Criticality Analysis, United States Military Standard, US Department of Defense.

APPENDIX I

FAILURE MODES EFFECTS ANALYSIS MINUTES AUTO AIR-CONDITIONING SYSTEM

FAILURE MODES AND EFFECTS ANALYSIS - WORKSHOP MINUTES

Attendees: Jan Goedhart, Barry Duckworth, Colin Spencer, Graham Nathan, Paul Kesley (part time), Ross Bradshaw, Steve Sylvester

Equipment: Compressor

Min.No.	Component	Failure Mode	Effects	Remarks/ Comments
1	Drive belt and pulleys	Belt breakage	Power not transmitted to the compressor from the engine, no air-conditioning, no hydrocarbon release	Air conditioner inoperable Not a hazardous event
2	Drive belt and pulleys	- Slipping belt - Pulley bearings seize - Compressor seizes - Compressor clutch seizes	- Pulley heats due to belt friction, pulley becomes red hot (metal glows red) - belt may deteriorate and break up - Seal melts in compressor - Gas/ oil release through seal - Ignition of oil on red hot pulley - belt slip	- Pressure at seal is about 350-700kPa - Can occur in both R134a and ER12 refrigerants as oil will ignite before gas - Vehicle must be running at high speed for pulley to become red hot - Belts are more likely to burn when vehicle is running compared to when it is stopped. Belts smoulder and melt rather than burning with flame - Whilst at speed the air passing through the engine compartment will dilute escaping gas/ oil mixture, with too much dilution for ignition to occur - Not likely to ignite at speed but may ignite when vehicle stops, it is likely that the gas has escaped by this time but small leaks could still persist - No leak in passenger compartment. No hazard to passenger
3	Clutch Coil	Open Circuit	Clutch does not engage, no drive to compressor, no air conditioning	Not a hazardous event

FAILURE MODES AND EFFECTS ANALYSIS - WORKSHOP MINUTES

Attendees: Jan Goedhart, Barry Duckworth, Colin Spencer, Graham Nathan, Paul Kesley (part time), Ross Bradshaw, Steve Sylvester

Equipment: Compressor

Min.No.	Component	Failure Mode	Effects	Remarks/ Comments
4	Clutch Coil	Short circuit, external wire	- Fuse blows - Melts wire if no fuse	- No internal effect on the compressor or A/C system – no refrigerant release - No hazard to passenger
5	Clutch Coil	Short circuit internal clutch coil	- Fuse blown - Melts wire if no fuse - Open circuit is the most common result	- No internal effect on the compressor or A/C system - No effect on the refrigerant - The FMEA group did not know of any history of major windings failure leading to fire or seal damage - No adverse effect on passenger
6	Shaft Seal	Worn Seal	- Refrigerant leak - Low potential for ignition as small leak through seal diluted by air circulation in engine bay while vehicle running	- Historically, leaks are difficult to find as they are very small, the group did not know of any sudden major releases of refrigerant from the compressor seal. This scenario is near impossible due to the construction of the compressor - Current leak detection methods include introduction of a dye into the system and using ultra-violet light to detect leak source. The leak is located by dye stain after the gas has escaped

FAILURE MODES AND EFFECTS ANALYSIS - WORKSHOP MINUTES

Attendees: Jan Goedhart, Barry Duckworth, Colin Spencer, Graham Nathan, Paul Kesley (part time), Ross Bradshaw, Steve Sylvester

Equipment: Compressor

Min.No.	Component	Failure Mode	Effects	Remarks/ Comments
7	Body seal or bolted suction/ discharge fitting	'O' ring or gasket failure	- Minor leak - Leak diluted by air circulation in engine bay while vehicle running - Potential ignition if leak is large enough. However, leak is normally too small to detect at this location	- Group could not recall historical evidence of a major leak or fire from this incident, from its experience - The group noted that there have been isolated cases where complete and catastrophic compressor failure has resulted in major release of all refrigerant contents into the engine bay. This would occur only when the engine is running, with consequent dilution in engine bay. This event was carried forward for detailed analysis in the Safety Study
8	Drive Shaft	Shear/ break	- Severe accident damage from vehicle impact - Release of refrigerant in the engine bay of the vehicle. Potential for ignition	- Shaft does not break during normal operation, clutch bearing will fail first - Accident damage causing shaft failure will result in significant vehicle damage. Gas will be released into the engine bay and escape to atmosphere. A flash fire may result if ignited
9	Pistons/ swash plate/ scroll	Internal failure of component	- Compressor seizes, major damage to internal components; no major gas release if compressor case is not breached. Small release may occur through seals - Major damage to compressor case resulting in large release of gas	- The group could not recall any major compressor failures in the scroll type compressors that resulted in case failure; however, swash plate/piston type compressors have demonstrated major compressor case breach. This was substantiated by the compressor repairer "Nippon Air Parts"

FAILURE MODES AND EFFECTS ANALYSIS - WORKSHOP MINUTES

Attendees: Jan Goedhart, Barry Duckworth, Colin Spencer, Graham Nathan, Paul Kesley (part time), Ross Bradshaw, Steve Sylvester

Equipment: Compressor

Min.No.	Component	Failure Mode	Effects	Remarks/ Comments
10	Discharge Fitting	Failed thread (stripped or failed discharge component)	- Refrigerant release under the bonnet of the vehicle	- Mainly occurs in accident situations, rather then normal operation. See comments on Item 8.
11	Discharge Fitting	Failed 'O' ring seal, wrong gas used which is incompatible with the seal	- Initially slow release becoming larger as seal is corroded by incompatible gas. Historically leak has occurred over a full day with R134a refrigerants	- Only applies to HFC blends as hydrocarbon blends will not affect any of the current seals used (neoprene or nitrobutane rubber) - All new 'O' ring seals available are compatible with ER12 refrigerant
12	Charge Ports	Schrader valve leaks	- Small external leak from compressor housing, usually occurring over a long period	- A cap is usually placed over the charge port to prevent dust and other debris fouling the Schrader valve. Leak must occur through the valve and cap, hence is very slow. Normally not detectable and will leak inside the cap

FAILURE MODES AND EFFECTS ANALYSIS – WORKSHOP MINUTES

Attendees: Jan Goedhart, Barry Duckworth, Colin Spencer, Graham Nathan, Paul Kesley (part time), Ross Bradshaw, Steve Sylvester

Equipment: Hose from Compressor

Min.No.	Component	Failure Mode	Effects	Remarks/ Comments
13	Aluminium bend on the compressor discharge hose	Bend fatigue resulting in crack and leak	- Instant discharge of 50% of the contents (about 150g) - Remainder of the gas leaks slowly depending on the ambient temperature and the quantity trapped in the oil	- Vapour pressure is lost, low pressure switch cuts the compressor off - Incident is the same for both HFC blend with HCFC or HC refrigerant - It is noted that there are no heat sources in the engine bay above autoignition temperature of HC to ignite the gas, but electrical sources are present - No release into passenger cabin; however, oil sprayed on the manifold may ignite
14	Crimp connection on hose	Connection becomes loose and leaks	- Very slow release will occur over a period of weeks or months	- The group indicated that it was very rare that crimp point at the hoses is the major cause of leaks, it is more likely that hoses fail catastrophically due to heat effects from the manifold (this is usually picked up during maintenance and repaired i.e. new hose) - It is noted that new hoses are now glued at the crimp connection. Historically this has proven to be more reliable
15	Flexible hose	Wrong refrigerant material used with incompatible hose	- Hose failure	- All hoses are compatible with HC refrigerants - Only HFC refrigerants are susceptible to hose incompatibility and potential failure with previously installed hoses that are not compatible - Current hoses ("Barrier Hose") available on the market are compatible with all refrigerants used. However, some older cars may use incompatible hoses which may be susceptible to hose failure should an upgrade from CFC to HFC be performed

FAILURE MODES AND EFFECTS ANALYSIS - WORKSHOP MINUTES

Attendees: Jan Goedhart, Barry Duckworth, Colin Spencer, Graham Nathan, Paul Kesley (part time), Ross Bradshaw, Steve Sylvester

Equipment: Compressor

Min.No.	Component	Failure Mode	Effects	Remarks/ Comments
16	Flexible Hose	Excessive pressure from: - condenser fan relay failure or blown condenser fan fuse - loss of cooling over the condenser	- High head pressure about 2000kPa with HFC about 1400kPa with HC (note, this latter pressure will not activate the high pressure switch) - refrigerant effect diminishes	- High pressure switch will cut the compressor at about 3200kPa. (95°C with R134a or overcharged, about 115°C with HC or system overcharged) - Hose working pressure is about 3500kPa. This pressure would not be reached with ER12 - No hazard to passenger from this event
17	Flexible Hose	Excessive pressure from overcharge of the system with gas	- Compressor failure - High head pressure about 2000-3500kPa with HFCs about 1400kPa with HC	- Mostly internal failure with no external release, compressor lock up and belt slip results - High pressure cut out will activate, or pressure relief valve (when fitted) will activate - No hazard to passenger from this event

FAILURE MODES AND EFFECTS ANALYSIS - WORKSHOP MINUTES

Attendees: Jan Goedhart, Barry Duckworth, Colin Spencer, Graham Nathan, Paul Kesley (part time), Ross Bradshaw, Steve Sylvester

Equipment: Compressor

Min.No.	Component	Failure Mode	Effects	Remarks/ Comments
18	Flexible Hose	Excessive charge of liquid (eg. system full of liquid)	- HC and HFC refrigerants will result in 3500kPa pressure - Hose failure will result in catastrophic release (liquid initially then vapour) - Compressor lock up and belt slip	- Operator is present during charging and can shut down fill cycle using isolation valves, if required - system would shut down automatically due to activation of high pressure switch - Charging procedures in place with training of operator in handling ER12 - Only release what is in the system - Mixture of oil and gas released - No known history of ignition and fire as a result of this incident (in either HFC, HCFC blends or HC) - Approximately 2500 CFM (1180 Litres/sec or 4250m^3/hr) of air passing through the engine bay whilst charging (i.e. from engine fan) - No release into passenger compartment - No adverse effect on passenger

FAILURE MODES AND EFFECTS ANALYSIS - WORKSHOP MINUTES

Attendees: Jan Goedhart, Barry Duckworth, Colin Spencer, Graham Nathan, Paul Kesley (part time), Ross Bradshaw, Steve Sylvester

Equipment: Compressor

Min.No.	Component	Failure Mode	Effects	Remarks/ Comments
19	Flexible Hose	Hose weakened by: - battery acid - heat from exhaust - rubbing and friction - oil impact over a longer period Resulting in hose failure	- Catastrophic failure and large release	- Release of gas occurs under bonnet of the car if car is running, over 2500 CFM is being blown into the engine space by the engine fan - If stationary, some of refrigerant is released immediately as liquid or vapour (depending upon location of hose failure), remainder is released as vapour over 30 min. to 1 hour

FAILURE MODES AND EFFECTS ANALYSIS - WORKSHOP MINUTES

Attendees: Jan Goedhart, Barry Duckworth, Colin Spencer, Graham Nathan, Paul Kesley (part time), Ross Bradshaw, Steve Sylvester

Equipment: Condenser

Min.No.	Component	Failure Mode	Effects	Remarks/ Comments
20	Condenser shell	Corrosion from moisture in the system (mainly with CFCs)	- Very minor failures (much smaller than pinhole, leaks over weeks and months)	- When water is left in the system and it is not removed by the filter drier, CFC forms acidic compounds - HCs do not absorb or are miscible with water therefore no acid compounds are generated - All moisture removed by vacuum before HC is charged - Release in engine bay only
21	Condenser shell	Impact on condenser in accident	- Distortion and cracks, minor leaks only - Major leak if serious accident	- In many cases, minor capillary type tubes are self-sealing in minor impact cases as aluminium distorts and seals fractured tube - Releases occur under the bonnet of the car forward of the radiator, dispersing into atmosphere
22	Condenser body	Weld failure	- Cracks and small leaks over a period of days to weeks	- Not likely, no significant historical evidence, leak is external to the engine bay, forward of radiator. Ignition may result in a flash fire. No adverse impact on passenger from the refrigerant. Accident impact is far more serious
23	Condenser Body	Mounting failure due to vibration	- Condenser fan mounting wear on condenser tubes, very small leak (much less than pinhole size)	- Radiator fan is close to leak source providing dispersion if in operation - Insufficient leak quantity for ignition - Potential ignition source at the fan is very low as fan motor is fully sealed, water proof and runs on permanent magnets (ie. no brushes)

FAILURE MODES AND EFFECTS ANALYSIS - WORKSHOP MINUTES

Attendees: Jan Goedhart, Barry Duckworth, Colin Spencer, Graham Nathan, Paul Kesley (part time), Ross Bradshaw, Steve Sylvester

Equipment: Condenser

Min.No.	Component	Failure Mode	Effects	Remarks/ Comments
24	Condenser Body	Body wear from rubbing components against body due to mounting not being adequately fixed	- Minor leaks (much less than pinhole size)	- Insufficient leak quantity for ignition

FAILURE MODES AND EFFECTS ANALYSIS - WORKSHOP MINUTES

Attendees: Jan Goedhart, Barry Duckworth, Colin Spencer, Graham Nathan, Paul Kesley (part time), Ross Bradshaw, Steve Sylvester

Equipment: Condenser to Dryer Pipe (Rigid Aluminium Pipe)

Min.No.	Component	Failure Mode	Effects	Remarks/ Comments
25	Joint failure – 'O' ring	Potential attack from wrong refrigerant, 'O' ring break down	- Small leaks over a period of days and weeks	- May occur with HFCs if neoprene 'O' ring for CFC is still used. HCs do not cause problems for current range of 'O' ring materials (i.e. neoprene used in CFC duty and nitrobutane rubber (HNBR) used in HFC duty) - All new 'O' rings currently available are compatible with all refrigerants used. This completely eliminates this failure mode of 'O' rings - Occurs under bonnet of vehicle - No adverse effect on passenger
26	Aluminium Pipe	Pipe corrosion	- Small leaks over a period of days to weeks	- May only occur with CFCs and HFCs due to acid formation from moisture in the refrigerant. HC with moisture does not form acid and is non-corrosive
27	Aluminium Pipe	Impact from accident	- Distortion and cracks, minor leaks only - Major leak if serious accident	- Release occurs under bonnet of the vehicle, forward of the radiator - See comments on Item 21

FAILURE MODES AND EFFECTS ANALYSIS - WORKSHOP MINUTES

Attendees: Jan Goedhart, Barry Duckworth, Colin Spencer, Graham Nathan, Paul Kesley (part time), Ross Bradshaw, Steve Sylvester

Equipment: Dryer

Min.No.	Component	Failure Mode	Effects	Remarks/ Comments
28	Hose joint (inlet and outlet)	'O' ring joint failure due to over tensionning of joints or loosening of joints Flared connection failure (older cars)	- Small leaks over days/ weeks	- Joints are nut and crimped connection type with 'O' ring seal. Historically seals degrade resulting in very small leak over days or weeks. Seals do not normally leak unless disturbed during maintenance
29	Sight Glass	Glass breaks	- Catastrophic leak from the system under the bonnet, into engine bay	- Historically there are not many leaks from this area - Glass is moulded into the dryer casing and is very unlikely to leak - The glass would have to be physically smashed to break - Pressure test is conducted at manufacturing completion
30	Pressure Switch	Switch fails open (shuts down the compressor)	- Compressor is shut down during normal operation. AC does not operate	- System is shut down and inoperable - No safety issues
31	Pressure Switch	Switch fails closed (does not activate when required)	- Potential for increase in pressure in the system resulting in pipe rupture	- Switch design prevents failure in this way - Engine bay release only - No safety issues
32	Pressure Switch	Central pin failure	- Minor leak through switch casing, leak occurs over days or weeks	Very small leak into engine bay with no safety issues
33	Cylinder or casing	Impact	- Dented, very unlikely to fail due to robust nature of the unit	- In an impact situation, it is more likely that other less robust components will fail (eg. pipework, condenser, etc.)

FAILURE MODES AND EFFECTS ANALYSIS - WORKSHOP MINUTES

Attendees: Jan Goedhart, Barry Duckworth, Colin Spencer, Graham Nathan, Paul Kesley (part time), Ross Bradshaw, Steve Sylvester

Equipment: Dryer

Min.No.	Component	Failure Mode	Effects	Remarks/ Comments
34	Cylinder or casing (inside dryer)	Corrosion	- Small pinholes leaking over a period of days to weeks	- Dryer casing is much thicker than other components in the system. More likely other components will corrode before the dryer casing
35	Cylinder or casing (inside dryer)	Desiccant clogs	- Pressure build up in the system, high pressure switch shuts down A/C	- No safety issues if pressure switch operates. Potential for desiccant blockage is very low
36	Cylinder or casing (inside dryer)	No desiccant or desiccant saturated (ie. fully absorbed with moisture)	- For HCs no issues - For CFCs and HFCs moisture carry over occurs and water/ CFC/HFC mix results in acid formation and corrosion	- No adverse effect on passenger
37	Pipe from dryer to the Tx valve	As per condenser to dryer pipe (minutes 25,26,27 above)		

FAILURE MODES AND EFFECTS ANALYSIS - WORKSHOP MINUTES

Attendees: Jan Goedhart, Barry Duckworth, Colin Spencer, Graham Nathan, Paul Kesley (part time), Ross Bradshaw, Steve Sylvester

Equipment: Thermostatic Expansion Valve (Tx valve)

Min.No.	Component	Failure Mode	Effects	Remarks/ Comments
38	Pipe joint to Tx valve	Joint failure	- Very small leaks over days or weeks	- Leaks at the joints are rare and are usually very small and occur over days to weeks - The group knew of no historical catastrophic joint failure without impact (e.g. accident)
39	'O' ring joint (block type Tx valve)	'O' ring failure	- Very small leaks over days or weeks	(as above)
40	Equalising tube – Tx valve	Tube failure (through fracture or rubbing) or blockage	- No sensing of temperature, evaporator ices up, no air flow	- No safety issue, may result in damage to the compressor internally - Pressure switches will shut down the AC system
41	Tx valve Internal components	Tx valve jams open	- May get liquid carry over to the compressor - Compressor could be damaged internally	- No safety issues
42	Tx valve Internal Components	Tx valve jams closed	- Low system pressure on suction side of compressor, low pressure cut out switch shuts down compressor	- No safety issues

Notes:
1. For Tx valves installed in the passenger compartment of the firewall, there is a potential for a leak to enter the cabin space.
2. Position of Tx valve inside the air conditioning ducting ("box") is critical in determining the amount of gas that leaks into the cabin. There is a drain outlet attached to the casing chamber ("box"), which takes condensed water to the outside of the car. In the event of small leaks some of the gas will escape out of the drain as it is heavier than air.

FAILURE MODES AND EFFECTS ANALYSIS - WORKSHOP MINUTES

Attendees: Jan Goedhart, Barry Duckworth, Colin Spencer, Graham Nathan, Paul Kesley (part time), Ross Bradshaw, Steve Sylvester

Equipment: Evaporator

Min.No.	Component	Failure Mode	Effects	Remarks/ Comments
43	Evaporator shell and tubes	Internal corrosion (small pinhole leaks in tubing)	- Leaks commence very small and release gas over a period of days and weeks. Difficult to detect, drain is often used as a detection point. New methods are to install dye into the system and use ultra violet light to detect the leak. - Leak into passenger cabin	- Hydrocarbon does not react with moisture in the system and hence acidic compounds are not formed. This reduces the chance of corrosion significantly - Gas is odorised and any leak in passenger cabin can be detected immediately
44	Evaporator shell and tubes	External corrosion from corrosive atmosphere (e.g. salt air)	(as above)	- Pinhole and small leaks releasing refrigerant charge over a period of days to weeks
45	Mounting points	Mounting failure or incorrect installation	- Weight of evaporator forces the inlet/ discharge lines to rub on the fire wall eventually leading to catastrophic failure of the lines and major release	Part of the gas will be released into the vehicle passenger compartment. The remainder will be released under the bonnet. Only occurs whilst travelling: - May often start as a small leak in areas with normal smooth roads - Catastrophic failure can occur when roads are rough - In stationary position, leak will occur over hours

FAILURE MODES AND EFFECTS ANALYSIS - WORKSHOP MINUTES

Attendees: Jan Goedhart, Barry Duckworth, Colin Spencer, Graham Nathan, Paul Kesley (part time), Ross Bradshaw, Steve Sylvester

Equipment: Thermostat

Min.No.	Component	Failure Mode	Effects	Remarks/ Comments
46	Thermostat Unit	Fails in the "on" position	- Compressor runs all the time whilst the evaporator fan is running - Ice builds up on the evaporator coils, liquid may be returned to the compressor	- Compressor may be damaged internally - No adverse impact on passenger
47	Thermostat Unit	Fails in the "off" position	- Compressor stops - No air-conditioning	- No safety issues

FAILURE MODES AND EFFECTS ANALYSIS - WORKSHOP MINUTES

Attendees: Jan Goedhart, Barry Duckworth, Colin Spencer, Graham Nathan, Paul Kesley (part time), Ross Bradshaw, Steve Sylvester

Equipment: Pipework from the evaporator to the compressor

Min.No.	Component	Failure Mode	Effects	Remarks/ Comments
48	Flexible suction hose	Small leaks as per flexible hose from the evaporator to the compressor Possible failure modes: - battery acid - wear and rubbing on engine/ vehicle components - hot exhaust pipe contact	- Leaks occur over days and weeks	- This part of the system is under low pressure - Large volume of air moving through the engine bay would create significant dilution of gas. Ignition potential very low. - Leak into engine bay only
49	Flexible suction hose	Catastrophic failure (failure modes as above)	- Tx valve closes immediately (1 to 2 seconds), isolating the leak (i.e. low temperature on discharge side of evaporator is sensed by the thermostat and TX is closed) - Low pressure switch shuts down compressor	- The group identified that there is a low history of failure in this hose due to low pressure - Large volume of air moving through the engine bay creates significant dilution. Ignition potential very low - The pressure switch will shut down the system - Leak into engine bay only

FAILURE MODES AND EFFECTS ANALYSIS - WORKSHOP MINUTES

Attendees: Jan Goedhart, Barry Duckworth, Colin Spencer, Graham Nathan, Paul Kesley (part time), Ross Bradshaw, Steve Sylvester

Equipment: Gas Charging

Min.No.	Component	Failure Mode	Effects	Remarks/ Comments
50	Filling Hoses	Installed wrong way around	Gas will not charge to the system	No safety issues
51	Filling Hoses	Rupture or split hose	- Hose maximum internal diameter is 0.125" (or 3mm) from cylinder to gauges - Potential release of refrigerant which could possibly lead to fire in the workshop	Note: - Person is adjacent to the charging point and cylinder and is therefore available to shut off the cylinder immediately - Gas is odorised and can be detected immediately - Shut down would take about 5-10 seconds The release and its effects in the workshop are carried forward in the study for detailed analysis
52	Gauges	Wrong reading or damaged gauges	- If gauges are badly damaged they are replaced automatically (as part of procedure) as system cannot be charged properly without gauges operating - Wrong reading may lead to slight over/ under charge but will not present a significant problem	- Scales are normally used as the major filling check, gauges are used as a back up check to adhere to recommended charge rates for ER12. The guages are used for a system functional check. - Scales are calibrated at regular intervals

FAILURE MODES AND EFFECTS ANALYSIS - WORKSHOP MINUTES

Attendees: Jan Goedhart, Barry Duckworth, Colin Spencer, Graham Nathan, Paul Kesley (part time), Ross Bradshaw, Steve Sylvester

Equipment: Gas Charging

Min.No.	Component	Failure Mode	Effects	Remarks/ Comments
53	Scales	Incorrect reading on scales or human error	- Minor overcharge or undercharge of the system	- No safety issues - Scales are the primary filling check. Gauges are used as a back up check - Scales are calibrated at regular intervals

FAILURE MODES AND EFFECTS ANALYSIS - WORKSHOP MINUTES

Attendees: Jan Goedhart, Barry Duckworth, Colin Spencer, Graham Nathan, Paul Kesley (part time), Ross Bradshaw, Steve Sylvester

Equipment: Vehicle Disposal/ Panel Shop Work

Min. No.	Component	Failure Mode	Effects	Remarks/ Comments
54	Hoses	Hoses cut through during dismantling of vehicle	- Immediate release of refrigerant gas and oil, aerosol - Jet fire if ignited	- Fire duration very low due to small inventory. Low escalation potential in the engine bay
55	Hoses and fittings	Fitting released with a full gas charge during dismantling	- Up to 350g release into engine bay area, depending on the type of vehicle - Flash fire if ignited	- It is most likely that the engine parts will be dismantled first resulting in release into the engine bay - Need to develop safe dismantling procedure and advise repairers/ wreckers

Note: Within the FMEA workshop, it was not decided if a failure event required to be carried forward for more detailed analysis. The information in this Appendix, along with survey results were reviewed to develop a set of incident scenarios. These scenarios are described in **Appendix 3**, along with the comment on whether or not a scenario was carried forward for detailed analysis, or screened out and the justification thereof.

APPENDIX 3

HAZARD IDENTIFICATION TABLE

TABLE OF CONTENTS

A3.1. INTRODUCTION

A3.1.1 Purpose

This Section contains the scenario based hazard identification tables that complement the Failure Modes and Effects Analysis (FMEA) study presented in **Appendix 2**.

The purpose of this section was to develop credible incident scenarios involving the leak or loss of ER12 hydrocarbon refrigerant during the handling and use of this material.

Results of the monitoring involving the use of ER12 hydrocarbon refrigerant is given in **Appendix 9**.

A3.1.2 Scope

The scenario based hazard identification addressed potential events that could arise during the life cycle of the hydrocarbon refrigerant from:

- manufacture of ER12;
- distribution of ER12 from distributor to workshop;
- re-charging of ER12 into a motor vehicle;
- use of ER12 in motor vehicle; and
- disposal of ER12.

For the purposes of this assessment, all workshop related activities associated with gas charging and dismantling have been combined into one section.

A3.2. RESULTS

A3.2.1 General

The major potential hazard associated with the use and handling of hydrocarbon refrigerant is fire. In the event of a release of flammable material, a fire could result if an ignition source is present. The likelihood of such ignition will depend on whether the hydrocarbon is present in flammable concentration, and whether there is an ignition source sufficient in strength to ignite such a mixture. These aspects are considered in **Appendix 7** and **Appendix 11**.

The overall study incorporated an extensive hazard identification process that involved a screening process based upon the nature of a hazard and the proposed safeguards. A set of scenarios that represented the type of hazards associated with the hydrocarbon refrigerant was developed. These events were based upon extensive discussions with personnel involved in the manufacture, distribution and end use of the refrigerant. In the latter, there was consultation with accredited automotive mechanics who have used both non-hydrocarbon and/or hydrocarbon refrigerants.

Incidents that were identified to be non-credible, either from an operational point of view or due to the chemical characteristics of the hydrocarbon refrigerant, were not carried forward for analysis.

Those events that have potentially adverse consequences to the passenger(s) were carried forward and subjected to a more detailed level of assessment. This involved analysing consequences and (if necessary), the frequency of occurrence. The hazard identification table is shown in **Table A3.3**.

A3.2.2 Scenarios Carried Forward for Assessment

Table A3.1 and **Table A3.2** summarise the credible incidents involving hydrocarbon refrigerant carried forward for further assessment.

The risks associated with the manufacture of ER12 was analysed only qualitatively, as the activity is similar to storage and handling of LP Gas, and are governed by AS 1596. Similarly, the risks associated with the distribution and disposal of the product was handled in a qualitative nature.

TABLE A3.1
CREDIBLE SCENARIOS CARRIED FORWARD FOR FURTHER ASSESSMENT (USE OF HYDROCARBON REFRIGERANT IN VEHICLE)

HAZID No.	Scenario	Status of Vehicle	Leak Location		Status of Air-conditioning System	
			Cabin	Engine Bay	On (operational)	Off (static)
Use of Hydrocarbon Refrigerant in Vehicle						
N-1	Leak under driving conditions	moving	■		X[2].	
N-2	Leak under driving conditions	moving		■	X	
N-3	Total release of refrigerant	collision		■		
N-4	Leak when car is parked [1]	stationary	■			X
N-5	Leak when car is parked [1]	stationary		■		X
N-6	Leak under driving conditions	moving		■		X
N-7	Leak under driving conditions	moving	■			X
N-8	Leak from overcharged system[3]	stationary	■	■		

Notes:

1. Denotes when car is either parked in a structure (e.g. garage) or outside (e.g. street).
2. "X" denotes applicable situation.
3. Denotes worst case scenario for overcharged system in terms of leak rate.

TABLE A3.2
CREDIBLE SCENARIOS CARRIED FORWARD FOR FURTHER ASSESSMENT (USE OF HYDROCARBON REFRIGERANT IN WORKSHOP)

HAZID No.	Scenario	Comment
Use of Hydrocarbon Refrigerant in Workshop		
W-1	Release of refrigerant in workshop	
W-2	Excessive quantity of refrigerant charged into AC system	considered in N-8
W-7	Workshop mechanic / auto-electrician unaware that air-conditioning system is charged with hydrocarbon refrigerant	considered in W-1
W-8	Leak of hydrocarbon refrigerant across running engine	considered in W-1
W-9	Venting of hydrocarbon refrigerant to atmosphere	considered in W-1

TABLE A3.3
SCENARIO BASED HAZARD IDENTIFICATION

ID No	Scenario	Cause	Potential Consequences	Safeguards	Carried forward for quantitative analysis?
Manufacture (M)					
M-1	HC blend is off specification: - wrong ratio propane/ iso-butane - contaminants (e.g. water)	- No quality control of raw materials - Unclean gas cylinder	- decreased performance of AC system	- quality control systems are implemented at both manufacturing facilities (Melbourne and Adelaide) - formal procedures include cleaning and checking gas cylinders prior to filling - procedure to check blend at NATA certified laboratory - cylinders are not filled if HC product is off-specification	no
M-2	Gas cylinder overpressurised	Overcharging of gas cylinder	Excess quantity of product charged into cylinder	- cylinder filling line based on weight - quality certified operating systems in place to ensure that correct quantity is charged into the cylinders	no
M-3	Wrong label on cylinder	Gas cylinder incorrectly labelled	No safety issue	- both plants (Melbourne and Adelaide) dedicated to the manufacture of HC refrigerant - both facilities operate with safety management systems (SMS)	no
M-4	Loss of HC from cylinder after filling	Faulty valve	Leak of HC to atmosphere	- all cylinders are inspected prior to packaging in accordance with AS 23371-1989 - quality control procedures - no history of leaking valves	no

TABLE A3.3
SCENARIO BASED HAZARD IDENTIFICATION

ID No	Scenario	Cause	Potential Consequences	Safeguards	Carried forward for quantitative analysis?
Storage (S)					
S-1	Leak of gas from cylinder	- Faulty valve - Stack topple	- leak of HC to atmosphere - fire if ignited	- inspected distribution centers have strict no smoking policy in warehouse (due to Health & Safety Regulations) - warehouses have fire protection systems in place - minimal quantities stored in warehouses - in case of stack topple, cylinder valve has safety impact ring around it	no
Use of Hydrocarbon Refrigerant in Vehicle (Normal Operations, N)					
N-1	Leak into cabin under driving conditions with AC on	Leak from AC system: - Tx valve (inside firewall) - pipework - screwed fitting - evaporator (porosity, corrosion) - 'O' ring seals	- HC ingress into passenger compartment - potential for mixture (air/ gas) reach LFL - potential for fire if mixture (above LFL) is ignited	- gas detected by odour as HC refrigerant is odourised with mercaptan - airflow through passenger compartment	yes

TABLE A3.3
SCENARIO BASED HAZARD IDENTIFICATION

ID No	Scenario	Cause	Potential Consequences	Safeguards	Carried forward for quantitative analysis?
N-2	Leak into engine bay under driving conditions with AC on	Leak from AC system: - Tx valve (outside firewall) - condenser - drier - compressor - pipework	- HC ingress into engine bay - potential for mixture (air/ gas) reach LFL - potential for fire if mixture (above LFL) is ignited	- free flowing air discharge to the floor when engine running as bonnet is closed - airflow through engine bay	yes
N-3	Release of refrigerant	Car collision/ crash	- HC ingress into engine bay - potential for mixture (air/ gas) reach LFL - potential for fire if mixture (above LFL) is ignited	- airflow in engine bay may prevent LFL being reached	yes
N-4	Leak into cabin when car is stationary and AC off	Leak from AC system: - Tx valve (inside firewall) - pipework - screwed fitting - evaporator	- build up of HC and fire if mixture (above LFL) is ignited		yes – analysis conducted for vehicle in: - open - garage

TABLE A3.3
SCENARIO BASED HAZARD IDENTIFICATION

ID No	Scenario	Cause	Potential Consequences	Safeguards	Carried forward for quantitative analysis?
N-5	Leak into engine bay when car is stationary and AC off	Leak from AC system: - Tx valve (outside firewall) - condenser - drier - compressor - pipework	- build up of HC and explosion/ fire if mixture (above LFL) is ignited	- no hot surfaces in stationary car	yes
N-6	Leak into cabin when car is moving and AC off	Leak from AC system: - Tx valve (inside firewall) - pipework - screwed fitting - evaporator	- HC ingress into passenger compartment - potential for mixture (air/ gas) reach LFL - potential for fire if mixture (above LFL) is ignited	- natural ventilation from car movement even if windows are closed - all new vehicles are currently installed with flow through ventilation in the passenger cabin	yes

TABLE A3.3
SCENARIO BASED HAZARD IDENTIFICATION

ID No	Scenario	Cause	Potential Consequences	Safeguards	Carried forward for quantitative analysis?
N-7	Leak into engine bay when car is moving with AC off	Leak from AC system: - Tx valve (outside firewall) - condenser - drier - compressor - pipework	- HC ingress into engine bay - potential for mixture (air/ gas) reach LFL - potential for fire if mixture (above LFL) is ignited	- high dilution rate due to radiator fan flow and discharge at road level as bonnet is closed	yes
N-8	Leak into cabin from overcharged vehicle	Workshop error may lead to overcharging (see W-2) Leak from AC system: - Tx valve (inside firewall) - pipework - screwed fitting - evaporator	- HC ingress into passenger compartment - potential for mixture (air/ gas) near LFL - potential for fire if mixture (above LFL) is ignited	- See W-2 for safeguards against overcharging	yes

TABLE A3.3
SCENARIO BASED HAZARD IDENTIFICATION

ID No	Scenario	Cause	Potential Consequences	Safeguards	Carried forward for quantitative analysis?
Workshop/ Charging/ Maintenance (W)					
W-1	Release of refrigerant in workshop	- Faulty valve - Venting AC system - Accidental repair/ damage to AC system	- leak of refrigerant - fire if smoking or welding	- cylinder tested prior to use - any leaking valve will not be used - no smoking in workshop - no welding if AC system is worked on - any leak immediately detected by odour - operator present continuously during this operation	yes
W-2	Excessive quantity of refrigerant charged into AC system	Over-charging of system	- noticeable poor performance of AC system in car - no safety issue	- workshop follows simple charging procedure - charge chart supplied with product - PSH cutout of compressor - charge quantity can be preset on weigh scale for automatic cutoff	yes – considered in N-8
W-3	Insufficient refrigerant in AC system	Undercharging of system	- poor performance of AC system in car - no safety issue	- workshop follows simple charging procedure - charge chart supplied with product	no
W-4	Recovery of HC refrigerant into CFC or HFC cylinder	Operator error	- contamination of cylinder with HC - no safety issue	- it is not necessary under regulations to reclaim HC refrigerant ER12 has low global warming and ozne depletion potential and is not damaging to the environment (compared to HFC, HCFC refreigerants)	no

TABLE A3.3
SCENARIO BASED HAZARD IDENTIFICATION

ID No	Scenario	Cause	Potential Consequences	Safeguards	Carried forward for quantitative analysis?
W-5	Charging HC refrigerant into AC system with residual HFC or CFC refrigerant	Operator error	- No safety issue	- No reaction between HFC/ CFC and HC	no
W-6	Charging HFC refrigerant into AC system with residual HC refrigerant	Operator error	- No safety issue	- No reaction between HFC/ CFC and HC	no
W-7	Workshop mechanic/ electrician unaware that AC system is charged with HC	HC label not in place on engine of car	- potential for HC to ignite if a leak from AC system occurs while under maintenance	- all vehicles charged with HC have identification labels on the AC system	considered in W-1
W-8	Leak of HC refrigerant across running engine	Blown hose	- potential to ignite HC and fire in engine bay		considered in W-1
W-9	Venting of HC refrigerant to atmosphere	Disposal of refrigerant	- no environmental issue as HC is greenhouse gas friendly		considered in W-1

TABLE A3.3
SCENARIO BASED HAZARD IDENTIFICATION

ID No	Scenario	Cause	Potential Consequences	Safeguards	Carried forward for quantitative analysis?
Disposal of Car (D)					
D-1	Release of refrigerant inventory to atmosphere	Release of refrigerant due to: - salvage of engine parts from used car - destruction of used car by crushing	- release of refrigerant to atmosphere - no environmental issue as HC is greenhouse gas friendly (has a low global warming potential and ozone depletion potential compared to HFC, HCFC refrigerants)	- no personnel present in the near vicinity of crushing of cars - no confinement of refrigerant would occur due to the open space - recommendation: All wrecking yards to be notified of the use of ER12 vehicles by Boral Energy (see Risk Management Section of Safety Study)	no

APPENDIX 4

STUDY ASSUMPTIONS

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A4.1. INTRODUCTION

The purpose of this section is to outline the assumptions and their justification used in the safety assessment. These assumptions have been divided into the following categories:

- Hazard identification;
- Leak rate;
- Release modelling; and
- Frequency and Risk Analysis.

Each assumption is given a justification and is referenced to the section(s) of the report in which it is used.

A4.2. STUDY ASSUMPTIONS

A4.2.1 Hazard Identification

Assumption 1

The hazard identification process was used to segregate potential incidents involving ER12 into different categories of:

- manufacture;
- storage and distribution;
- workshop; and
- end use of product.

Justification 1

A life cycle analysis approach of the ER12 refrigerant product was adopted for the Safety Study in line with comments provided in the 1998 Esanty submission to the Queensland Gas Examiner. This approach allowed the convenient segregation of incidents into these categories (**Appendix 3**).

Assumption 2

For the incident involving an accidental overcharging of the vehicle air-conditioning system, analysis was conducted only for the case of moving vehicle.

Justification 2

The moving case was considered to be the worst case scenario as the air-conditioning system could experience the full range of possible leak scenarios up to rupture. However, the risk analysis implicitly covered the situation when the vehicle was stationary.

A4.2.2 Leak Rate Calculations

Assumption 3

Release rates were evaluated for two cases that best represented typical Australian conditions at:

- average ambient temperature of 20°C; and
- average ambient temperature of 40°C.

Justification 3

The average ambient temperature value used was 20°C which is representative of the southern Australian states. For tropical and sub-tropical zones an average ambient temperature of 40°C was used. This was known as Case 1 and also represented conditions where higher temperatures are experienced frequently during the summer months. The corresponding vapour pressure at these temperatures was used in the leak rate calculations (**Appendix 6**).

Assumption 4

Release locations were divided into two distinct groupings:

- Engine bay; and
- Passenger cabin.

Justification 4

The vehicle air-conditioning system was able to be divided into its components located behind the firewall in the passenger cabin and those located in the engine bay. This was based upon physical observation and discussions with accredited automotive mechanics. A parts count has been conducted for the Safety Study and diagrams have been provided detailing the location of air-conditioning components in a vehicle (**Appendix 12**).

Assumption 5

It was assumed that for vehicles manufactured by General Motors Holden and Ford Australia, the thermal expansion (Tx) valve was located in the engine bay. For all other vehicles, the Tx valve was assumed to be located in the passenger cabin (**Appendix 6**).

Justification 5

This assumption was a general rule of thumb provided in discussions with workshop mechanics. Observations of the popular makes of family sized vehicles from Ford and Holden also confirmed this general rule (**Appendix 6**).

Assumption 6

The leak size rule sets shown in **Table A4.1** were used in the analyses.

TABLE A4.1
LEAK SIZE RULE SET

Location	Leak Category	Equivalent Hole Size
Engine Bay	Pinhole	0.1mm
	Large	1.0mm
	Catastrophic	vapour – 12mm
		liquid – 8mm
Passenger Cabin	Pinhole	0.01mm
	Large	0.1mm
	Catastrophic	> 1mm

Justification 6

The leak rule sets were derived in the following way by:

- outcomes from the FMEA study (**Appendix 2**);
- physical inspection of faulty air-conditioning equipment (**Appendix 9**); and
- consultation with accredited automotive mechanics (**Appendix 12**).

Assumption 7

A sudden and complete loss of ER12 charge from an air-conditioning circuit was assumed to occur following a collision.

Justification 7

It was found that a sudden loss of ER12 charge could only be caused through a vehicle accident. The study found that under normal driving conditions, it was extremely unlikely that a refrigeration system would rupture (**Appendix 6**).

Assumption 8

The leak rate from a pinhole (0.01mm) was treated as a semi-continuous release.

Justification 8

The assessment found that a typical loss of the ER12 charge would occur over a period of weeks and months. As such, this assumption was considered conservative as in fact, gradual depressuring would occur and hence the release rate would also correspondingly be lower (**Appendix 6**).

Assumption 9

For releases from large and catastrophic sized holes, the release rate versus time depressuring profile was calculated based upon the system pressure and ER12 charge.

Justification 9

For a vapour release from large hole sizes, the release rate would not remain at the instantaneous value. The pressure and corresponding flow would steadily decrease until the system pressure was at ambient. For these scenarios, the depressuring curve was calculated based upon the temperature and corresponding pressure as well as inventory in the system (**Appendix 6**).

Assumption 10

For release rate calculations, discharge coefficient value of 0.8 was used.

Justification 10

This is based on a discussion by Lees (Ref.1) who quotes a common value of 0.8 used in risk assessment for leaks (**Appendix 6**).

Assumption 11

The time to vent (excluding vacuum) of ER12 refrigerant from a vehicle air-conditioning circuit was taken to be on average 90 seconds.

Justification 11

In discussion with workshop mechanics, the duration of vented release varies between 30 seconds to 5 minutes. An average value of 90 seconds was chosen. This was considered conservative as a smaller vent time yielded a relatively higher vent release rate (**Appendix 6**).

A4.2.3 Release Modelling

Assumption 12

For the purposes of calculations, the estimation of a vehicle volume was based around a series of "boxes".

Justification 12

The car passenger compartment volume was required for the calculation of refrigerant concentration in the passenger compartment. This data was unavailable from car manufacturers and hence was measured during the course of this study.

In order to estimate the car passenger compartment volume, a number of measurements were taken inside the car and the approximate volume was calculated from these. It was not possible to estimate the car volume taking into account all the details of the cabin using this method and so a series of "boxes" was used. When compared with car volumes estimated through experiment by Maclaine-Cross (Ref.2), the measured values from this study were generally lower than those of Maclaine-Cross indicating that the measured values used in this study were conservative (**Appendix 5**).

Assumption 13

For the purposes of the analyses, passenger vehicles were divided into three categories of large, medium, small on the basis of volume.

Justification 13

The car passenger compartment volumes were measured and the cars grouped into three categories for the purposes of the analysis. The three categories were representative of the majority of passenger vehicles on Australian roads and were considered adequate for the analysis (**Appendix 5**).

Assumption 14

The associated ER12 charge mass was based upon the average of those vehicles in that category and these were:

- Large sized vehicles (300 grams);
- Medium sized vehicles (228 grams);
- Small and micro sized vehicles (216 grams);
- Micro sized vehicles (210 grams).

(For the study, small and micro vehicles were grouped together).

Justification 14

The ER12 charge masses for each car group (by volume) was taken from the Boral Esanty suggested charge charts. These were averaged over the car group that the car was in to give the average charge mass for each grouping. This was considered adequate for the analysis particularly considering the fact that the difference between charge masses of any cars was not great (**Appendix 5**).

Assumption 15

The concentration in the passenger cabin following a release of ER12 refrigerant is well mixed.

Justification 15

Based upon experimental trials involving gases (i.e. carbon dioxide – 44 gram/mole, ER12 – 48 gram/mole) with molecular weights heavier than air of 29 g/mole, it was found a vapour release resulted in a uniform concentration within the car cabin within 2-20 minutes. Momentum jet release simulation also confirmed experimental observations.

Assumption 16

It was assumed that stationary vehicle had all vents in the closed position to limit the associated air exchange rate.

Justification 16

This was considered the most pessimistic assumption giving the lowest air exchange rates.

Assumption 17

The air exchange rates (ACH) values shown in **Table A4.2** were used in the assessment.

TABLE A4.2
ACH VALUES

Situation	Car Type	Minimum ACH Value (h^{-1})	Comment
Vehicle parked in enclosure (Winter day and evening)	Late Model	0.3	Experimental
	Early Model	0.3	Experimental
Vehicle parked in open area (Winter day and evening)	All models	1.0	Experimental / HSE
	Late Model	0.7	Experimental / HSE
	Early Model	1.1	Experimental / HSE
Vehicle Moving	All Models	10	HSE

Justification 17

The ACH values for stationary vehicles located in open and closed positions were derived from tracer gas experimentation. These values were derived under Sydney winter conditions and under near still wind conditions. Hence these values are conservative, as a low air exchange rate results in a higher concentration of refrigerant in the vehicle cabin.

A literature review found that the ACH values for moving vehicles were dependent on vehicle speed. For the purposes of this study, an ACH value of 10 /hour was chosen representing a vehicle travelling at 36 kilometre per hour. This is a conservative assumption as speeds in built up areas vary from 40 to 60 km/h.

Assumption 18

The physical state of release from the leak sizes considered in the study were:

Pinhole	(vapour phase);
Large	(vapour phase); and
Catastrophic	(two phase initially followed by vapour phase).

Justification 18

Based upon ER12 experiments (**Appendix 9**), the physical state of release was observed to be those reported above.

Assumption 19

Incidents that displayed a peak concentration at or above 50% LFL were carried forward for further analysis.

Justification 19

Although the average concentration may be at or near 50% LFL, there may be pockets where the concentration could be higher. A widely used method is to adopt a peak to mean ratio of two to allow for non-uniform mixing (Ref. 3). This made the assessment conservative.

Assumption 20

A full rupture of the air-conditioning system when the vehicle was stationary (for example, parked in a garage) was not feasible.

Justification 20

In a critical analysis of a vehicle air-conditioning system, the only components located inside the passenger cabin are the evaporator and the thermal expansion valve (for vehicles manufactured overseas). Given that these parts are non moving and that the piping connecting these parts is seamless and has screwed 'O' ring fittings, the potential for a sudden complete failure is considered extremely unlikely when the vehicle is stationary.

Assumption 21

An accidental overcharge of ER12 into a vehicle air-conditioning system would be detected by the workshop mechanic during post-charging inspections. Hence a human error probability of 0.09 was assigned.

Justification 21

This value was taken from Ref.4. As part of ER12 charging procedures, a recommended charge rate book is provided with the product. A set of scales is used to determine the charge rate entering the system. Further, thermocouples are placed in the circuit to ensure that the required temperature efficiency is achieved. Experimental trials showed that an overcharge has the effect of drastically decreasing the cooling efficiency of the system and would be detected by the accredited automotive mechanic. Recommendations have been provided in the Safety Study addressing this issue.

Assumption 22

The ACH values could be estimated using a first order decay equation.

Justification 22

The tracer gas study found that the concentration versus time decay profile measured in the passenger cabin followed an exponential decay. Hence this assumption is considered valid (**Appendix 10**).

Assumption 23

The ACH values used in the present assessment for stationary vehicles were derived for Sydney winter conditions.

Justification 23

The tracer gas studies found that under still wind conditions, the ACH value was heavily dependent on ambient temperature. A correlation was developed and as the temperature increased, the ACH correspondingly rose to a value greater than 1 at 20°C. Hence under summer conditions where the ambient temperature is relatively high, the ACH value would also be relatively high. Hence the ACH value chosen for this assessment is very conservative.

Assumption 24

It was assumed that all of the refrigerant leak from the evaporator or Tx valve would go into the passenger compartment.

Justification 24

This is a conservative assumption due to the fact that there is a drain outlet at the base of the casing chamber containing the evaporator and Tx valve through which a portion of the refrigerant leak would escape.

Assumption 25

The volume occupied by the seats in the passenger cabin was not subtracted from the total volume measured to obtain the free volume.

Justification 25

The volume occupied by the seats varied between different car types and a single value could not be used. In order to minimise the number of parameters, the above assumption was made. However, it was found that this assumption did not influence the conclusions arrived at for the air exchange calculations.

Assumption 26

The charge masses used in calculations for an overcharged system were as follows:

- large car: 400g (133% of nominal charge of 300g);
- medium and small car: 300g (nominal charge 220g).

Justification 26

These values were assigned to each situation as a realistic estimate of the overcharging that may occur in a workshop. 133% of the nominal charge was chosen for the large car and the large car nominal charge was chosen for the small and medium car.

Assumption 27

For engine bay calculations, the free volume of the engine bay was assumed to be 20% of the total volume of the area.

Justification 27

This assumption was made due to the congested nature of the engine bay area and the resulting limited free volume in the space.

A4.2.4 Frequency and Risk Analysis

Assumption 28

The data results obtained from the workshop surveys was used to represent failures of vehicle air-conditioning systems.

Justification 28

A total of 68 workshops were surveyed in Perth, Adelaide and Melbourne. These cities were chosen since both hydrocarbon refrigerant and HFC refrigerant are used there. It was stated that the average operational experience of an accredited automotive mechanic was 10 years. This collectively gave 680 years of experience.

Assumption 29

It was assumed that at least 52% of passenger vehicles in Australia are fitted with air-conditioning systems.

Justification 29

The survey data found that just over half of the passenger vehicles serviced had been fitted with an air-conditioning system. This value is close to the reported value of 50% by NSW Motor Vehicle Industry Repair Association (Ref.5).

Assumption 30

In a typical motor vehicle air-conditioning system and assuming the Tx valve is located inside the passenger cabin, there are 2 'O' rings representing 25% of the total 'O' rings present in the system.

Justification 30

A parts count of a typical passenger vehicle air-conditioning system was undertaken based upon physical observation (**Appendix 12**).

Assumption 31

Sixty percent of passenger vehicles in Australia have the Tx valve located inside the passenger cabin.

Justification 31

This was based upon road sale figures of popular makes and models in Australia (**Appendix 12**).

Assumption 32

On average, a person spends approximately 1.8 hours in a vehicle per day.

Justification 32

This value was taken from US statistics as there was no Australian published data. A sensitivity analysis was performed on this variable. An estimate for Australian conditions was made based on 20,000 km per year and an average speed of 30 km/hour.

Assumption 33

It was assumed that a passenger vehicle is parked equally in the open (i.e. carpark or street) or in an enclosure (i.e. probability value of 0.5).

Justification 33

There is no data to support this assumption, therefore a sensitivity analysis was conducted on this variable.

Assumption 34

In assessing the minimum ignition current using the methodology of AS 2380.7 (Ref.6), circuits were assumed to be resistive if the measured inductance was less than 1 milliHenry.

Justification 34

The methodology is based on Section 5.5.2 of AS 2380.7 (Ref.6).

Assumption 35

The minimum ignition current was determined assuming a battery voltage of 16V.

Justification 35

Most car battery systems operate at 12V, but theoretically could be charged as high as 16V. 16V was used as a conservative value.

A4.3. REFERENCES

1 Lees F. P. (1996): "Loss Prevention in the Process Industries", Butterworth Heinemann, Oxford, p. 15/8.

2 Maclaine-Cross (1997): "Refrigerant Concentrations in Car Passenger Compartment", UNSW.

3 Cox, Lees and Ang (1990): "Classification of Hazardous Locations", IChemE, Rugby, p. 150

4 Williams, J.C. (1988): "A data based method for assessing and reducing Human Error", Proceedings of IEEE 4th Conference on Human Factors in Power Plants, Monterey, California.

5 NSW Motor Vehicle Repair Industry Association (1996): "Briefing Paper: Alternatives to CFC as Refrigerants in Motor Vehicle Air-Conditioners – Hydrocarbons Compared to R134a", Sydney, January.

6 Standards Australia (1987): AS 2380.7i – 1987, "Intrinsic Safety".

APPENDIX 5

CAR VOLUME MEASUREMENT AND REFRIGERANT CHARGE

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A5.1. INTRODUCTION

A5.1.1 Purpose

The purpose of this Appendix was to tabulate typical car volumes and associated refrigerant charges. This data is required in order to calculate the concentration of ER12 hydrocarbon refrigerant in the car passenger compartment following a leak. Data on refrigerant charge was sourced from the recommended charge rate book developed for all vehicle types (up to 1998) by Boral Esanty. However, due to confidentiality concerns, Granherne was unable to obtain passenger compartment volumes from the car manufacturers. Hence, measurements of motor vehicles were undertaken in order to calculate the corresponding car volume.

A5.1.2 Scope

Car measurements of popular makes and models were conducted. The following models were covered:

- Ford
- General Motors Holden
- Honda
- Hyundai
- Mazda
- Mitsubishi
- Nissan
- Toyota

A5.2. CAR VOLUME MEASUREMENT

A5.2.1 Methodology

This section presents the methodology adopted in estimating the car volumes. A reproducible protocol was developed for both sedan/ hatch motor vehicles and wagons.

A5.2.2 Sedan/ Hatch

The volume of a sedan/ hatchback car was calculated using the following formula:

$$V = (l-a-b)hw + 1/2a(d+h)w + 1/2bcw$$

Each of these parameters is explained by **Figure A5.1** and **Table A5.1**.

TABLE A5.1
DIMENSIONS USED FOR CALCULATION OF CAR CABIN VOLUME – SEDAN/ HATCH

No.	Description	Symbol
1	Maximum height of cabin: Measure height from centre of cabin	h
2	Measure distance from front edge of dashboard at base of windscreen to back window	l
3	Measure the width of the car cabin just in front of the driver/ passenger front seats at base of window	w
4	Measure depth of dashboard	a
5	Measure depth of back ledge	b
6	Measure height from top of back seats to roof	c
7	Measure the height from the floor to the top of the dashboard	d

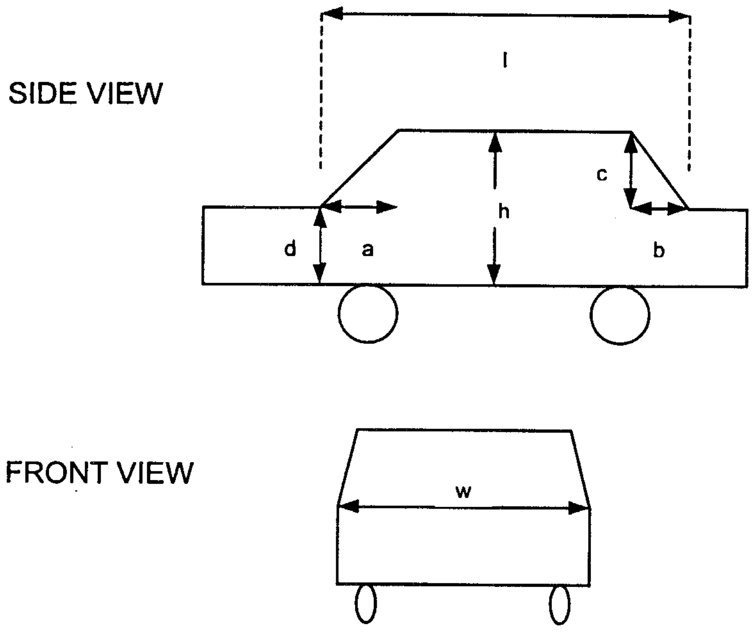

FIGURE A5.1
SEDAN/ HATCH DIMENSIONS USED FOR CAR CABIN VOLUME CALCULATION

A5.2.3 Wagon

The volume of a wagon had to be calculated slightly differently. The following formula was used:

$$V = (l-a)hw + 1/2a(d+h)w + bew$$

TABLE A5.2
DIMENSIONS USED FOR CALCULATION OF CAR CABIN VOLUME - WAGON

No.	Description	Symbol
1	Measure height from centre of cabin ie: just behind driver's seat	h
2	Measure distance from front edge of dashboard at base of windscreen to top of back seats	l
3	Measure the width of the car cabin just in front of the driver/ passenger front seats at base of window	w
4	Measure depth of dashboard	a
5	Measure the length of the boot space from back seats to base of back window	b
6	Measure height from top of back seats to roof	c
7	Measure the height from the floor to the top of the dashboard	d
8	Measure the height of the boot space from floor to roof	e

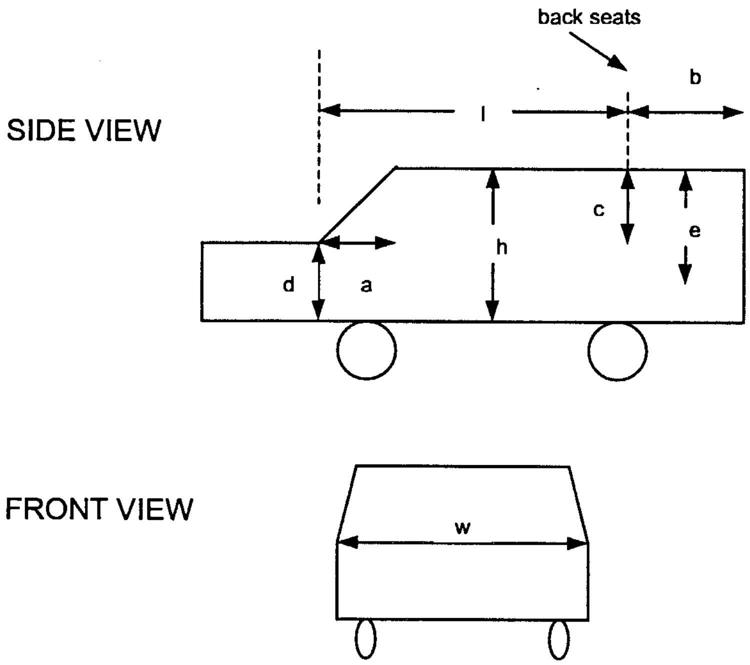

FIGURE A5.2
WAGON DIMENSIONS USED FOR CAR CABIN VOLUME CALCULATION

A5.2.4 Results

The volumes measured are shown in **Table A5.3** for each of the car models investigated. Using the charge charts provided by Boral Esanty, the refrigerant charge mass of ER12 assigned for each model is also given in **Table A5.3**. For the purposes of the study, cars were rationalised on the basis of their volumes into the following categories:

- large;
- medium;
- small; and
- micro.

A summary of the values used in the Safety Report is given in **Table A5.4**.

TABLE A5.3
CAR VOLUMES AND REFRIGERANT CHARGES

Car Type	Year	Model	Volume (m^3)	Refrigerant Charge (g)[1] (Note 1)
Acclaim	1995	Wagon	5.43	235
Commodore	1998	Wagon	6.04	235
Commodore	1998	Sedan	4.32	235
Magna GLX	1992	Sedan	4.70	225
Magna Verada	1998	Wagon	4.99	225
Applause 4 door	1998	Hatch	3.23	165
Camry	1989	Sedan	3.31	200
Camry	1997	Sedan	3.73	240
Camry	1997	Sedan	3.82	240
Charade 4 door	1998	Hatch	3.06	195
Corolla	1996	Hatch	3.56	210
Corolla	1986	Hatch	3.21	210
Corolla	1986	Sedan	3.16	210
Excel 2 door	1996	Hatch	3.92	210
Laser	1985	Hatch	3.10	225
Laser	1998	Hatch	3.65	225
Magna	1994	Sedan	3.66	225
Magna	1998	Sedan	3.81	190
Mazda 121	1997	Hatch	3.23	190
Mazda 626	1997	Hatch	3.56	235
Mirage 2 door	1998	Hatch	3.32	190
Pulsar	1997	Hatch	3.54	190
Pulsar LX	1996	Sedan	3.55	190
Telstar	1984	Hatch	3.75	235
Vectra	1998	Sedan	3.53	270
Coupe (Hyundai)	1996	Hatch	2.87	210
Falcon	1998	Sedan	3.77	300
Mondeo	1998	Sedan	3.33	220
Festiva	1998	Hatch	2.85	210
Verada	1998	Sedan	3.81	225
Honda Civic	1998	Hatch	2.95	185

Note 1: Charge mass provided by Boral Esanty Refrigerants for ER12.

TABLE A5.4
RATIONALISED CAR VOLUMES AND CHARGE MASS USED IN THE STUDY

Vehicle Grouping	Size Category (m^3)	Average Volume (m^3)	Nominated Charge Mass (g)
Large	> 5	5.7	300
Medium	4 – 5	4.7	228
Small	3 – 4	3.5	216
Micro	< 3	2.9	210

APPENDIX 6

LEAK RATE CALCULATIONS

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A6.1. INTRODUCTION

A6.1.1 Purpose

This Appendix outlines the methodology, calculations and results of modelling hydrocarbon refrigerant release rates.

A6.1.2 Credible Release Scenarios

In order to develop credible leak scenarios for consequence analysis, data was gathered from the following sources:

- FMEA Study (**Appendix 2**);
- HAZID Table (**Appendix 3**);
- Survey Data (**Appendix 12**); and
- Experimental Work (**Appendix 9**).

The leak scenarios carried forward for assessment are shown in **Table A6.1** and **Table A6.2**. Two cases were studied for incidents involving hydrocarbon refrigerant in the passenger vehicle (**Table A6.1**):

1. Base Case – typical operations (average ambient temperature of 20°C); and
2. Case 1 – operations under high ambient temperatures (40°C).

These were conducted for conditions when the passenger vehicle air-conditioning (AC) system was either operating (AC on) or static (AC off).

A6.1.2.1 Case Studies

The Base Case represented the typical operating conditions in a car for most of Australia. That is, ambient temperatures of around 20°C. Case 1 represented high ambient conditions as found in northern Queensland and the Northern Territory with ambient temperatures around 40°C. These temperatures can also be experienced for short periods during summer in the southern part of Australia. In these high temperatures, the operating pressure of the air-conditioning system in the car would be higher, thus increasing the release rate of refrigerant in the event of a leak.

TABLE A6.1
SCENARIOS CARRIED FORWARD FOR FURTHER ASSESSMENT USE OF HYDROCARBON REFRIGERANT IN VEHICLE
(Ref: Appendix 3)

HAZID No.	Scenario	Status of Vehicle	Leak Location		Status of Air-conditioning System	
			Cabin	Engine Bay	On (operational)	Off (static)
Use of Hydrocarbon Refrigerant in Vehicle						
N-1	Leak under driving conditions	moving	■		X[2.]	
N-2	Leak under driving conditions	moving		■	X	
N-3	Total release of refrigerant	collision		■		
N-4	Leak when car is parked [1]	stationary	■			X
N-5	Leak when car is parked [1]	stationary		■		X
N-6	Leak under driving conditions	moving		■		X
N-7	Leak under driving conditions	moving	■			X
N-8	Leak from overcharged system[4.]	stationary	■	■		

Notes:

1. Denotes when car is either parked in a structure (i.e. garage) or outside (i.e. street).
2. "X" denotes applicable situation.
3. Denotes worst case scenario for overcharged system in terms of leak rate.

TABLE A6.2
SCENARIOS CARRIED FORWARD FOR FURTHER ASSESSMENT USE OF HYDROCARBON REFRIGERANT IN WORKSHOP
(Ref: Appendix 3)

HAZID No.	Scenario	Comment
Use of Hydrocarbon Refrigerant in Workshop		
W-1	Release of refrigerant in workshop.	
W-2	Excessive quantity of refrigerant charged into AC system.	considered in N-8
W-7	Workshop mechanic unaware/ auto-electrician unaware that air-conditioning system is charged with hydrocarbon refrigerant.	considered in W-1
W-8	Leak of hydrocarbon refrigerant across running engine.	considered in W-1
W-9	Venting of hydrocarbon refrigerant to atmosphere.	considered in W-1

A6.1.3 Hole Sizes

The release hole sizes were developed in two distinct groups:

- engine bay releases; and
- passenger compartment releases.

Table A6.3 summarises the potential leak sources of hydrocarbon refrigerant based upon surveys of air-conditioning systems (**Appendix 12**).

TABLE A6.3
POTENTIAL LEAK SOURCES AND LOCATIONS OF CAR REFRIGERANT[1]

Leak Location	Passenger Vehicle Air-conditioning Components
Inside passenger vehicle cabin	- Thermal expansion (Tx) valve - only if inside firewall. - Evaporator. - Seals and o'rings associated with Tx valve and evaporator. - Pipework.
Engine bay	- Compressor. - Condenser. - Receiver/ drier. - Thermal expansion (Tx) valve - only if outside firewall. - Seals and o'rings associated with above components. - Pipework.

Note:

1. This applies to both non-hydrocarbon and hydrocarbon refrigerant

A6.1.3.1 Engine Bay

The engine bay release rule set used in the study is shown in **Table A6.4**:

TABLE A6.4
ENGINE BAY RELEASE RULE SET

Leak Category	Equivalent Hole Size	Comment
Pinhole	0.1mm	Based upon FMEA study and site visits to workshops
Large	1.0mm	
Catastrophic	vapour – 12mm	
	liquid – 8mm	

The hole size rule set for the engine bay was developed to take account of the ways in which leaks could occur from the air-conditioning system in this area.

A full rupture of the circuit in the engine bay is possible in a vehicle collision.

A6.1.3.2 Passenger Compartment

The passenger compartment rule set developed in the study is shown in **Table A6.5**.

TABLE A6.5
PASSENGER CABIN RELEASE RULE SET

Leak Category	Equivalent Hole Size	Comment
Pinhole	0.01mm	Based upon FMEA study and site visits to workshops
Large	0.1mm	
Catastrophic	> 1mm	

These hole sizes were developed particularly through the survey work given in **Appendix 12** and the experimental work conducted with ER12 (**Appendix 9**). All of the air-conditioning components that can be located within the passenger compartment of the vehicle consist of seamless piping and there are no moving parts. This leads to the pinhole leak size of 0.01mm being the most likely (a hairline fracture which is difficult to detect in the workshop).

A6.1.4 Summary of Releases

The release characteristics and operating conditions considered in the analysis are shown in **Table A6.6**.

TABLE A6.6
LEAK RATE CONDITIONS[1]

Study	Passenger Compartment				Engine Bay			
	Phase	Hole Size (mm)	Pressure (kPag)	Temp. (°C)	Phase	Hole Size (mm)	Pressure (kPag)	Temp. (°C)
Air-conditioning System Operating (AC On)								
Base Case (typical)	Vapour	0.01 0.1 1	260	20	Vapour	0.1 1 12	260	20
	2 phase	0.01 0.1 1	260	5	Liquid	0.1 1 8	1100	48
Case 1 (high ambient)	Vapour	0.01 0.1 1	331	40	Vapour	0.1 1 12	331	40
	2 phase	0.01 0.1 1	331	10	Liquid	0.1 1 8	1655	64
Air-conditioning System Static (AC Off)								
Base Case	Vapour	0.01 0.1 1	465	20	Vapour	0.1 1 12	465	20
					Liquid (receiver drier)	0.1 1	465	20
Case 1	Vapour	0.01 0.1 1	836	40	Vapour	0.1 1 12	836	40
					Liquid [2] (receiver drier)	0.1 1	836	40

Note: 1. The frequency of such events are considered in **Appendix 12** and the main report The actual release phase has also been considered in experiments (**Appendix 9**).

For instance, a release equivalent to 0.1mm immediately downstream of Tx valve was found to be vapour and not two phase. This vapour phase release would also apply to leaks smaller than 0.1mm.

2. When the AC system is off, the receiver drier contains the entire liquid inventory of refrigerant and there is therefore very little or no liquid held in the other components of the air-conditioning system. Further, the receiver drier is the lowest point of the air-conditioning system and hence all liquid drains to this spot. The pressure, however, would equalise on either side of the Tx valve in a short time following the AC shutdown.

A6.2. LEAK RATE CALCULATION

A6.2.1 Introduction

Leaks of refrigerant could be vapour, two phase or liquid leaks and a different method was required for the calculation of each of these leaks. The methods used and input data are given in the following sections.

A6.2.2 Vapour Leaks

In order to calculate the vapour leak rate, the release was modelled as a "Gas release through hole in vessel" using the software TNO EFFECTS 2.1. The input parameters for each release are shown in **Table A6.7**.

TABLE A6.7
VAPOUR LEAK PARAMETERS

Case	Leak Location	Hole Size (mm)	Pressure (kPa abs)	Temperature (K)	Vessel Volume (m^3)
Air-Conditioning System Operating (AC On)					
Base	PC[1]	0.01 0.1 1	361	293	0.0363[3] 0.0266[4]
	EB[2]	0.1 1 12	361	293	0.0363[3] 0.0266[4]
Case 1	PC	0.01 0.1 1	432	313	0.0324[3] 0.0238[4]
	EB	0.1 1 12	432	313	0.0324[3] 0.0238[4]
Air-Conditioning System Static (AC Off)					
Base	PC	0.01 0.1 1	566	293	0.022[3] 0.0161[4]
	EB	0.1 1 12	566	293	0.022[3] 0.0161[4]
Case 1	PC	0.01 0.1 1	937	313	0.0135[3] 0.00987[4]
	EB	0.1 1 12	937	313	0.0135[3] 0.00987[4]

Note:

1. PC denotes "passenger cabin"
2. EB denotes "engine bay"
3. Refrigerant charge 300g (large cars)
4. Refrigerant charge 220g (medium/small cars)

A coefficient of discharge (C_d) of 0.8 was used for all calculations.

The receiver vessel volume was calculated from the charge mass (300g large cars, 220g medium/ small cars) and the vapour density of the material at the given temperature and pressure. A sample calculation is given here (for the Base Case):

Vapour density (mixture) = 8.27 kg/m^3

Receiver vessel volume = 0.3kg/ 8.27 kg/m^3 = 0.0363 m^3

These values were entered into the EFFECTS model and the resulting leak rates are shown in **Table A6.11** where all leak rates are summarised.

A6.2.3 Two Phase Leaks

Two-phase leaks were calculated in a spreadsheet, using the following correlations.

Method

Leak rates of two phase leaks were calculated using the Fauske equation. The following method was used:

1. Calculation of vapour fraction of material.

$$x = 1 - \exp[-\frac{C_p}{\lambda}(T - T_c)]$$

where x = vapour fraction of material

C_p = liquid heat capacity (J/ kgK)

λ = latent heat of vaporisation (J/kg)

T = temperature (K)

T_c = choke temperature (K), i.e. temperature at which internal flashing of liquid occurs at the orifice.

The liquid heat capacity for the refrigerant mixture of propane and iso-butane was calculated from the average of the heat capacity for propane and iso-butane. The latent heat of vaporisation was calculated similarly.

2. Calculation of vapour density.

$$\rho_g = \frac{12.03}{T_c} P_c M$$

where ρ_g = vapour density (kg/m^3)

P_c = choke pressure (bara), i.e. pressure at which internal flashing occurs at the orifice.

M = molecular weight (kg/kmol)

The ratio for choke pressure to system pressure has been established from empirical data to be 0.55. Thus $P_c = 0.55P$, where P is the pressure of the release.

3. Calculation of density of mixture.

$$\rho_{mix} = \frac{1}{\frac{x}{\rho_g} + \frac{1-x}{\rho_l}}$$

where ρ_{mix}= density of two phase mixture (kg/m^3)

ρ_l = density of liquid (kg/m^3)

The density of the liquid mixture of propane and iso-butane was calculated from the following formula:

$$\rho_{liqmix} = \frac{1}{\frac{y}{\rho_{liqprop}} + \frac{1-y}{\rho_{liqbut}}}$$

where ρ_{liqmix} = density of liquid mixture of propane and iso-butane (kg/m^3)

$\rho_{liqprop}$ = liquid density of propane (kg/m^3)

ρ_{liqbut} = liquid density of iso-butane (kg/m^3)

y = mass fraction of propane in liquid mixture

4. Calculation of leak rate.

$$m = C_d A \sqrt{2\rho_{mix}(P - 0.55P)}$$

where m = leak rate (kg/s)

C_d = coefficient of discharge

A = area (m^2)

P = pressure of release (Pa abs)

Data

Two phase leaks were only modelled coming into the passenger compartment. The input data required for the above equations is given in **Table A6.8**.

TABLE A6.8
INPUT DATA FOR TWO PHASE LEAKS

Case	Parameter	Value
Air-conditioning System Operating (AC On)		
Base	Pressure	260 kPag
	Temperature	5 ^{o}C
	Hole size	0.01mm; 0.1mm; 1mm
	Area	7.85E-11 m^2; 7.85E-09 m^2; 7.85E-07 m^2
	Coefficient of discharge	0.8
	Choke pressure ratio	0.55
	Choke pressure	198.55 kPa abs
	Choke temperature	261 K
	Heat of vaporisation of liquid	460 kJ/kg
	Molecular weight	51 g/mol
	Density of liquid refrigerant mix	547 kg/m^3
	Liquid heat capacity of refrigerant mix	2.395 kJ/kg.K
Case 1	Pressure	331 kPag
	Temperature	10^{o}C
	Choke pressure	238 kPa abs
	All other parameters as for Base Case	
Air-conditioning System Static (AC Off)		
No two phase leaks for this case		

The leak rates calculated are shown in **Table A6.11**.

A6.2.4 Liquid Leaks

Liquid leak rates were calculated using Bernoulli's equation.

$$m = C_d A\rho\sqrt{2\frac{P}{\rho} + 2gh}$$

where m = leak rate (kg/s)

C_d = coefficient of discharge

A = area of hole (m^2)

P = pressure of release (Pa g)

h = static head (m)

g = acceleration due to gravity, 9.8 ms^{-2}

ρ = density of liquid (kg/m^3)

Again, the density of the liquid mixture of propane and iso-butane was calculated from the densities of each component.

TABLE A6.9
INPUT DATA FOR LIQUID LEAK RATE CALCULATIONS

Case	Parameter	Value
Air-conditioning System Operating (AC On)		
Base	Pressure	1201 kPa abs
	Temperature	48°C
	Hole size	0.1mm, 1mm, 8mm
	Coefficient of discharge	0.8
	Density of refrigerant mixture	484 kg/m^3
	Static head	0 m
Case 1	Pressure	1756 kPa abs
	Temperature	64°C
	Hole size	0.1mm, 1mm, 8mm
	Coefficient of discharge	0.8
	Density of refrigerant mixture	454 kg/m^3
	Static head	0 m
Air-conditioning System Static (AC Off)		
Base	Pressure	566 kPa abs
	Temperature	293 K
	Hole size	0.1mm, 1mm
	Coefficient of discharge	0.8
	Density of refrigerant mixture	528 kg/m^3
	Static head	0 m
Case 1	Pressure	937kPa abs
	Temperature	313 K
	Hole Size	0.1mm, 1mm
	Coefficient of discharge	0.8
	Density of refrigerant mixture	498 kg/m^3
	Static head	0 m

The leak rates calculated are shown in **Table A6.11**.

A6.2.5 Release in Workshop

A release in the workshop was modelled to determine the rate and duration of the release from the air-conditioning system when venting the refrigerant to air. TNO EFFECTS 2.1 was used to model the vapour release with the duration of the release set at 90 seconds. The duration of release is dependent on the operator and can range from 30 seconds to 5 minutes with a reported average of 90 seconds. For the purposes of this study, this value was chosen for the analysis. The release hole size was altered to give the desired release duration.

Two cases were modelled, for a refrigerant inventory of 300g (large car) and 220g (medium/ small cars). The release pressure was taken as the vapour pressure at the ambient temperature (20°C for Base Case; 40°C for Case 1). The input data for the release model is shown in **Table A6.10**.

TABLE A6.10
INPUT DATA FOR WORKSHOP REFRIGERANT RELEASE

Parameter	Value
Base Case	
Pressure	566 kPa abs
Temperature	293 K
Receiver Vessel Volume (300g inventory) Receiver Vessel Volume (220g inventory)	0.022 m^3 0.0161 m^3
Discharge coefficient	0.8
Case 1	
Pressure	937 kPa abs
Temperature	313 K
Receiver Vessel Volume (300g inventory) Receiver Vessel Volume (220g inventory)	0.0135 m^3 0.00987 m^3
Discharge coefficient	0.8

A6.2.6 Leak Rates

The initial leak rates calculated using the above methods are shown in **Table A6.11**. Initial leak rates were the same for the refrigerant masses of 300g and 220g.

TABLE A6.11
LEAK RATES OF REFRIGERANT

Study	Passenger Compartment			Engine Bay		
	Phase	Hole Size (mm)	Leak Rate (kg/s)	Phase	Hole Size (mm)	Leak Rate (kg/s)
Air-conditioning System Operating (AC On)						
Base Case (typical)	Vapour	0.01	6.54E-08	Vapour	0.1	6.54E-06
		0.1	6.54E-06	P= 260 kPag	1	6.53E-04
		1	6.54E-04	T= 20°C	12	0.095
	2 phase	0.01	2.56E-07	Liquid	0.1	2.05E-04
		0.1	2.56E-05	P= 1100 kPag	1	2.05E-02
		1	2.56E-03	T= 48°C	8	1.31 *
Case 1 (high ambient)	Vapour	0.01	7.56E-08	Vapour	0.1	7.56E-06
		0.1	7.56E-06	P= 331 kPag	1	7.54E-04
		1	7.54E-04	T= 40°C	12	0.11
	2 phase	0.01	2.86E-07	Liquid	0.1	2.44E-04
		0.1	2.86E-05	P= 1655 kPag	1	2.44E-02
		1	2.86E-03	T= 64°C	8	1.56 *
Air-conditioning System Static (AC Off)						
Base Case	Vapour	0.01	1.03E-07	Vapour	0.1	1.03E-05
		0.1	1.03E-05	P=465 kPag	1	1.02E-03
		1	1.03E-03	T= 20°C	12	0.15
				Liquid	0.1	1.39E-04
				P=465 kPag	1	1.39E-02
				T= 20°C		
Case 1	Vapour	0.01	1.64E-07	Vapour	0.1	1.64E-05
		0.1	1.64E-05	P= 836 kPag	1	1.63E-03
		1	1.63E-03	T= 40°C	12	0.24
				Liquid	0.1	1.81E-04
				P= 836 kPag	1	1.81E-02
				T= 40°C		

* This is greater than the inventory, indicating instantaneous release of full inventory of 220-300 grams.

TABLE A6.12
WORKSHOP RELEASE RATES

Study	Large Car (300g refrigerant inventory)		Small/ Medium Car (220g refrigerant inventory)	
	Phase	Leak Rate (kg/s)	Phase	Leak Rate (kg/s)
Base Case	Vapour	4.5E-03	Vapour	3.3E-03
Case 1	Vapour	5.9E-02	Vapour	4.2E-03

A6.3. DEPRESSURING CURVES

A6.3.1 Introduction

The release rates given above are the initial or instantaneous leak rates calculated at the beginning of each release. As the release progresses, the pressure in the system will decrease, thus also reducing the leak rate. The curves showing the decay of leak rate with time are shown in this section for vapour and two phase leaks into the passenger compartment.

Depressuring curves are shown for both a refrigerant mass of 300g and of 220g, because the duration of the release was dependent on the initial mass of refrigerant thus causing the curves to differ. **Table A6.13** summarises the curves given in this Appendix.

No depressuring curves were generated for 0.01mm leaks as there were holes as pseudo-continuous releases. This is a conservative assumption as in reality such leaks do depressure. Such leak durations have been reported to span over up to 3 months.

TABLE A6.13
DEPRESSURING CURVES SUMMARY

Car Volume Size	Case	Depressuring Curve			
		AC On		AC Off	
		Vapour 0.1mm	Two Phase 1mm	Vapour 0.1mm	Vapour 1mm
Large	Base Case	Figure A6.1	Figure A6.13	Figure A6.3	Figure A6.5
	Case 1	Figure A6.2	Figure A6.14	Figure A6.4	Figure A6.6
Medium/ Small	Base Case	Figure A6.7	Figure A6.15	Figure A6.9	Figure A6.11
	Case 1	Figure A6.8	Figure A6.16	Figure A6.10	Figure A6.12

For the purpose of the Safety Report, analysis was conducted for the 1mm two phase release (as representing both two phase and vapour phase releases) as these release rates were more onerous than the 1mm vapour phase release.

Depressuring curves are only shown for the releases into the passenger compartment. The duration of liquid releases into the engine bay is calculated and given in **Section A6.3.4**.

A6.3.2 Vapour Leaks

The depressuring curves are shown in the following sub-sections. It should be noted that about 40% of the system inventory would remain in the refrigeration system at low temperature as residual and total release would not occur except in the case of instantaneous release following hose rupture or collision. Therefore, the area under the curves would not add up to the total inventory.

A6.3.2.1 Large Car Volume

TNO EFFECTS 2.1 gives the depressuring curve for the leak rate vs time as part of the results of the "Gas release through hole in vessel" model.

Air-conditioning System Operational

Figure A6.1 and **Figure A6.2** show the depressuring curves for a vapour leak for both the Base Case and Case 1 for a refrigerant mass of 300g.

FIGURE A6.1
DEPRESSURING CURVE FOR BASE CASE, AC ON, VAPOUR 0.1mm
LARGE CAR

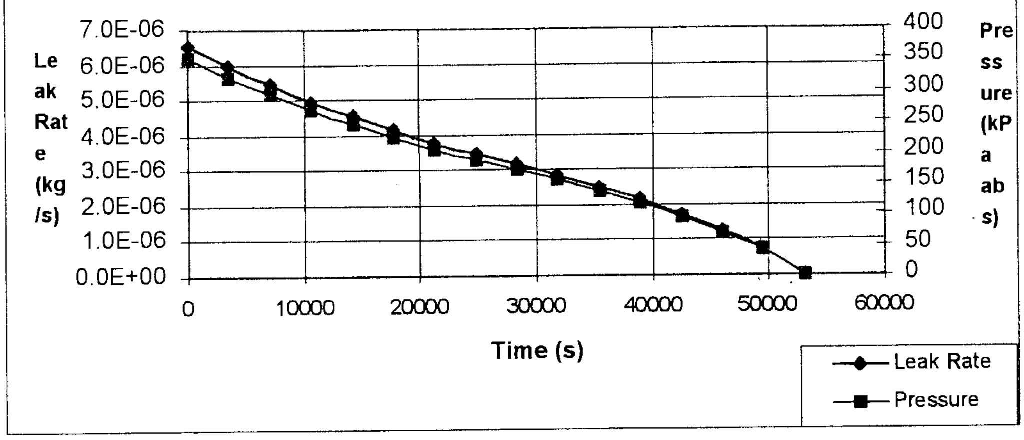
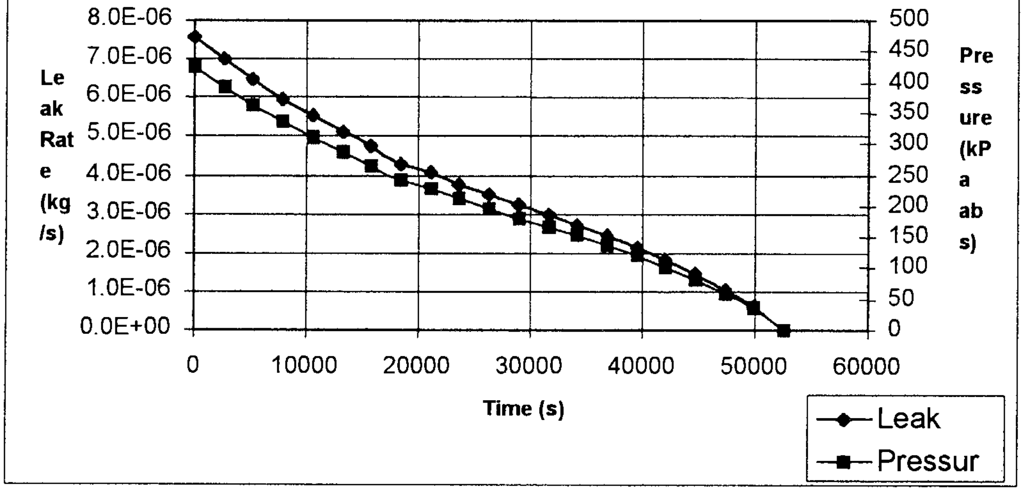


FIGURE A6.2
DEPRESSURING CURVE FOR CASE 1, AC ON, VAPOUR 0.1mm
LARGE CAR



Air-conditioning System Static

Figure A6.3 and **Figure A6.4** show the depressuring curves for a 0.1mm vapour leak for both the Base Case and Case 1 for a refrigerant mass of 300g.

FIGURE A6.3
DEPRESSURING CURVE FOR BASE CASE, AC OFF, VAPOUR 0.1mm LEAK,
LARGE CAR VOLUME

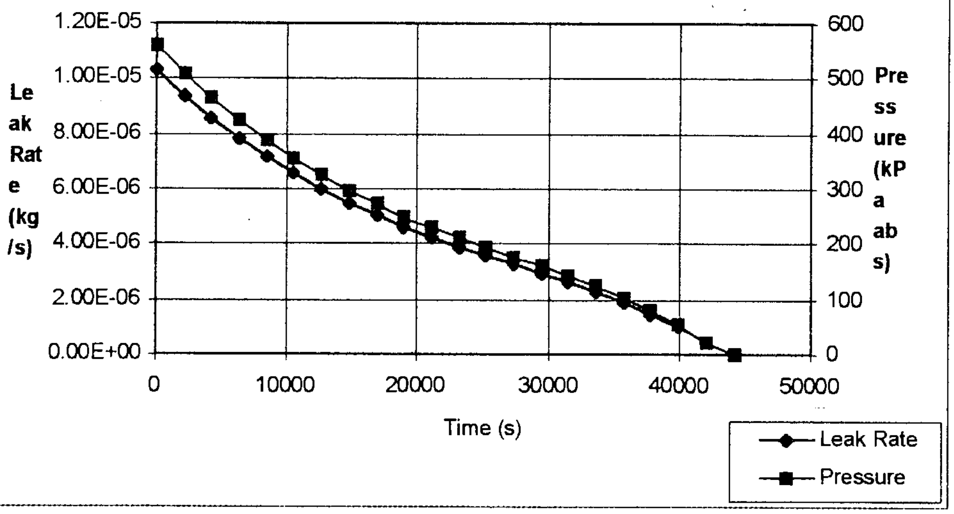


FIGURE A6.4
DEPRESSURING CURVE FOR CASE 1, AC OFF, VAPOUR 0.1mm LEAK, LARGE CAR

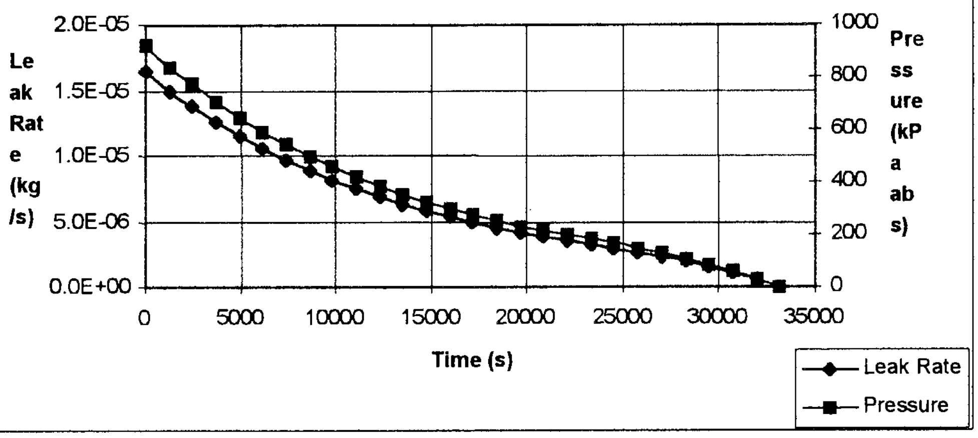


Figure A6.5 and **Figure A6.6** show the depressuring curves for a 1mm vapour leak for both the Base Case and Case 1 for a refrigerant mass of 300g.

FIGURE A6.5
DEPRESSURING CURVE FOR BASE CASE, AC OFF, VAPOUR 1mm LEAK, LARGE CAR

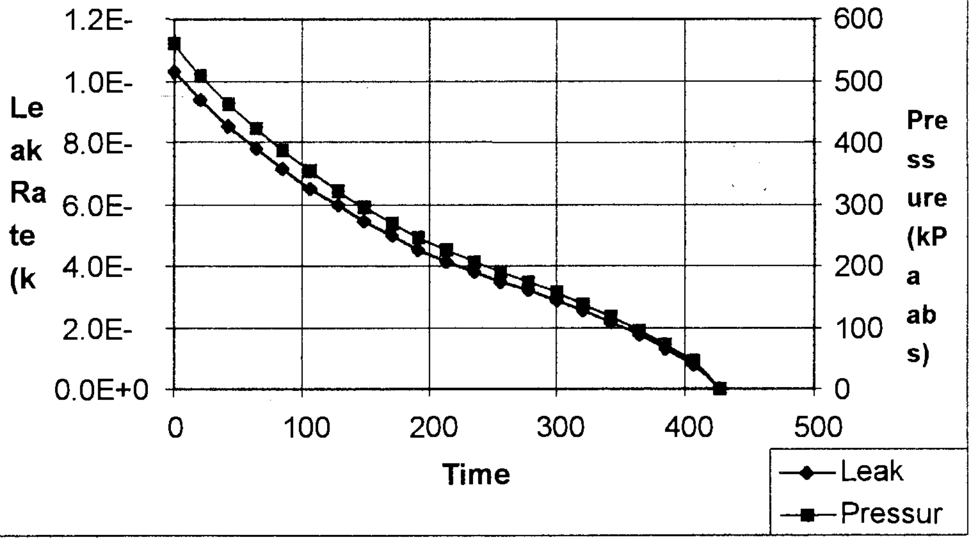
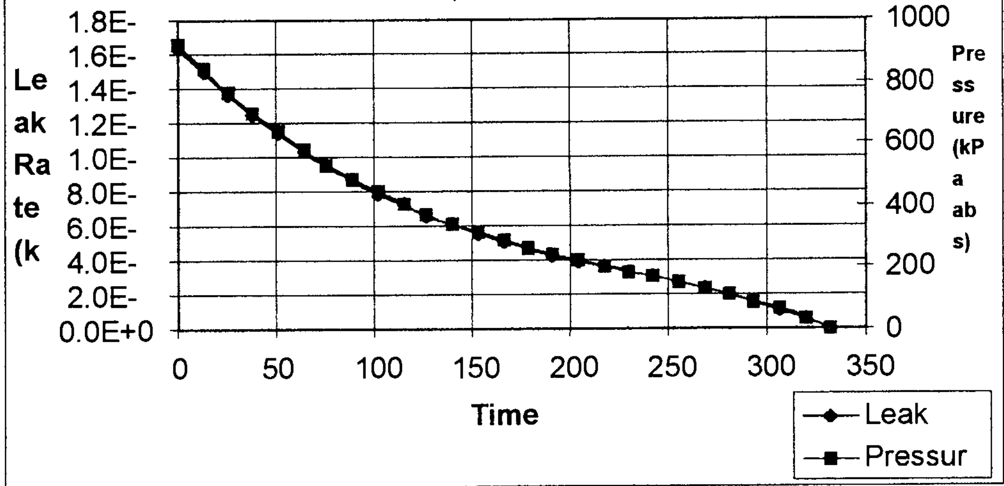


FIGURE A6.6
DEPRESSURING CURVE FOR CASE 1, AC OFF, VAPOUR 1mm LEAK, LARGE CAR



A6.3.2.2 Medium/ Small Car Volume

Air-conditioning System Operational

Figure A6.7 and **Figure A6.8** show the depressuring curves for a vapour leak for both the Base Case and Case 1 for a refrigerant mass of 220g.

FIGURE A6.7
DEPRESSURING CURVE FOR BASE CASE, AC ON, VAPOUR 0.1mm LEAK, MEDIUM/ SMALL CAR

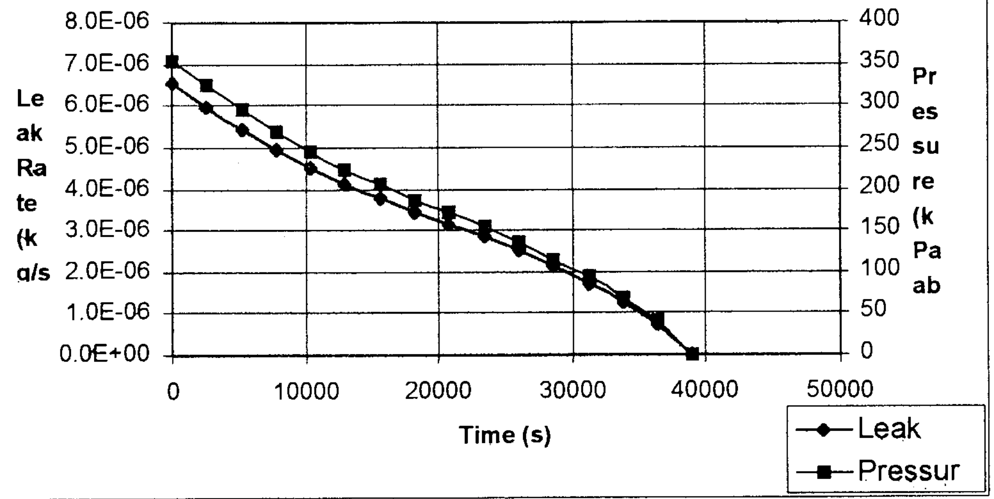
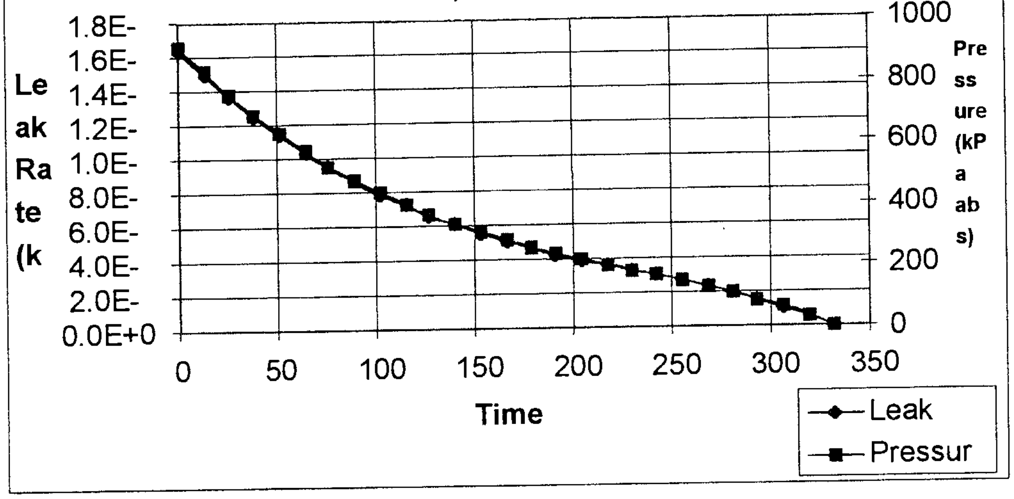


FIGURE A6.6
DEPRESSURING CURVE FOR CASE 1, AC OFF, VAPOUR 1mm LEAK, LARGE CAR



A6.3.2.2 Medium/ Small Car Volume

Air-conditioning System Operational

Figure A6.7 and **Figure A6.8** show the depressuring curves for a vapour leak for both the Base Case and Case 1 for a refrigerant mass of 220g.

FIGURE A6.7
DEPRESSURING CURVE FOR BASE CASE, AC ON, VAPOUR 0.1mm LEAK, MEDIUM/ SMALL CAR

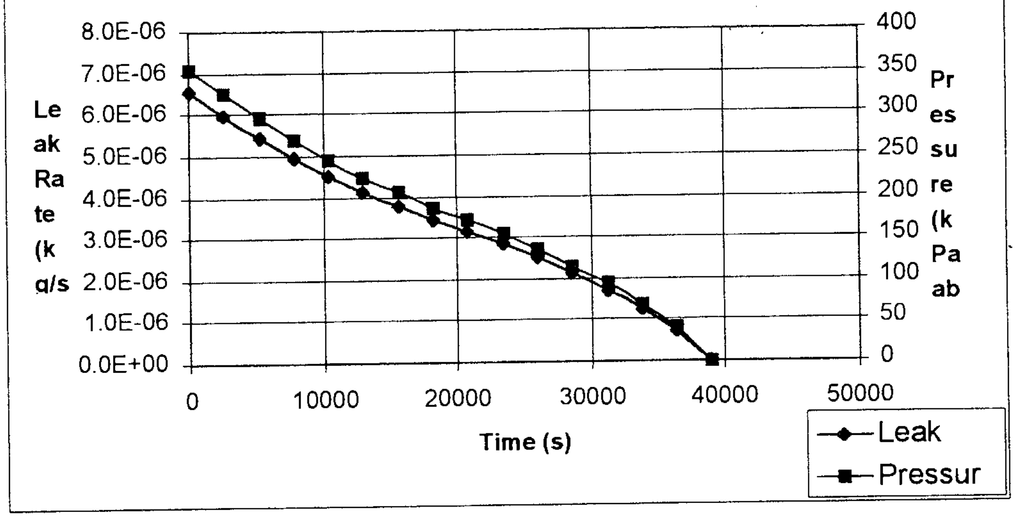


FIGURE A6.10
DEPRESSURING CURVE FOR CASE 1, AC OFF, 0.1mm VAPOUR LEAK, MEDIUM/ SMALL CAR VOLUME

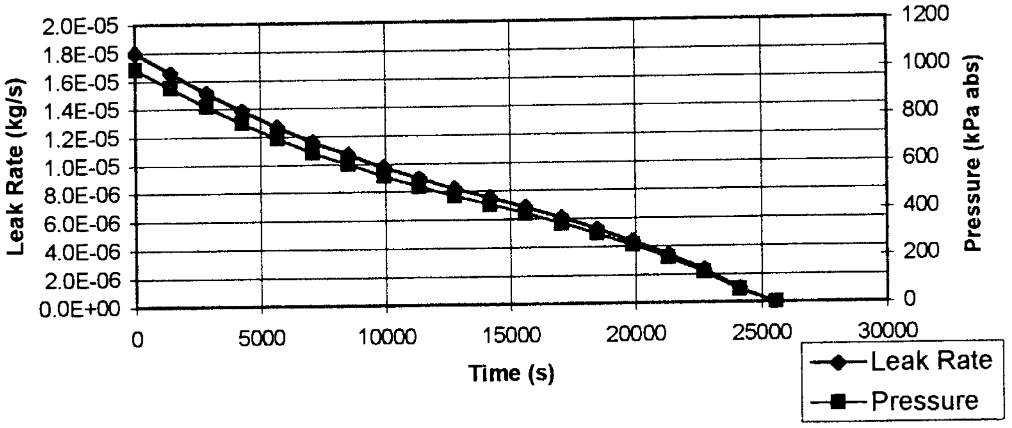


Figure A6.11 and **Figure A6.12** show the depressuring curves for a 1mm vapour leak for both the Base Case and Case 1 for a refrigerant mass of 220g.

FIGURE A6.11
DEPRESSURING CURVE FOR BASE CASE, AC OFF, VAPOUR 1mm MEDIUM/ SMALL CAR VOLUME

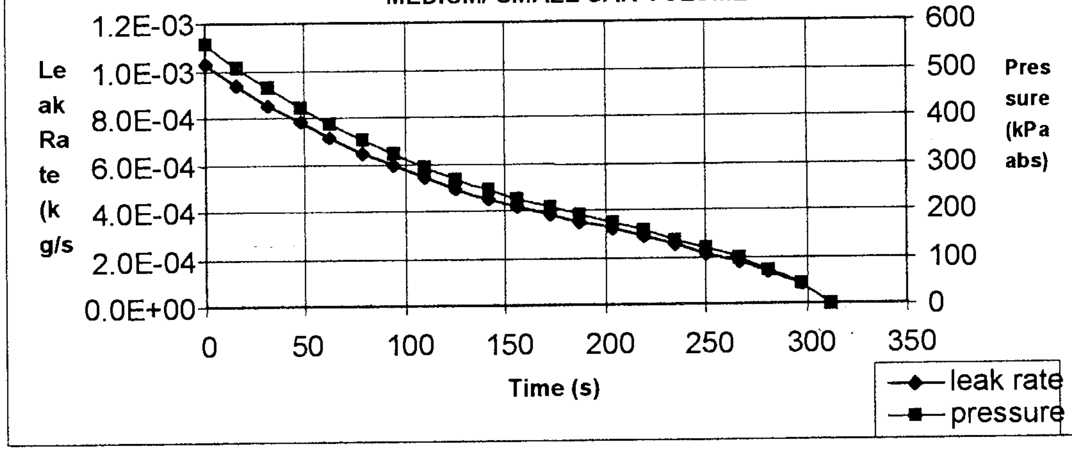
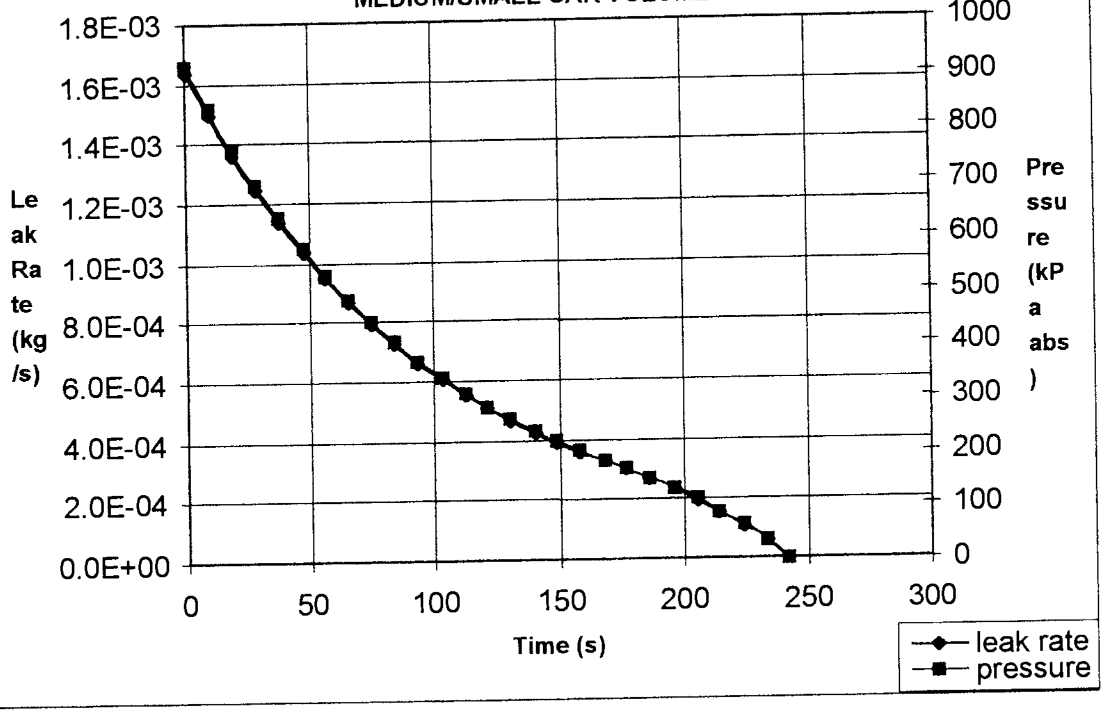


FIGURE A6.12
DEPRESSURING CURVE FOR CASE 1, AC OFF, VAPOUR 1mm LEAK, MEDIUM/SMALL CAR VOLUME



A6.3.3 Two Phase Leaks

Air-conditioning System Operational

In order to generate the depressuring curve for two phase leaks, the TNO EFFECTS 2.1 "Gas release through hole in vessel" model was used. The hole size in the input data was altered to give the initial release rate as calculated for the two phase release. The depressuring curve could then be used for the two phase release. This is a conservative assumption because a two phase release will depressure more quickly than a vapour release.

A6.3.3.1 Large Car Volume

Figure A6.13 and **Figure A6.14** show the curves for a two phase release for the air-conditioning system operating, with an initial refrigerant charge mass of 300g.

FIGURE A6.13
DEPRESSURING CURVE FOR BASE CASE, AC ON, TWO PHASE 1mm LEAK, LARGE CAR VOLUME

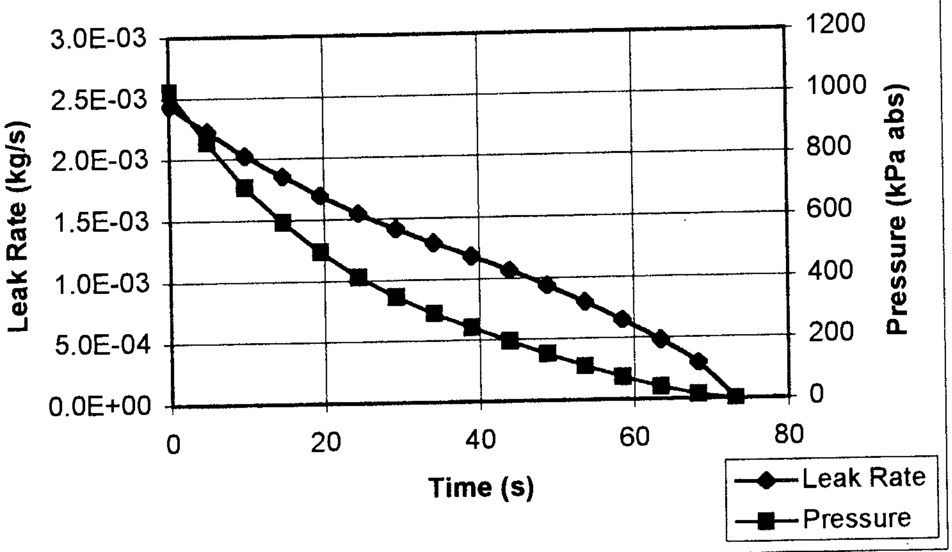
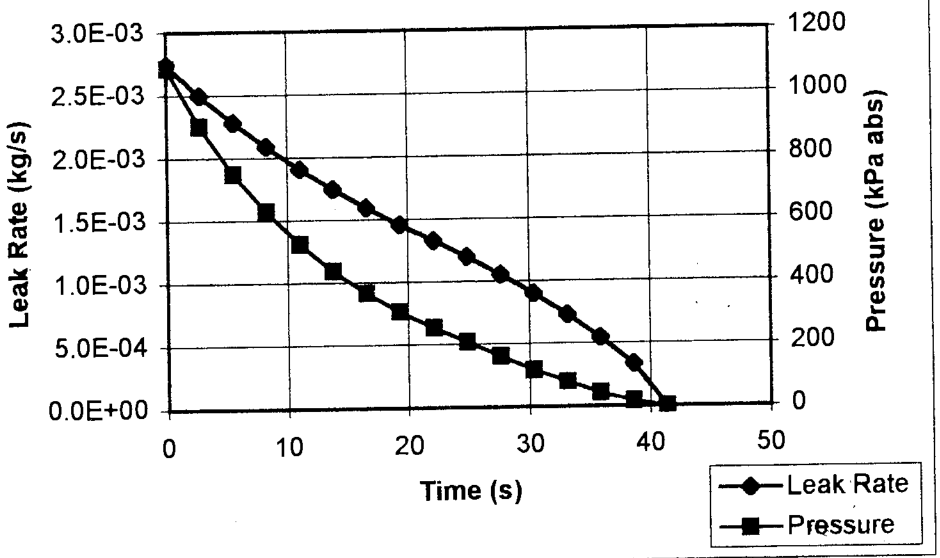


FIGURE A6.14
DEPRESSURING CURVE FOR CASE 1, AC ON, TWO PHASE 1mm LEAK, LARGE CAR VOLUME



A6.3.3.2 Small/ Medium Car Volume

Figure A6.15 and **Figure A6.16** show the curves for a two phase release for the air-conditioning system operating, with an initial refrigerant charge mass of 220g.

FIGURE A6.15

DEPRESSURING CURVE FOR BASE CASE, AC ON, TWO PHASE 1mm LEAK, MEDIUM/SMALL CAR VOLUME

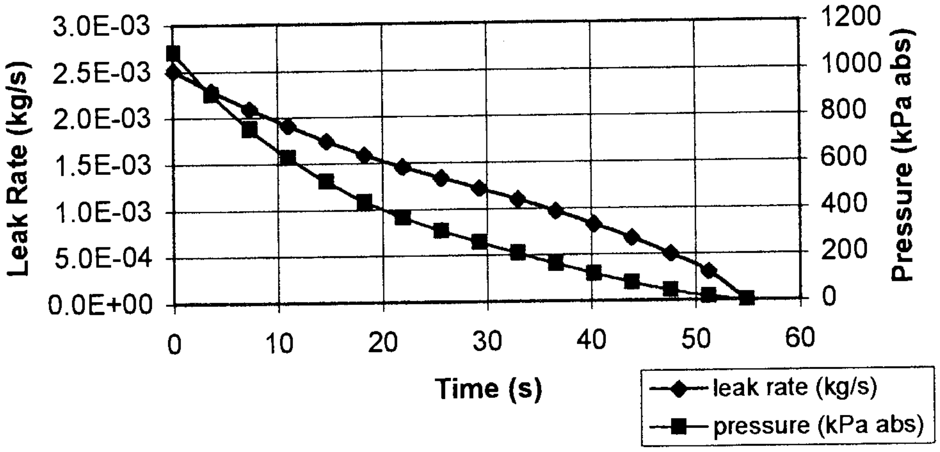
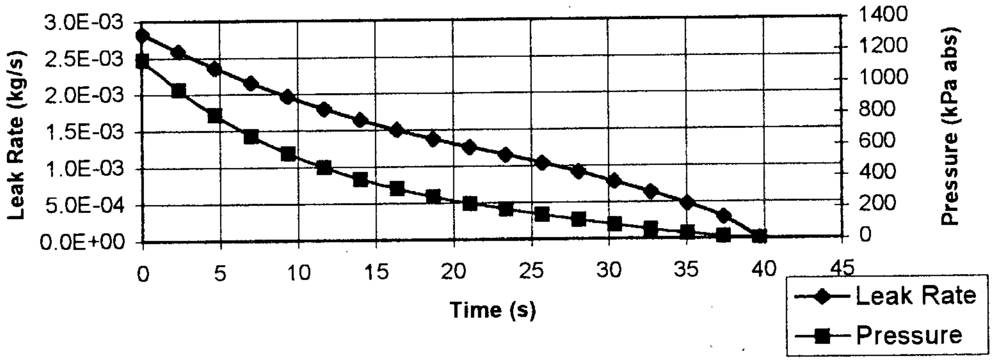


FIGURE A6.16

DEPRESSURING CURVE FOR CASE 1, AC ON, TWO PHASE 1mm LEAK, MEDIUM/SMALL CAR VOLUME



A6.3.4 Liquid Leaks

No depressuring curves were drawn for liquid leaks, however, the release duration was calculated for each of the liquid leak scenarios.

A6.3.4.1 Large Car Volume

A refrigerant inventory of 300g was assumed in this calculation.

TABLE A6.14
LIQUID RELEASE DURATION

Case	Leak into Engine Bay		
	Leak Size (mm)	**Leak Rate (kg/s)**	**Leak Duration (s)**
AC On			
Base	0.1	2.05E-04	1463
	1	2.05E-02	15
	8	1.31	0.23
Case 1	0.1	2.44E-04	1229
	1	2.44E-02	12
	8	1.56	0.19
AC Off			
Base	0.1	1.39E-04	2158
	1	1.39E-02	22
Case 1	0.1	1.81E-04	1657
	1	1.81E-02	17

A6.3.4.2 Small/ Medium Car Volume

A refrigerant inventory of 220g was assumed in this calculation.

TABLE A6.13
LIQUID RELEASE DURATION

Case	Leak into Engine Bay		
	Leak Size (mm)	**Leak Rate (kg/s)**	**Leak Duration (s)**
AC On			
Base	0.1	2.05E-04	1073
	1	2.05E-02	11
	8	1.31	0.17
Case 1	0.1	2.44E-04	902
	1	2.44E-02	9
	8	1.56	0.14
AC Off			
Base	0.1	1.39E-04	1583
	1	1.39E-02	16
Case 1	0.1	1.81E-04	1215
	1	1.81E-02	12

A6.3.5 Release in Workshop

The duration of the workshop releases was set at approximately 90 seconds. The depressuring curves are shown here for each release scenario.

FIGURE A6.17

WORKSHOP DEPRESSURING CURVE, BASE CASE, LARGE CAR

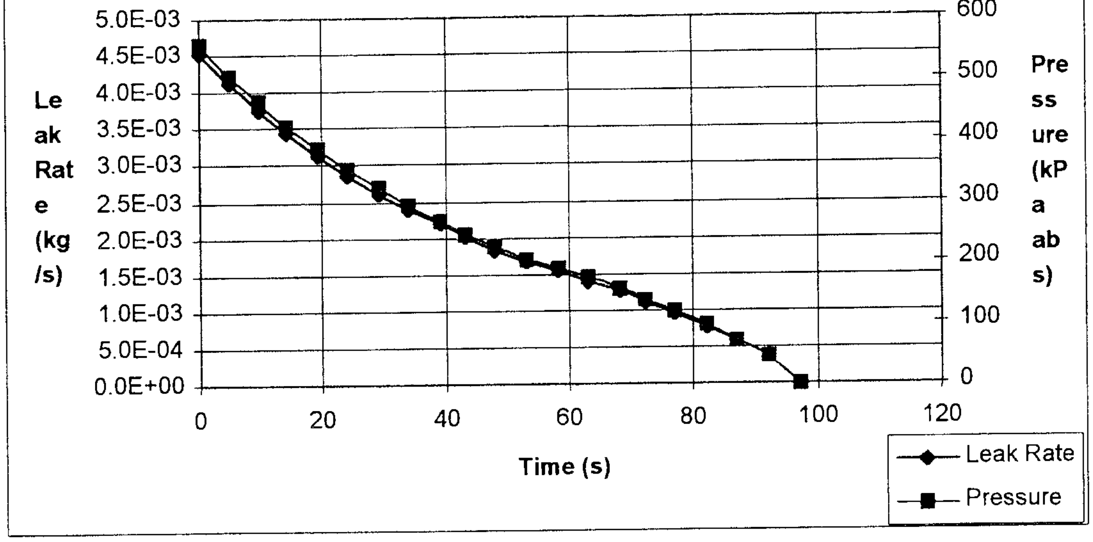


FIGURE A6.18

WORKSHOP DEPRESSURING CURVE, BASE CASE, MEDIUM/ SMALL CAR

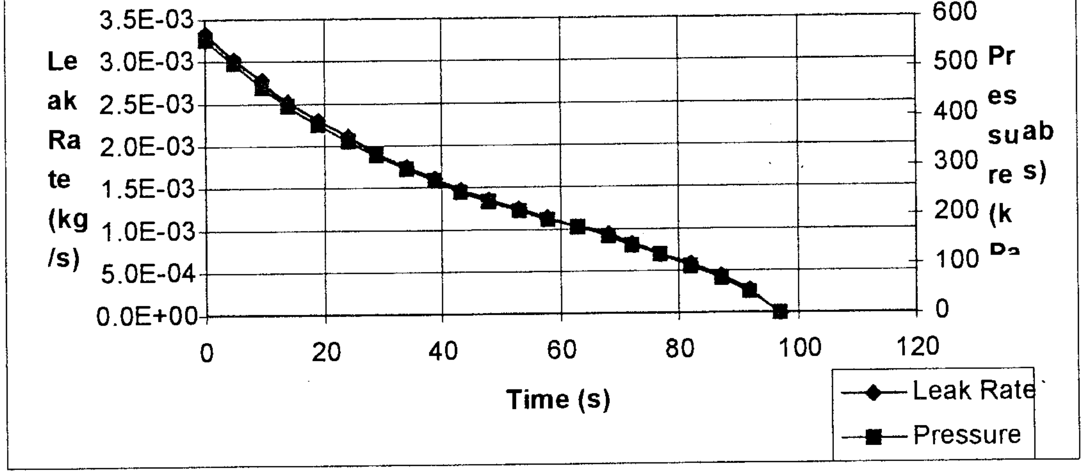


FIGURE A6.19
WORKSHOP DEPRESSURING CURVE, CASE 1, LARGE CAR

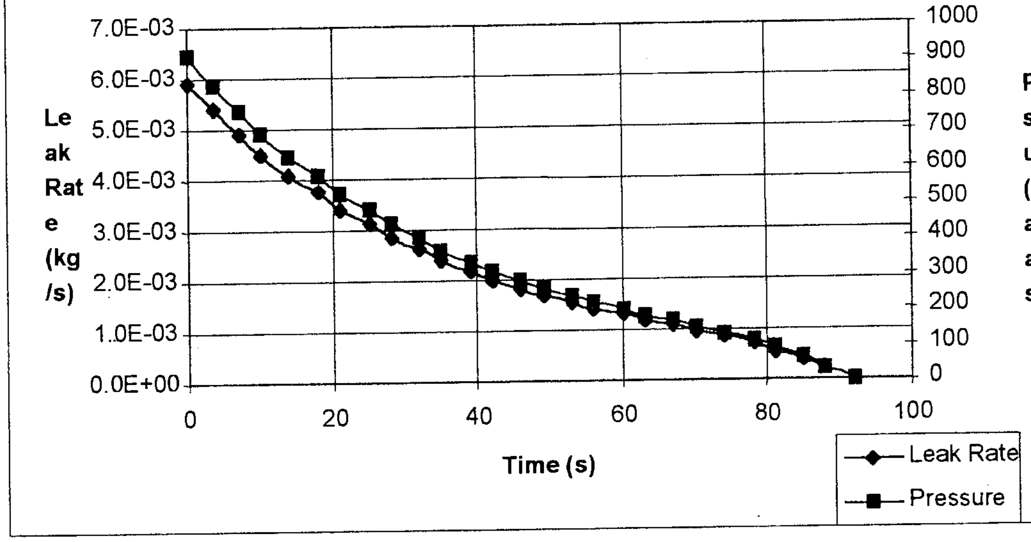
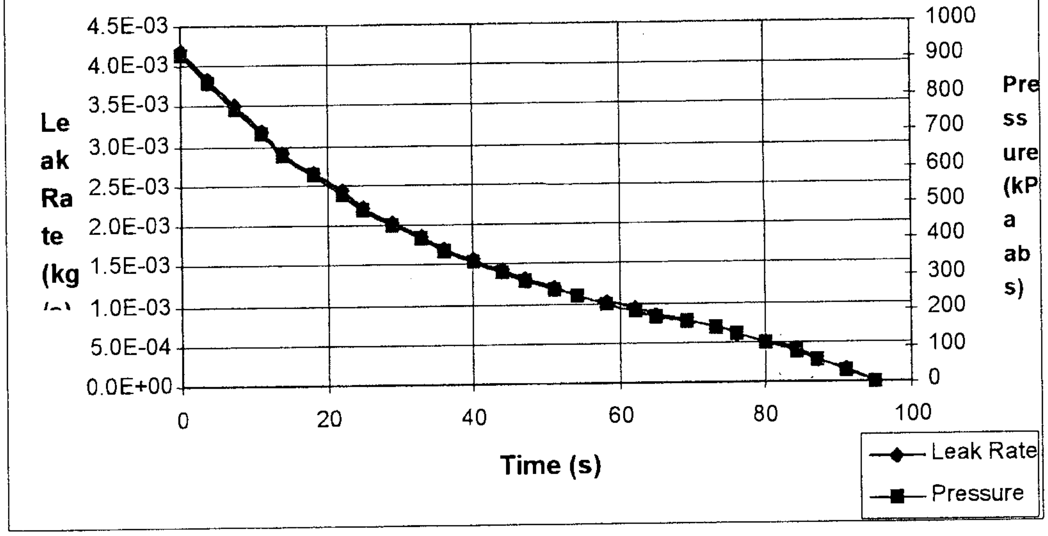


FIGURE A6.20
WORKSHOP DEPRESSURING CURVE, CASE 1, MEDIUM/ SMALL



APPENDIX 7

MODELLING OF ER12 REFRIGERANT RELEASE IN PASSENGER CABIN

TABLE OF CONTENTS

A7.1. INTRODUCTION

A7.1.1 Purpose

The purpose of this Appendix is to outline the methodology, calculations and results of modelling of ER12 refrigerant release in the passenger cabin. The modelling focused on estimating the concentration profile of the hydrocarbon refrigerant versus time.

A7.1.2 Objectives

The objectives of this Appendix were to:

- develop a methodology for determining concentration profiles under moving and stationary conditions;
- determine the characteristics of a release of hydrocarbon refrigerant from the air-conditioning system in terms of mixing;
- determine the gas concentration in passenger cabin for release scenarios (given in **Appendix 2** and **Appendix 3**) for a passenger vehicle moving or stationary and with the AC on or off;
- determine the minimum ventilation flowrate required to maintain the refrigerant concentration below the lower flammability limit (LFL);
- compare resulting concentration profiles with published documents.

A7.1.3 Scope

The scope of this appendix covered the situations outlined in **Table A7.1**.

TABLE A7.1
MODELLED SCENARIOS FOR PASSENGER CABIN

HAZID No. (App.3)	Condition	Car Size	Air Flow Pattern	Status of Air-conditioning System	
				On (Operational)	**Off** (Static)
N-1	Leak under driving conditions	- Large - Medium - Small	Fresh Air	X	X
			Recirculation	X	X
N-4	Leak when car is parked	- Large - Medium - Small	not applicable	-	X
N-8	Leak from overcharged system	- Large - Medium - Small	Recirculation	-	X

Note:

1. "X" denotes situation is applicable and simulation modelling conducted.

A7.2. METHODOLOGY

A7.2.1 Release Characteristics

In order to determine the characteristics of a hydrocarbon refrigerant release under pressure, it was necessary to conduct field trials and dispersion modelling. The results of this analysis formed a direct input into the development of the concentration profile models.

Since the refrigerant is heavier than air, one would expect that a release would slump to the floor. However, a vapour release under pressure results in a turbulent momentum jet with significant air entrainment, and mixing. Therefore, for the small release rates estimated in **Appendix 6** it is possible that the mixing would be more uniform within the passenger cabin. The mixing profile is best determined by actual field experiments using a tracer gas that is similar in density to the HC refrigerant.

The purpose of the tracer studies was to determine whether upon release the hydrocarbon refrigerant would be either uniformly distributed (concept of "well mixing") or slump to the floor in the vehicle's passenger cabin.

A series of experiments involving ER12 (**Appendix 9**) and tracer gas (**Appendix 10**) were undertaken to investigate mixing. Details are provided in these Appendices and are not repeated here.

The computer package, TECJET developed by DNV Technica Ltd, was also used to investigate mixing. The program is specific for modelling the dispersion of free turbulent momentum jets and plumes. The model takes into account high-pressure releases and may be used for determination of shape and concentration of flammable plumes.

The model required the input parameters of pressure and hole size. Propane was chosen as the component for developing the jet profile at specified lower flammability limit (LFL) concentrations.

A7.2.2 Concentration Profiles

In order to assess the concentration profile of released hydrocarbon refrigerant in the passenger vehicle cabin, it was necessary to develop a model that linked with the dynamics of the system. The basis of such fundamental models is the mass balance:

$$\textit{Accumulation} = \textit{Incoming} + \textit{Generation} - \textit{Out} - \textit{Consumption} \qquad \text{(A7.1)}$$

In this process, the generation and consumption terms may be taken to be zero, as no refrigerant is created or consumed by chemical reaction. Using the results from the experimental analysis, the hydrocarbon refrigerant in the passenger cabin may be treated as homogenous and well mixed. As such the governing mass balance equation may be written as:

$$V\frac{dC}{dt} = \dot{m}_{in}(t) - vC_{out} \qquad \text{(A7.2)}$$

and $m_{(in)}(t) = ae^{-bt}$ (A7.3)

The constants 'a' and 'b' are obtained by curve fitting the depressuring curve.

Initial condition: At t = 0, C = 0. (A7.4)

where:

V = volume of passenger vehicle cabin (m^3)
dC/dt = rate of concentration change over time
$m(t)$ = mass flow rate in (kg/s), i.e. leak rate (time variant)
t = time (s)
ν = ventilation air rate (m^3/s)
C_{out} = resultant concentration (kg/m^3), in outgoing ventilation air

A7.2.2.1 Fresh Air Flow

The situation when fresh air is allowed to flow into the passenger cabin is depicted in **Figure A7.1**.

Solving the mass balance equation given above with the initial condition where the concentration in the cabin is zero, the following equation is obtained:

Governing Equation

$$C = \frac{a}{V(ACH - b)}\left[e^{-b.t} - e^{-(ACH)t}\right] \qquad \text{(A7.5)}$$

for $t <= T_R$

where

V = volume of passenger vehicle cabin (m^3)
C = concentration of hydrocarbon refrigerant in passenger cabin(kg/m^3)
t = time (s)
ACH = Air Exchange Rate/sec
T_R = Release duration (s)

For $t>T_R$, the following equation applies:

$$\frac{C}{C(T_R)} = \exp\left[-ACH(t-T_R)\right] \qquad \text{(A7.6)}$$

The ventilation rates required to keep the concentration of refrigerant in the car passenger compartment below the following levels were calculated:

- LFL;
- 50% LFL; and
- 20% LFL.

This was done by plotting concentration vs time in the passenger compartment and altering the ventilation rate until the peak concentration was below the required value.

The passenger cabin volume was divided by the required ventilation rate to give the required air exchange rate in units of time.

A7.2.2.2 Recirculating Flow

The situation when the fan is on recirculation or the vents are in a closed position is depicted in **Figure A7.2**. This covers the following events:

- vehicle is moving (and vents are in closed position); and
- vehicle is parked in an enclosure or in the open (vents are in closed position).

For the purposes of this study, this was considered the worst case scenario and a corresponding low ACH value was used in the assessment.

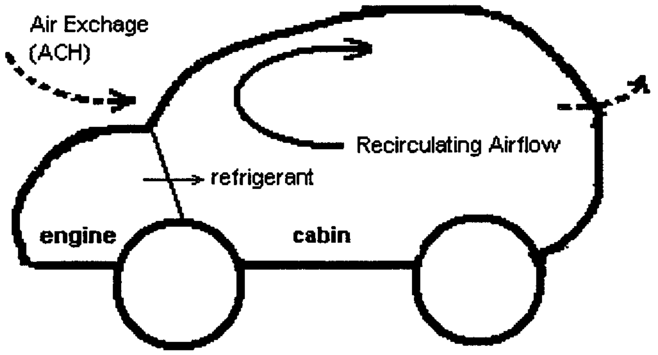


FIGURE A7.1
SCHEMATIC OF VEHICLE – FRESH AIR

Air Exchange Rate (ACH)

Associated with any fitted enclosure such as a vehicle body, there will be a characteristic exchange rate between the enclosure and surroundings. This exchange rate is unique for every enclosure and is primarily influenced by its construction type.

The ventilation rate or air exchange rate per hour (ACH) is a measure of the leak paths in the vehicle body. A vehicle will exhibit a low ACH if all vents are closed. Conversely, a vehicle with windows open and fan drawing fresh air will exhibit a correspondingly higher ACH.

There has been some research conducted by universities and government bodies such as the UK Health and Safety Executive (HSE) into quantifying and developing correlations of ACH (Ref.1). This is a comprehensive study and has been conducted under controlled conditions to obtain reliable results.

For a vehicle travelling with its air vents in the closed position, the ACH values were found to increase with increasing speed. For a vehicle travelling at an average speed of 54 km/hr (15 m/s), the lower bound ACH value was measured to be 15 whilst at a vehicle speed of 108 km/hr (30 m/s), the lower bound ACH value was found to be 35. For the purposes of the Safety Report, an ACH value of 10 was chosen to represent low vehicle average speed of 36 km/hr (10 m/s).

In a literature review conducted by Granherne, current studies have focused on determining the ACH values for vehicles (with vents in the closed position) parked in an open area. In the U.K. Health Safety Executive (HSE) tests, it was concluded that the ACH rate was primarily influenced by wind effects as no significant temperature difference was noted during the course of the experiments. For a late model vehicle, the HSE found that ACH varies with wind speed (V_s) by $V_s^{1.15}$. This was also confirmed by a study conducted at Adelaide University (Ref.2).

Granherne undertook a series of field trials to determine the air exchange rates for stationary vehicles parked in an enclosure (i.e. garage). The trial and results are detailed in **Appendix 10**. The study found that in the absence of wind, the dominant mechanism influencing the ACH rate was attributed to temperature, i.e. natural convection.

Based upon the field trials conducted in this present study and past work by other institutions (Refs.2,3), the ACH values suggested for use in this Safety Report are presented in **Table A7.2**.

TABLE A7.2
ACH VALUES TO USE IN SAFETY STUDY

Situation	Car Type	Minimum ACH Value (h^{-1})	Comment	Ref.
Vehicle parked in enclosure (Winter day and evening	Late Model	0.3	Experimental	App.10
	Early Model	0.3	Experimental	App.10
Vehicle parked in open area (winter day and evening)	All models	1.0	Experimental / HSE	App.10/ Ref.15
	Late Model	0.7	Experimental / HSE	App.10/ Ref.15
	Early Model	1.1	Experimental / HSE	App.10/ Ref.15
Vehicle Moving	All Models	10	HSE (car moving at 36km/h)	Ref.15

Equation (A7.4) is equally applicable to the recirculated flow condition, with the proviso that instead of the ventilation flow rate, the air-exchange rate under 'closed vent' conditions in **Table A7.2** would apply.

A7.3. RELEASE CHARACTERISTICS

A7.3.1 Experimental Work

The concept of well mixing was investigated in the experiments outlined in **Appendix 9** and **Appendix 10**. The studies found that complete mixing of the introduced refrigerant gas within the passenger vehicle cabin was found to occur within 2-20 minutes of release. The same result also occurred when tracer gas (carbon dioxide) was used.

The studies demonstrated that although the molecular weights of ER12 (51 kg/kmol) or carbon dioxide (44 kg/kmol) was greater than air (29 kg/kmol), no slumping of the gas would occur. Studies (**Appendix 9**) investigating the physical state of refrigerant release found that for the hole sizes considered in the study, leaks in the passenger cabin would be vapour phase releases.

A7.3.2 TECJET Simulation

The jet plume dispersion package TECJET was used to model the hydrocarbon refrigerant releases into the passenger compartment of the vehicle in order to determine the release characteristics. Case 1 results were used as input data for the model, that is, 40°C, relative humidity 70%. A surface roughness of 0.1m was used and a flow through speed of 0.1m/s. The input data for each release is shown in **Table A7.3**.

TABLE A7.3
TECJET INPUT DATA

Leak Type and Size	AC on/ off	Pressure (kPa abs)	Temperature (K)	Leak Rate (kg/s)
2 phase – 1mm	on	432	278	2.56E-03
vapour – 0.1mm	on	432	313	7.56E-06
vapour - 1mm	off	937	313	1.63E-03
vapour - 0.1mm	off	937	313	1.64E-05

The following table presents the TECJET results, from which it can be seen that the release does not 'slump' and due to its release characteristics will disperse into the entire volume of the passenger cabin.

TABLE A7.4
TECJET RESULTS

Leak Type and Size	Release Velocity (m/s)	Dimensions of Gas Release	
		Length (m)	Width (m)
AC On			
2 phase – 1mm	21	0.1[1] 0.7[2]	0.01[3] 0.04[4]
vapour – 0.1mm	242	0 0	0 0
AC Off			
vapour – 1mm	229	0.1 0.3	0 0.02
vapour – 0.1mm	229	0 0.1	0 0

Notes:

1. length at 10 vol% concentration (UFL)
2. length at 2 vol% concentration (LFL)
3. width at 10 vol% concentration (UFL)
4. width at 2 vol% concentration (LFL)

Since it is possible that the jet momentum effect could be lost due to impingement on obstacles, a plume dispersion run was carried out using the Aeroplume model. The distances to LFL and 50% LFL concentration are shown in **Table A7.5.**

TABLE A7.4
AEROPLUME RESULTS

Leak Type and Size	Dimensions of Gas Release	
	Length (m)	Width (m)
AC On		
2 phase – 1mm	1[1] 0.6[2]	0.1[3] 0.01[4]
Vapour – 0.1mm[5]	-	-
AC Off		
Vapour – 1mm	0.7 0.4	0.2 0.01
Vapour – 0.1mm[6]	-	-

Notes:

1. length at 50% LFL concentration
2. length at LFL concentration
3. width at 50% LFL concentration
4. width at LFL concentration
5. No results due to small release rate
6. No results due to small release rate

A7.4. CONCENTRATION RESULTS – FRESH AIR (VEHICLE MOVING)

A7.4.1 Introduction

This section gives the results of modelling done for the situation where there is:

- fresh air flow into the passenger compartment; and
- a moving vehicle (large, medium and small type).

The results are presented as the minimum required ventilation rate to keep the concentration of refrigerant in the car passenger compartment below limits at which ignition may occur.

The lower flammability limit (LFL) of the hydrocarbon is normally taken as the limit below which it is not possible to ignite the vapour-air mixture. However, in a dispersing vapour-air mixture, the concentrations fluctuate due to turbulent mixing. To allow for this, the value of one-half LFL is also used as the limiting concentration.

AS/NZS 1677.1 – 1998 (Ref.4) suggests that the practical limit of Class A3 refrigerants is about one-fifth of the lower explosive limit (LEL).

It was therefore decided to calculate the minimum ventilation rates required for LFL, 50% LFL and 20% LFL.

The lower flammability limit of ER12 is 2% in air. This is converted to a concentration of 0.04kg/m^3 in air for LFL, 0.02 kg/m^3 for 50% LFL, and 0.008kg/m^3 for 20%LFL.

Results are not shown for 0.01mm vapour leaks because the ventilation rates required for 0.1mm leaks are very low, thus ensuring that a refrigerant leak hole size of 0.01mm would not cause refrigerant concentrations to reach 20% LFL.

A7.4.2 Air-conditioning (AC) On

The formula given in **Section A7.2.2.1** for the concentration of refrigerant in the passenger vehicle versus time for fresh air flow (Eq.A7.5) was used to calculate the minimum required ventilation rates for a large car with AC on.

The leak rates calculated in **Appendix 6** were used in the calculations. The car volumes were taken from **Appendix 5**. The results of these calculations are shown in **Table A7.6**.

To further interpret the results, the equivalent minimum air exchange rate was estimated by dividing the calculated air flow rate (L/s) by the car volume (m^3), adjusted to appropriate units for dimensional consistency.

It was found that for all cases, the ACH required to reach LFL concentration was <0.001 ACH, whereas the ACH value is about 10 per hour for a slow moving vehicle.

The profiles for Case 1 for the large (0.1mm) and catastrophic (1mm) release cases are shown in **Figure A7.3** and **Figure A7.4** respectively.

TABLE A7.6
VENTILATION RATES FOR FLAMMABLE GAS CONCENTRATIONS - CAR MOVING WITH AC ON AND FRESH AIR CIRCULATION

Case	Leak Phase	Leak Size (mm)	Required Ventilation (L/s) and ACH value (hr^{-1})			
			Below 50% LFL		Below 20% LFL	
			Rate	ACH	Rate	ACH
Large Car						
Base	Vapour	0.1	<0.001	<0.001	0.35	0.22
		1	<0.001	<0.001	40	25
Case 1	Vapour	0.1	<0.001	<0.001	0.40	0.25
		1	<0.001	<0.001	45	28
Medium Car						
Base	Vapour	0.1	<0.001	<0.001	0.30	0.23
		1	<0.001	<0.001	35	27
Case 1	Vapour	0.1	<0.001	<0.001	<0.001	<0.001
		1	<0.001	<0.001	40	31
Small Car						
Base	Vapour	0.1	<0.001	<0.001	0.40	0.41
		1	<0.001	<0.001	45	46
Case 1	Vapour	0.1	<0.001	<0.001	0.50	0.51
		1	<0.001	<0.001	50	51

Note:

1. To estimate the ACH value for a large car, the following formula was used:- [flow rate L/s] divided by [5.7 m^3]. Resulting value multiplied by [3600 s/hr x 1m^3/1000 L].
2. For a medium sized car:- [flow rate L/s] divided by [4.7 m^3]. Resulting value multiplied by [3600 s/hr x 1m^3/1000 L].
3. For a small sized car:- [flow rate l/s] divided by [3.5 m^3]. Resulting value multiplied by [3600 s/hr x 1m^3/1000 L].

A7.4.2.1 Discussion of Results

A review of the results given in **Table A7.6** demonstrates that for a large release, the minimum ventilation rate required to keep the concentration of refrigerant below LFL when the AC is on is < 0.001 L/s. Similarly, to keep the concentration of refrigerant below 20% LFL, ventilation rates between 0.3 L/s and 0.5 L/s are required, for a 0.1mm leak.

For a moving vehicle with AC on, the ventilation rate will be greater than these values (see **Section A7.7** for actual measured values). As given earlier, the UK HSE has measured ACH values when a late model vehicle was driven at constant speed with air vents in the closed position. The lowest recorded ACH value for a vehicle travelling at 54 km/hr was 15. The study used an ACH value of 10 for a vehicle travelling at 36 km/hr.

It was found that for a catastrophic leak of 1mm in size, the number of air changes required to maintain the concentration at or below 20% LFL would exceed available ventilation rate. However LFL and 50% LFL concentrations would not result.

The following conclusions may be reached from the above analysis:

- for the case when the AC on and the vehicle is in motion, for all leak sizes, the concentration in the passenger cabin would not reach LFL level;
- for large leak sizes of up to 0.1mm, the concentration would be less than 20% LFL, for the available ACH of 10-15;
- for a catastrophic leak size of 1mm (i.e. entire refrigerant inventory leaks in less than 10 minutes), the concentration in the passenger cabin would exceed 20% LFL, but would be less than 50% LFL;
- when the vehicle is in motion and AC is on, the maximum concentration of refrigerant in the passenger cabin for all leak sizes would not reach a level that could ignite.

This case was not analysed further.

A7.4.3 Air-conditioning (AC) Off

The same calculations were re-performed for the scenario when the vehicle is moving and a refrigerant leak occurs inside the cabin with the air-conditioning system off (AC off).

The profile for Case 1 for the large (0.1mm) and catastrophic (1mm) release cases were generated and the results of these calculations are shown in **Table A7.7**.

TABLE A7.7
MINIMUM RATES FOR CAR MOVING WITH AC OFF AND FRESH AIR

Case	Leak Phase	Leak Size (mm)	Required Ventilation (L/s) and ACH value (hr^{-1})			
			Below LFL		Below 20% LFL	
			Rate	ACH	Rate	ACH
Large Car						
Base	Vapour	0.1	<0.001	<0.001	0.55	0.35
		1	<0.001	<0.001	55	35
Case 1	Vapour	0.1	<0.001	<0.001	0.85	0.54
		1	<0.001	<0.001	80	51
Medium Car						
Base	Vapour	0.1	<0.001	<0.001	0.45	0.34
		1	<0.001	<0.001	45	34
Case 1	Vapour	0.1	<0.001	<0.001	0.65	0.50
		1	<0.001	<0.001	65	50
Small Car						
Base	Vapour	0.1	<0.001	<0.001	0.60	0.62
		1	<0.001	<0.001	60	62
Case 1	Vapour	0.1	<0.001	<0.001	0.95	0.98
		1	<0.001	<0.001	95	98

Note:

1. To estimate the ACH value for a large car, the following formula was used:- [flow rate L/s] divided by [5.7 m^3]. Resulting value multiplied by [3600 s/hr x 1m^3/1000 L].
2. For a medium sized car:- [flow rate L/s] divided by [4.7 m^3]. Resulting value multiplied by [3600 s/hr x 1m^3/1000 L].
3. For a small sized car:- [flow rate l/s] divided by [3.5 m^3]. Resulting value multiplied by [3600 s/hr x 1m^3/1000 L].

A7.4.3.1 Discussion of Results

A review of the results given in **Table A7.7** indicates that for a large release, the minimum ventilation rate required to keep the concentration of refrigerant below LFL when the AC is on is < 0.001 L/s. Similarly, to keep the concentration of refrigerant below 20% LFL, ventilation rates of 1 ACH or less are required for leaks up to 0.1mm.

As discussed previously, for large releases, the ACH of a vehicle moving at speed will be sufficient to ensure that the concentration in the vehicle is below LFL and 20% LFL. This is also confirmed when the ventilation rates are compared to measured value given in **Section A7.7**.

For a catastrophic release, the minimum ventilation rate required to keep the concentration of refrigerant below LFL when the AC is on is < 0.001 L/s. To keep the concentration of refrigerant below 20% LFL, ventilation rates between 45 L/s and 98 L/s are required. It can be seen that whilst LFL will not be reached in the vehicle, the ventilation in a vehicle may not be sufficient to provide a cabin concentration less than 20% LFL.

The ACH required for 50% LFL was found to be 0.001/hour for a catastrophic release. This ACH is available when the vehicle is in motion. Therefore 50% LFL would not be reached.

It was concluded that, a flammable concentration level that could ignite, would not result for all leak sizes.

A7.5. CONCENTRATION RESULTS – RECIRCULATING AIR (CAR MOVING)

This section gives the results of modelling done for the situation where there is:

- recirculating air in the passenger compartment; and
- a moving vehicle (large, medium or small type).

As a conservative assumption, an air exchange rate (ACH) of ten per hour was used for calculations. This had the effect of assuming that the car was travelling slowly (average speed of 36 km/hr) with vents in the closed position. In reality, the ACH value would be in excess of this value as measured by the UK HSE (Ref.1).

A7.5.1 Results

The calculations were performed only for Case 1 conditions as they result in higher release rates of refrigerant and hence potentially higher concentrations in the passenger compartment.

The concentration profiles exhibited a sharp rise to a maximum value and then a gradual decline. The growth phase of the release is marked by the initial release rate. As the refrigerant inventory depletes and depressures, the release rate drops and hence the concentration in the cabin declines slowly. The rate of decline is controlled by the ACH.

The analysis found that the concentration in the cabin will not reach LFL levels. The results of these calculations using the time-variant release rates are shown in **Table A7.8**. These results summarise the situation when the car air-conditioning system is either on (AC on) or static (AC off).

TABLE A7.8
CABIN CONCENTRATIONS FOR CAR MOVING WITH VENTS CLOSED

Case	**Air-conditioning Status**	**Car Type**	**Leak Size (mm)**	**Peak Concentration**	
				Value (kg/m³)	**% LFL**
Case 1	On	Large	0.1	1.82E-5	<0.1
			1	1.43E-2	36
		Medium	0.1	1.92E-5	<0.1
			1	1.35E-2	34
		Small	0.1	2.58E-5	<0.1
			1	2.12E-2	53
	Off	Large	0.1	1.03E-3	<1
			1	2.52E-2	63
		Medium	0.1	4.10E-5	<0.1
			1	2.20E-2	55
		Small	0.1	6.28E-5	<0.1
			1	3.44E-2	86

A7.5.2 Discussion of Results

This analysis was considered to be the worst case for a refrigerant leak inside the cabin whilst the vehicle was in motion. For large releases (0.1mm), the concentrations within the cabin were less than 1% of LFL for all car types.

A catastrophic release (1mm) inside the cabin did not result in peak concentrations above LFL. A 50% LFL concentration could occur for catastrophic leaks, when the AC is off.

A7.5.3 Overcharging of Air-conditioning Circuit

The hazard identification study had identified overcharging as a potential incident to consider in the Safety Case. As a sensitivity case, analyses were conducted for the situation when a charge equivalent to a large car was introduced into a medium and small car. The assessment was based upon Case 1 conditions and catastrophic releases (1mm). Based upon test results (**Appendix 12**), a charge corresponding to 400g of refrigerant (133% of the nominal charge) was introduced into a large car. The results of this analysis are shown in **Table A7.9**.

TABLE A7.9
CABIN CONCENTRATIONS DUE TO ACCIDENTAL OVERCHARGING

Case	Car Type	Scenario	Leak Size (mm)	Peak Concentration	
				Value (kg/m^3)	% LFL
Air-conditioning System On (AC On)					
1	Large	400 gram charge placed in system (33% overcharge)	1	0.018	45
2	Medium	Large car charge placed in system (36% overcharge)	1 0.1	0.0174 2.2E-05	44 0.06
3	Small	Large car charge placed in system (36% overcharge)	1 0.1	0.023 2.9E-05	57 0.07
Air-conditioning System Off (AC Off)					
4	Large	400 gram charge placed in system (33% overcharge)	1	0.019	48
5	Medium	Large car charge placed in system (36% overcharge)	1 0.1	0.031 1.3E-03	77 3.2
6	Small	Large car charge placed in system (36% overcharge)	1 0.1	0.041 1.7E-03	100 4.2

From a review of the results, the following observations can be made:

- an accidental overcharge of the air-conditioning system resulted in a slight rise in the peak concentration;
- when the AC is on, for catastrophic leaks, 50% LFL concentration was not reached in large/ medium cars, but could occur in small cars;
- when the AC is off, LFL concentration could be reached in small cars for catastrophic leaks, when the car is in motion;
- for large leaks, in small and medium cars, the 50%LFL concentration was not reached.

A7.6. CONCENTRATION RESULTS – STATIONARY VEHICLE

A7.6.1 Introduction

This section gives the results of modelling done for the situation where there is:

- a stationary vehicle; and
- the vehicle parked either in an enclosure (i.e. garage) or in the open.

This scenario had been identified in the hazard identification study as a potential incident to consider in the Safety Report. In particular, it had been surmised that if a leak occurred whilst the vehicle was parked overnight in a garage, the concentration of refrigerant in the cabin may reach a level above LFL.

The governing equation given in **Section 7.2** was used in the analysis. The air exchange rates (ACH) used for these calculations were taken from the tracer gas experiments conducted at the University of Sydney (**Appendix 10**). These are shown in **Table A7.10** and were observed under little or no wind conditions.

TABLE A7.10
ACH VALUES

Situation	Car Type	Minimum ACH Value (hr^{-1})	Comment
Vehicle parked in enclosure (winter day and evening)	Late Model	0.3	Experimental
	Early Model	0.3	Experimental
Vehicle parked in open area (winter day and evening) No wind	All models	1.0	Experimental/ HSE
	Late Model	0.7	Experimental/ HSE
	Early Model	1.1	Experimental/ HSE

The ACH values used for calculation were:

- vehicles parked in enclosure: 0.3/hr; and
- vehicles parked in open areas: 0.7/hr.

The ACH value for a vehicle located inside an enclosure is associated with cold winter conditions and is thus considered conservative. In summer conditions or in tropical/ semi-tropical regions, the higher ambient temperature would serve to increase the ACH value. Thus the analytical results are considered conservative.

An ACH value of 0.7/hr was chosen for vehicles parked in open areas as a conservative value for the assessment. This neglects any wind effects around the vehicle that would increase the ACH. This value is typically associated with a vehicle parked on a cold evening with no breeze or wind.

As given in supporting appendices, the analyses were conducted for typical (0.01mm) and large (0.1mm) release cases. These were considered to be the worst case events given that there are no moving parts and that all metal connections are seamless piping in a vehicle air-conditioning system. In other words, a sudden catastrophic failure of the evaporator and pipe work was not considered credible for a parked car with the engine turned off.

A7.6.2 Results

The concentration profiles for Case 1 for a large (0.1mm) and typical release (0.01mm) when the air-conditioning system is static (AC off) were calculated. This is for the situation when a vehicle is parked in an enclosure.

The results of these calculations are shown in **Table A7.11** and **Table A7.12** in terms of peak concentration and the time that it occurred. Results are also shown of the concentration in the cabin after a period of 6, 8 and 10 hours. This was done to demonstrate the likely cabin concentration experienced by a person returning to their car following overnight rest.

TABLE A7.11
CABIN CONCENTRATIONS IN STATIONARY VEHICLE PARKED INSIDE ENCLOSURE

Vehicle Type	**Leak Size (mm)**	**Concentration Level (kg/m^3) at Interval (hrs)**		
		Level	**Value**	**% LFL**
Vehicle Located inside Enclosure				
Large car	Large 0.1	Peak @ 3.6 hr	1.46E-02	37
		@ 6 hours	7.2E-03	18
		@ 8 hours	3.95E-03	9.9
		@ 10 hours	2.17E-03	5.4
	Typical 0.01	Peak @ 20 hr	2.76E-04	0.7
		@ 6 hours	2.31E-04	0.6
		@ 8 hours	2.51E-04	0.6
		@ 10 hours	2.62E-04	0.7
Medium Car	Large 0.1	Peak @ 3.2 hr	1.78E-02	45
		@ 6 hours	7.74E-03	19
		@ 8 hours	4.25E-03	11
		@ 10 hours	2.33E-03	5.8
	Typical 0.01	Peak @ 22 hr	3.3E-04	0.8
		@ 6 hours	2.8E-04	0.7
		@ 8 hours	3.05E-04	0.5
		@ 10 hours	3.18E-04	0.8
Small	Large 0.1	Peak @ 3.2 hr	2.39E-02	60
		@ 6 hours	1.03E-02	26
		@ 8 hours	5.65E-03	14
		@ 10 hours	3.10E-03	7.8
	Typical 0.01	Peak @ 25 hr	4.5E-04	1.1
		@ 6 hours	3.75E-04	0.9
		@ 8 hours	4.09E-04	1.0
		@ 10 hours	4.27E-04	1.1

TABLE A7.12
CABIN CONCENTRATIONS IN STATIONARY VEHICLE PARKED IN THE OPEN

Vehicle Type	Leak Size (mm)	Concentration Level (kg/m^3) at Interval (hrs)		
		Level	Value	% LFL
Vehicle Located in Open Area				
Large car	Large 0.1	Peak @ 2.2 hr	8.95E-03	22
		@ 6 hours	6.44E-04	1.6
		@ 8 hours	1.59E-04	0.4
		@ 10 hours	3.92E-05	0.1
	Typical 0.01	Peak @ 7.5 hr	1.15E-04	0.3
		@ 6 hours	1.14E-04	0.3
		@ 8 hours	1.15E-04	0.3
		@ 10 hours	1.15E-04	0.3
Medium Car	Large 0.1	Peak @ 2.0 hr	1.13E-02	28
		@ 6 hours	6.95E-04	1.7
		@ 8 hours	1.71E-04	0.4
		@ 10 hours	4.22E-04	0.4
	Typical 0.01	Peak @ 9 hr	1.4E-04	0.4
		@ 6 hours	1.38E-04	0.3
		@ 8 hours	1.39E-04	0.3
		@ 10 hours	1.40E-04	0.4
Small	Large 0.1	Peak @ 2.1 hr	1.51E-02	38
		@ 6 hours	1.01E-03	2.5
		@ 8 hours	2.50E-04	0.6
		@ 10 hours	6.17E-05	0.2
	Typical 0.01	Peak @ 9.5 hr	1.88E-04	0.5
		@ 6 hours	1.85E-04	0.5
		@ 8 hours	1.87E-04	0.5
		@ 10 hours	1.88E-04	0.5

A7.6.3 Discussion

The following observations are made:

- As can be expected, the peak concentration was highest for the larger leak size and if the vehicle is parked inside an enclosure.
- For a “large” release, the concentration within the vehicle was found to reach a maximum and gradually decline as the inventory was depleted.

- For a “typical” release, the concentration was found to reach a steady maximum value, since the leak rate is very small and can be treated as a constant continuous release. This confirms reports by accredited automotive mechanics that the refrigerant loss from very small leak sizes would not be noticed for a significant period in the order of 3-6 months.

- For the stationary vehicle parked in the open, the maximum concentration in passenger cabin even for large leaks did not reach 50% LFL concentration at any time.

- For the stationery vehicle parked in an enclosure, the maximum concentration reached 60% LFL for a large leak in a small car. For all other cases the maximum concentration was less than 50% LFL.

- For typical leaks of 0.01mm size, the maximum concentration was less than 1% LFL, for all car types.

The analyses concluded that for the release sizes considered, the resulting concentration in the passenger cabin would not reach LFL. However, this event was carried forward for risk analysis.

LFL concentration could be reached in the cabin only in the unlikely event that a rupture of the air-conditioning system occurred on the passenger side of the firewall. This event is considered remote given that the vehicle is stationary (i.e. not moving) and the system is not operating. Further, the system components located within the cabin are static with no rotating parts.

A7.7. COMPARISON WITH PUBLISHED DATA

Previous experiments carried out in this field are reported in the papers of:

1. Maclaine-Cross (Ref.5); and
2. Fletcher and Saunders (Ref.1).

The relevant results of these papers are presented below so that they can be compared with those obtained in the study.

A7.7.1 The Work of Maclaine-Cross

In his paper, "Refrigerant Concentrations in Car Passenger Compartments" (Ref.5), Maclaine-Cross gives the results of experiments carried out on ten different types of Australian cars giving their volumes and ventilation rates in different conditions. His results can be seen in **Table A7.13**.

TABLE A7.13
MACLAINE-CROSS VOLUME AND FRESH AIR FLOWS

Model	Year	Volume (m^3)	Fresh Air (L/s)			
			1	2	3	4
Kingswood	1970	5.81	1.05	2.52	2.52	-
Volvo	1978	6.48	4.00	20.8	22.0	1363
Commodore	1979	3.81	5.78	-	85.0	-
Pulsar	1984	4.16	0.61	20.2	77.4	-
Corolla	1985	5.68	3.00	20.0	149.7	262.2
Falcon	1987	4.44	38.03	164.0	134.5	151.2
Laser	1988	3.48	1.42	4.56	85.1	41.0
Berlina	1989	4.36	2.95	173.0	173.0	-
Magna	1989	6.12	6.00	37.0	100.7	987
Astron	1989	5.50	50.0	143.0	136.0	312

Notes:
1. Windows closed.
2. Windows closed, fan operating at full flow.
3. Windows closed, fan operating at full flow, fresh air vent open.
4. Windows closed except driver window, fan operating at full flow, fresh air vent open.

It can be seen that for the majority of cases described in **Section A7.4**, the ventilation rates shown in **Table A7.13** are higher than that could cause LFL concentrations.

A7.7.2 The Work of Fletcher and Saunders

Fletcher and Saunders (Ref.1) in their paper, "Air change rates in stationary and moving motor vehicles", published volume flow rates through vehicles that they had determined experimentally. The flow rates calculated are given in **Table A7.14**.

TABLE A7.14
RESULTS FROM FLETCHER AND SAUNDERS

Car Model	Volume Flow Rate (L/s)			
	Moving		Stationary	
	Vents Open	Vents Closed	Vents Open	Vents Closed
Renault 21	23	16	19	12
Nissan Micra	17	11	16	9
Renault Master	41	25	40	27
Ford Transit Van	44	40	41	37
Ford Transit Bus	39	35	38	33

It can be seen that for the majority of cases described in **Section A7.4**, the required ventilation rates were lower than those shown in **Table A7.14**.

A7.7.3 Private Communication

The data shown in **Table A7.15** was obtained through private communication with Boral Energy (September 1998).

TABLE A7.15
SELECTED HOLDEN AIRFLOW RATES

Car	Scenario	Airflow (L/s)
Commodore	AC on	150
Commodore	AC off, parked	50[1]
Vectra	AC on	130

Note: 1. This value was not certain and was thought to be high.

The AC on airflow rates given for the Commodore and Vectra are higher than the required ventilation rates given for the AC on case in **Table A7.6**.

A7.8. INCIDENTS CARRIED FORWARD FOR FURTHER ANALYSIS

The incidents carried forward for further analysis are shown in **Table A7.16**. For the purposes of the risk analysis it was necessary to assign a unique number to each incident associated classified under the generic hazard identification number. These events (twenty in total) were used for the remainder of the study.

Incidents were carried forward based on whether they could cause a concentration greater than 50% LFL in the passenger cabin.

TABLE A7.16
PASSENGER CABIN INCIDENTS CARRIED FORWARD FOR ANALYSIS

ID No.	No.	Vehicle Status	Car Type	Fresh/ Recirculating	AC Status	Hole Size (mm)	Concn > 50% LFL	Comments
N-1	1	Moving	All	Fresh	On	0.01, 0.1, 1	No	Table A7.5
N-7	2	Moving	All	Fresh	Off	0.01, 0.1, 1	No	Table A7.6
N-1	3	Moving	Large	Recirculating	On	0.01, 0.1, 1	No	Table A7.7
N-1	4	Moving	Medium	Recirculating	On	0.01, 0.1, 1	No	
N-1	5	Moving	Small	Recirculating	On	0.01, 0.1	No	
N-1	6	Moving	Small	Recirculating	On	1	Yes	
N-7	7	Moving	All	Recirculating	Off	0.01, 0.1	No	
N-7	8	Moving	All	Recirculating	Off	1	Yes	
N-4	9	Stationary (inside)	Large	Recirculating	Off	0.01, 0.1	No	Table A7.10
N-4	10	Stationary (inside)	Medium	Recirculating	Off	0.01, 0.1	No	
N-4	11	Stationary (inside)	Small	Recirculating	Off	0.01	No	
N-4	12	Stationary (inside)	Small	Recirculating	Off	0.1, 1	Yes	
N-4	13	Stationary (outside)	All	Recirculating	Off	0.01, 0.1	No	Table A7.11
N-8	14	Overcharged	Large	Recirculating	On/ Off	0.01, 0.1, 1	No	Table A7.8
N-8	15	Overcharged	Medium	Recirculating	On	0.01, 0.1, 1	No	
N-8	16	Overcharged	Medium	Recirculating	Off	0.01, 0.1	No	
N-8	17	Overcharged	Small	Recirculating	On/ Off	0.01, 0.1	No	
N-8	18	Overcharged	Medium	Recirculating	Off	1	Yes	
N-8	19	Overcharged	Small	Recirculating	On/ Off	1	Yes	
N-3	20	Collision	All	-	-	-	Yes	-

Note: 1. No loss of refrigerant incidents in the engine bay were found to affect the passenger compartment

2. **ID No.** refers to the numbering of incidents given in **Appendix 3**.

A7.9. FIRE MODELLING IN PASSENGER CABIN

The following methodology was used for modelling a flashfire in the passenger cabin (Ref.6).

1. Calculate the vapour content in the cabin for concentrations of 50% LFL and LFL, for a typical car volume of $4m^3$ (small to medium size car, where the potential exists for formation of 50% LFL concentrations).

2. Calculate the heat evolved from the heat of combustion (taken as 45,000 kJ/kg) and, using an energy balance, calculate the maximum possible temperature flame temperature in the cabin (adiabatic flame temperature). In reality, this temperature would never be reached. Stoichiometric concentrations generally produce flame temperatures of 1000°C, and lower temperatures are expected for leaner mixtures. If the adiabatic flame temperature exceeds, 1000°C, it is restricted to this temperature.

3. Using a flame emissivity of 0.9, calculate the incident heat flux using the Stefan-Boltzmann equation. The heat flux is in kW/m^2.

4. Calculate the duration of fire using the fireball duration calculation, $t = 0.852 M^{0.26}$, where M is the mass of vapour in kg, and t is in seconds.

5. Calculate the thermal load (TL) using the correlation Thermal load = $I^{4/3}.t$

6. Calculate the Probit values using the following equations (Ref.7):

$Y = -14.9 + 2.56 \ln (TL)$	for risk of fatality
$Y = -43.14 + 3.02 \ln (TL)$	for second-degree burns
$Y = -39.83 + 3.02 \ln (TL)$	for first-degree burns

7. Calculate the probability of fatality/ injury, using the probit values.

The results are shown in **Table A7.17**.

TABLE A7.17
FLASHFIRE CALCULATION RESULTS

Parameter	Case 1	Case 2
%LFL	50	100
LFL, kg/m^3	0.04	0.04
Car volume, m^3	4	4
Mass of gas, kg	0.08	0.16
Heat of combust. kJ/kg	45000	45000
Heat liberated, kJ	3600	7200
Mass of air, kg	4.8	4.8
Cp of air, kJ/kg-K (average)	1	1
Temp.difference (adiabatic)	750	1500
Ambient temp, K	303	303
Adiabatic flame temperature, K	1053	1803
Actual flame temperature, K	1053	1273
Emissivity	0.9	0.9
Stefan-Boltzmann Const, W/m^2-K^4	5.67E-11	5.67E-11
Incident hear flux, kW/m^2	62.7	134
Duration of fire, seconds	0.44	0.53
Thermal load, s.(kW/m^2)$^{4/3}$	110	363
Probit (fatality)	-7.65E-01	2.29E+00
Probit (2nd deg.burns)	-1.14E+00	2.46E+00
Probit (1st deg.burns)	2.17E+00	5.76E+00

From the probit values, it can be seen that the probability of fatality and the probability of second-degree burn injury are zero, indicating that such an impact would not occur. For 50% LFL concentration, even 1st degree burns would not occur, which is expected for the LFL concentration, at about 80% probability.

Hymes et al. (Ref.8) have stated that, for a probability of 1% chance of fatality, the thermal load should be 1060. The value calculated is 5-10 times lower than this level.

The main reason for such a low impact is the small amount of vapour in the passenger cabin and the very low flashfire duration on ignition.

A7.10. REFERENCES

1 Fletcher, B., Sanders, C.J., (1994), "Air Change Rates in Stationary and Moving Motor Vehicles", Journal of Hazardous Materials, 38, pp 243-256.

2 Crowe, A., (1999), "Measurement of Air Exchange Rate of Stationery Vehicles and Estimation of In-vehicle Exposure", thesis, University of Adelaide.

3 Granherne Pty Ltd (1999), "Use of Hydrocarbon Refrigerants in Automobile Air-Conditioners, Tracer Gas Studies – Experimental Report, Document No. 80065-BOR-TN-X-7000.

4 Standards Australia, "AS/NZS 1677.1 – Refrigerating Systems, Part 1: Refrigerant classification", 1998.

5 Maclaine-Cross, I.L., (1997): "Refrigerant Concentrations in Car Passenger Compartments", Proceedings of the International Conference on Ozone Protection Technologies", Baltimore, Maryland, pp.403-412, November.

6 Lees, F.P. (1996): "Loss Prevention in the Process Industries", 2nd Edition, Vol.2, Butterworth- Heinemann, Oxford. pp.16-186 to 16-190.

7 Lees, F.P. (1996): "Loss Prevention in the Process Industries", 2nd Edition, Vol.2, Butterworth- Heinemann, Oxford. page. 16-256.

8 Hymes, I, W. Boydell and B. Prescott, (1996): Major Hazards Monograph: "Thermal Radiation: Physiological and Pathological Effects.", IChemE, Rugby, England.

APPENDIX 8

SIMULATION MODELLING – ENGINE BAY

TABLE OF CONTENTS

A8.1. INTRODUCTION

A8.1.1 Purpose

This appendix outlines the methodology and results of the consequence modelling done for the potential releases of refrigerant in the engine bay of a passenger vehicle.

The leak rates used in this modelling were taken from **Appendix 6**, both for passenger compartment releases and engine bay releases of refrigerant.

A8.1.2 Potential Consequences

The potential consequences resulting from an ignition of a flammable mixture of hydrocarbon refrigerant were presented in **Table A8.1**.

TABLE A8.1
ENGINE BAY CONSEQUENCE SCENARIOS

No.	Type of Incident	Consequences
1	Explosion	Explosion Overpressure
2	Jet Fire	Flame Dimensions
3	Flash Fire	-

A8.2. METHODOLOGY

A8.2.1 Explosions

There are a large number of correlations for calculating pressure rise in explosion venting (Ref.1). The various methods give results that could vary by 1 order of magnitude.

Two methods were used to determine the explosion overpressure in the case of an explosion of refrigerant in the engine bay:

- Sapko et al.; and
- Bradley and Mitcheson.

The Sapko method uses a venting nomograph to determine the factor β in order to calculate the overpressure of a vented explosion. The nomograph is shown in **Figure A8.1**. Each parameter was calculated as follows:

$$a = \frac{(E-1)S_u}{C_d}$$

where: a = acoustic velocity, cm/s
E = expansion factor
S_u = burning velocity, cm/s
C_d = coefficient of discharge

Vessel volume, V is calculated as 20% (and 40%, sensitivity case) of the volume of the engine bay. 20% of the volume of the engine bay was taken as the "free volume" in the engine bay area.

Vent area, A is calculated as the area of the bottom and front of the engine bay.

The factor β could then be determined from the nomograph and used in the following equation to give the vent pressure:

$$P = \frac{E\rho_u}{\beta} + P_0$$

where P = vent pressure, atm
ρ_u = gas density, g/cm^3
P_0 = atmospheric pressure, atm

Step 1. a to V to X Step 2. X to A to β

Example:

S_u = 45 cm/sec, E = 7.50, C_d = 0.8, V = 4 cum, ρ_u = 1.134 x 10^{-3} g/cc, $P\text{-}P_i$ = 0.0068 atm

Vent area ≅ 3.5 sq m

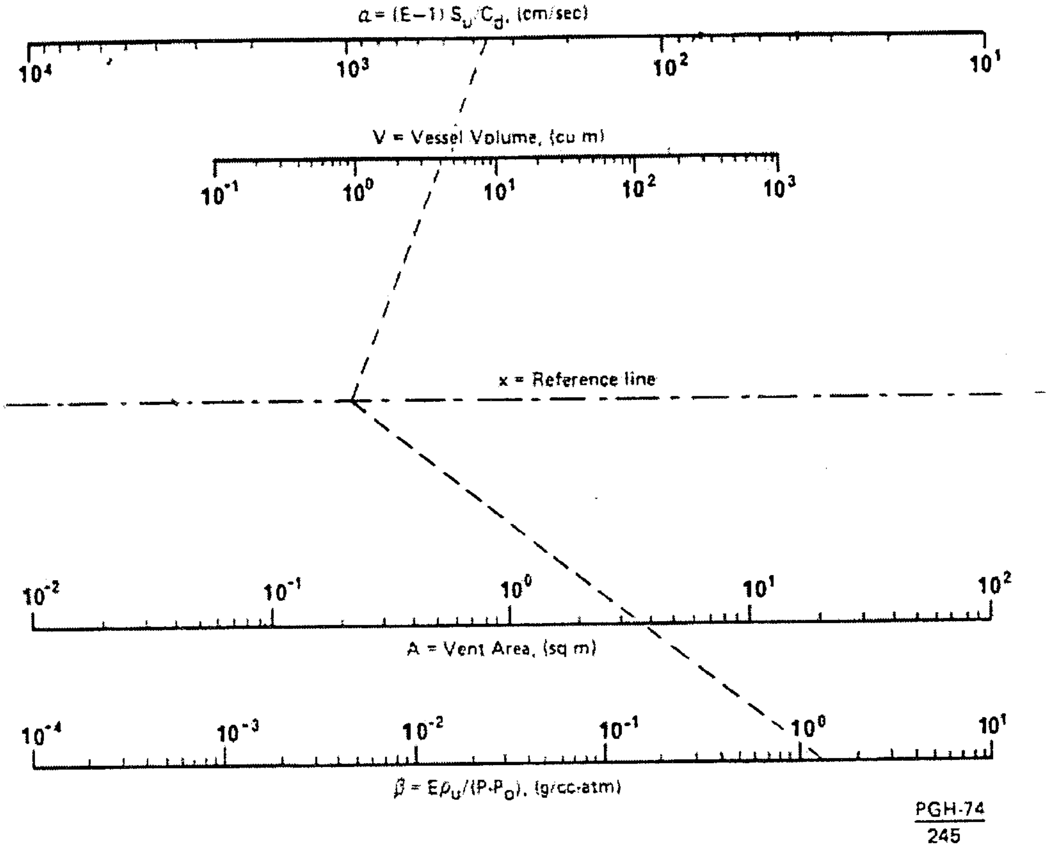


Fig. 24 Venting nomograph for spherical flame propogations in various size enclosures at 300°K and 1 atm. (Metric Units). (10)

FIGURE A8.1
VENTING NOMOGRAPH FOR SPHERICAL FLAME PROPAGATIONS IN VARIOUS SIZE ENCLOSURES AT 300K AND 1 ATM (REF.1)

The Bradley and Mitcheson method was also used to calculate the explosion overpressure in the engine bay. The vent area was assumed to be initially open, as indeed underneath the engine and the front of the engine bay are open to atmosphere. Two formulae are available for this situation, one for (P_v-P_0) < 1bar and one for (P_v-P_0) > 1 bar. The vent pressure will be less than 1 bar in this case, so the former formula was used:

$$P_v - P_0 = 0.7\left(\frac{A}{S_0}\right)^{-2}$$

where P_v = required pressure, atm

P_0 = atmospheric pressure, atm
A = vent area, m^2
S_0 = burning velocity, cm/s

The dimensions of the engine bay were estimated in order to calculate the volume and the vent area for the calculations. The free volume of the engine bay was estimated to be 20% of the total volume.

The calculated explosion overpressures are also compared with that reported for the engine bay in "Risk Assessment of Flammable Refrigerants Part 3: Car Air-conditioning", by Arthur D. Little (ADL, Ref.2).

The overpressures calculated using these methods were then compared with those shown in **Table A8.2** to determine the effects of an ER12 explosion in the engine bay.

TABLE A8.2
EXPLOSION OVERPRESSURE EFFECTS

Description of Effect	Overpressure (atm)	Ref.
50% window breakage	0.020	ADL
90% window breakage	0.034	DUAP
Glass damage	0.048	ADL
Damage to internal partitions, joinery, but can be repaired Probability of injury is 10%. No fatality	0.068	DUAP
Repairable damage to buildings	0.10	ADL
House uninhabitable and badly cracked	0.14	DUAP

Note: Arthur D. Little (ADL, Ref.2)
NSW Department of Urban Affairs and Planning (DUAP, Ref.3)

A8.2.2 Jet Fires

The dimensions of a jet fire were estimated using a computer model.

The model required the input parameters of pressure and hole size. An approximate ER12 composition was used as the component for developing the jet fire dimensions.

A8.2.3 Flash Fires

A flash fire in the engine bay may occur if the release is ignited. The refrigerant/ air mixture will take up the entire free volume of the engine bay. A flash fire would not cause any damage to the engine bay, due to the small inventory of flammable gas

(300g) and the short duration of the fire. No flash fire calculations were performed due to the small size of the fire and its short duration.

A8.3. RESULTS

A8.3.1 Explosions

A8.3.1.1 Dimensions of Engine Bay

The dimensions of the engine bay were estimated as follows:

length	1.2m
width	1.5m
depth	0.5m

This gave a volume of 0.9m^3, with a free volume (20%) estimated to be 0.18m^3. As a sensitivity case, a free volume of 40% was also used in calculations.

The vent area was taken to be the bottom and front of the engine bay and was found as follows:

$$A = 1.2*1.5 + 1.5*0.5$$
$$= 2.55\text{m}^2$$

These values of volume and vent area were required for the explosion calculations presented in the following Section.

A8.3.1.2 Explosion Overpressure

The results of the explosion overpressure calculations are shown in **Table A8.3**.

TABLE A8.3
EXPLOSION OVERPRESSURES

Method	Free Volume (m^3)	Explosion Overpressure (atm)
Sapko	0.18	1.3E-04
	0.36	4.2E-04
Bradley and Mitcheson	0.18	1.1E-03
	0.36	1.1E-03
ADL	not given	2.7E-02

The following observations are made from **Table A8.3**:

- Explosion overpressures calculated using the Sapko and Bradley and Mitcheson methods give lower values than that given in the ADL Report. Explosion venting correlations are known to give results varying in a band.

- No noticeable effects from explosion overpressures calculated using Sapko and Bradley and Mitcheson would be observed.
- The overpressure given by ADL would cause an effect of less than 90% window breakage (see **Table A8.2**).

It was concluded that the explosion overpressure effects in the engine bay would be negligible and the incident was not carried forward for further analysis.

A8.3.2 Jet Fires

The jet fire dimensions are given in **Table A8.4**.

TABLE A8.4
JET FIRE DIMENSIONS

Leak Type and Size	**Leak Rate**	**Flame Length**	**Width End**
	(kg/s)	**(m)**	**(m)**
Vapour 1mm	1.63E-03	0.7	0.07
Vapour 0.1mm	Too small to model		

This incident was not carried forward for further analysis due to the short duration of the fire (approximately 100 seconds maximum) and the small dimensions of the jet flame which would be fully contained within the engine bay.

Should this incident occur in the workshop during testing of the air-conditioning unit, there is a potential for injury to personnel.

A8.4. CONCLUSIONS

The potential consequences arising from an ignition of a flammable mixture of hydrocarbon refrigerant were investigated. By virtue of the open area present at the base of the engine bay, the potential for explosion was considered minimal. Further, the high air flow rates through the engine bay serve to "flush" out any leaked refrigerant. This is especially so when the vehicle is moving.

The assessment concluded that a fire or explosion would result in minimal damage to the engine and the occupants in the vehicle.

A8.5. REFERENCES

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APPENDIX 9

ER12 EXPERIMENTAL REPORT

BORAL ENERGY

USE OF ER12 HYDROCARBON REFRIGERANTS IN AUTOMOBILE AIR-CONDITIONERS

ER12 REFRIGERANT STUDIES

EXPERIMENTAL REPORT

DOCUMENT NO: **80065-BOR-TN-X-701**

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Boral Energy
Use of ER12 Hydrocarbon Refrigerants in Automobile Air-Conditioners
ER12 Refrigerant Studies – Experimental Report

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ABBREVIATIONS

Abbreviation	Explanation
ACH	air exchange rate
ER12	Esanty Refrigerant brand name product
FID	Flame Ionisation Detector
g	grams
g/mole	grams per mole
hr	hours
kg	kilograms
kg/kmol	kilograms per kilo-mole
L	litres
LCD	Liquid Crystal Display
LFL	Lower Flammability Limit
m	metres
m^3	cubic metres
min	minutes
°C	degrees Celsius
PID	Photoionisation detector
ppm	parts per million
s	seconds
$T_{ambient}$	ambient air temperature
$T_{cabin/outlet}$	cabin/ outlet temperature
T_{liquid}	liquid temperature
Tx	Thermostatic Expansion Valve

1. ABSTRACT

A series of experiments involving the hydrocarbon refrigerant ER12, a blend of propane and butane, were conducted. The tests were undertaken in relation to a motor vehicle air-conditioning system:

- to investigate effects on system from overcharging of refrigerant;
- to identify the physical release phase of the refrigerant upon release for 'catastrophic – 1mm' and 'large - 0.1mm' hole sizes from identified locations in the system;
- to determe the concentration profile within the vehicle cabin from a refrigerant leak classified as "typical" (0.01mm) and "large" (0.1mm); and
- to determine parameters to be used for the Safety Report on the refrigerant.

In the first series of testing, the performance of the air-conditioning system was found to decrease dramatically by overcharging the system by greater than 50% of the recommended charge limit. This was detected by the system unable to provide the required cooling. This excessive overcharge was done deliberately in the experiments to observe the effects. In practice, the event would be detected by the accredited automotive mechanics.

The second series of testing focused on identifying the physical state of the refrigerant on release from the system, when the system was running or static. Investigation focused on components of the air-conditioning system that are located within the passenger cabin, namely, the evaporator, Tx valve and associated hard piping and joints. For the "credible" and "large" leak cases, the release from a static system was found to be vapour phase. For the purposes of the Safety Report, all releases inside a stationary vehicle with the air-conditioning system in static mode were taken to be vapour.

The final series of experiments involved a release of ER12 inside vehicles and each test was conducted with the ventilation system in the vehicle under closed (recirculating) mode. Three late model vehicles were used in the study. A continuous release of refrigerant was mixed with the air in the passenger vehicle cabin and its concentration was measured with time. Complete mixing of the refrigerant within the passenger vehicle cabin was found to occur within 10 minutes of release. The concentration versus time profile was found to contain two distinct parts: a growth and a steady phase. The concentration in the vehicle was found to reach a steady state. A model developed in the Safety Report also estimated that for a continuous release and an air exchange rate (ACH), the concentration in the cabin would reach a steady value.

Two leak size categories were investigated, “large” and “typical”. The leak rate was determined from accredited automotive mechanics experienced in servicing motor vehicle air-conditioning systems. The experimental results showed that for a “typical leak” within the passenger cabin, the peak refrigerant concentration was only 18 ppm. This is well below the LFL (18500 ppm). This supports the claims by accredited automotive personnel that refrigerant leaks are typically very small and cannot be detected.

Similarly for a “large leak” of refrigerant, the peak concentration (2000 ppm) within the cabin was found to be significantly lower than the LFL (less than 20% LFL).

2. INTRODUCTION

2.1 General

This technical report has been prepared by Granherne to accompany the Safety Report (Ref.1) investigating the use of hydrocarbon refrigerant in passenger vehicles. A series of tests involving a hydrocarbon refrigerant were conducted. The refrigerant used was a Boral Esanty product known as ER12 that is a mixture of isobutane and propane.

The first series of tests involved investigating the effects on a motor vehicle air-conditioning system when it was deliberately overcharged with refrigerant. The second series of tests involved determining the physical state of the hydrocarbon refrigerant upon release from specified locations in a motor vehicle air-conditioning system. The final series involved releasing ER12 into a stationary vehicle inside an enclosure and measuring the concentration profile in the cabin over time. The leak rate was based upon the experience of accredited automotive air-conditioning specialists as reported in the Safety Report.

The field test results were compared with the simulation model developed in the Safety Report for a pseudo-continuous leak into the car cabin. Air exchange rates (ACH) obtained in separate field trials (Ref. 2) by Granherne were used to validate the model as well as to estimate the leak rate. The ACH parameter is necessary in estimating the concentration-time profile in the passenger cabin of a motor vehicle, following a leak of refrigerant into the car cabin.

This report contains details of the methodology, results and discussion of the ER12 refrigerant studies.

2.2 Objectives and Scope of Study

2.2.1 Objectives of Study

The objectives of the experiments were divided into three trials:

Trial 1 - Overload of Air-conditioning System

- observe and record the effects on a motor vehicle air-conditioning system when it is deliberately overcharged with refrigerant;

Trial 2 - Physical State of Release

- determine the physical state of the refrigerant upon release from specified locations in the motor vehicle air-conditioning system when it is static (i.e. not operating);

- observe the type and magnitude of credible leaks from motor vehicle air-conditioning components; and
- based upon these observations and discussions with air-conditioning specialists, develop an attachment with a a fixed orifice such that it could simulate a consistent leak size, thus giving a credible leak rate.

Trial 3 - ER12 Release in Vehicles

- determine the concentration time profile of released ER12 in a stationary vehicle located inside an enclosure with vents in the closed position. The release rate was based upon a review undertaken in the Safety Report and in Trial 1 of these experiments;
- determine the concentration time profile of an ER12 release in late model vehicles;
- compare the results against the simulation model developed to estimate the concentration time profile for a continual leak of refrigerant;
- determine based upon the experimental results and ACH values from previous testing, the actual refrigerant leak rate;
- ensure that conducted tests are reproducible; and
- prepare a technical report that can then be used as an input into the Safety Report.

2.2.2 Scope of Study

Granherne personnel conducted and supervised the experimental work, which was undertaken in Adelaide (01 to 03 June 1999) and Melbourne (08 and 09 June 1999). ER12 concentration studies were conducted on three (3) different car types.

3. METHODOLOGY

3.1 General

The purpose of this section is to outline the experimental methodology and equipment for the following trials:

- over charging of motor vehicle air-conditioning system (**Section 3.2**);
- physical release state from a motor vehicle air-conditioning system (**Section 3.3**);
- ER12 release in a passenger vehicle parked inside a garage (**Section 3.4**).

Photographs of the experimental setup may be found in **Appendix II**.

3.2 Trial 1 – Overload of Air-conditioning System

3.2.1 Refrigerant

The refrigerant used in the experiments was the Esanty product ER12, which is a hydrocarbon blend consisting of a mixture of propane and butane. The product is manufactured and distributed by Esanty Refrigerants, a wholly owned subsidiary of Boral Energy (Australia).

3.2.2 Equipment Used in Study

A fully operational motor vehicle air-conditioning system known as the “test rig” (see **Appendix III** for photograph) was used in this experiment. The unit is semi-portable and is used by Boral Esanty for demonstrations at trade fairs and technical college classes.

The capacity of the receiver drier is rated at 660 grams for R134a refrigerant which is equivalent to a corresponding charge of 220 grams if ER12 is used.

3.2.3 Experimental Methodology

Preliminary

1. The air-conditioning system was vented down to atmosphere to remove the ER12 refrigerant. This process took approximately 2 minutes.
2. A vacuum pump was then attached to the air-conditioning system to evacuate any residual refrigerant. This process was conducted for approximately 20 minutes.
3. At the completion of this evacuation, the system was ready for re-charging.

Charging of System

4. A bottle of ER12 refrigerant was placed on a set of digital scales and hooked to the appropriate gauge manifold to allow charging into the AC system.

5. The scale was then zeroed (i.e. reading on scales was 0.0 grams).

6. The gas bottle valve was slowly cracked open and refrigerant was allowed to enter into the air-conditioning system through the appropriate charging methods.

7. The following cumulative mass of refrigerant was charged into the system.

   - 60 grams
   - 100 grams
   - 150 grams
   - 200 grams
   - 290 grams
   - 430 grams
   - 600 grams
   - 720 grams
   - 830 grams

8. At each mass charge, observations were made on the effect on the air-conditioning system.

9. The experiment was terminated and the system was vented down in the manner previously described.

3.3 Trial 2 – Physical State of ER12 Release

3.3.1 Equipment Used in Study

The test rig as described in **Section 3.2.2** was used in this second series of experiments. In order to observe the physical state of ER12 refrigerant release from the nominated points in the air-conditioning system, Schrader valves had been welded into place (see **Appendix III**). This allowed copper tubing of approximately 0.1mm to be attached to these valves in order to observe large leaks.

3.3.2 Experimental Methodology

Physical Release

Table 3.1 details the tests that were performed on the test rig.

TABLE 3.1
PHYSICAL RELEASE TESTS OF ER12 REFRIGERANT

Location of Test Points in Air-conditioning System		Status of Air-conditioning System	
		Running "On"	Stationary "Off"
A	upstream of Tx valve	experiment 1	experiment 4
B	downstream of Tx valve	experiment 2	experiment 5
C	downstream of evaporator	experiment 3	experiment 6

Leak Testing

In addition, known faulty components of a motor vehicle air-conditioning system were obtained from a workshop in Adelaide. These components were subjected to pressure testing to observe the magnitude of leakage.

A compressor with a discharge of 414 kPa or 65 psi (low side pressure, greater than the expected pressure of an air-conditioning system in summer) was connected to the air-conditioning component. The component was placed under water to observe any leaks noticed as air bubbles.

The components studied in this manner were:

- evaporators (low pressure side of system);
- compressor (low pressure side); and
- discharge line – rigid (high pressure side).

3.4 Trial 3 – ER12 Release in Vehicle

3.4.1 Equipment Used in Study

Two type of gas detection equipment were used in the ER12 release experiments:

- Foxboro TVA1000 flame ionisation detector FID (experiment 1); and
- HNU Systems DI-101 photoionisation detector PID (experiment 2 and experiment 3).

Foxboro TVA1000 FID

The Foxboro TVA1000 FID is a portable flame ionisation detector able to measure the concentration of hydrocarbons (including butane and propane) in air within the range of 0 to 50000 ppm. The analyser is able to provide direct and continuous concentration readings. The response time of the instrument is 2 seconds and the concentration is displayed on a LCD.

The gas analyser was calibrated before hire using butane to determine the zero gas reading. The calibration certificate may be found in **Appendix I**. This instrument was used successfully in the Adelaide experiments. However, it was unable to be used in the latter experiments due to a critical component malfunctioning.

HNU Systems DI-101

The HNU Systems DI-101 is a portable photoionization detector that provides a direct and continuous reading of a variety of ionizable gases. By inserting a 11.7 eV lamp (isobutylene reference), the unit is able to detect both propane and butane. When analysis is required for a mixture of hydrocarbons in air, isobutylene is selected as the reference compound as it provides a response that bests approximates the hydrocarbons. The calibration certificate may be found in **Appendix I**.

The PID unit consists of an ultraviolet lamp and ion chamber. A sample enters into the ion chamber where it is exposed to photons (generated by the adjacent UV lamp) of energy equivalent to the reference lamp and becomes ionized. A positively based accelerator electrode repels these ions and causes them to travel to the collecting electrode. The ions generate a signal at the collector which is proportional to the concentration.

The PID instrument was used in the later experiments and proved to a be a more reliable instrument as it was more accurate for the lower range of the concentrations of interest.

3.4.2 Scales

Digital scales as used in motor vehicle workshops for charging air-conditioning systems were used to observe the decrease in mass of the ER12 cylinder during the course of the experiments. The accuracy of these scales is reported as ±10 grams.

3.4.3 Vehicles Used in Study

Three vehicle types were investigated in the experiments as shown in **Table 3.2**. These vehicles were chosen to represent typical family sized sedan vehicles.

TABLE 3.2
CAR TYPES AND VOLUMES

Vehicle Type	**Year**	**Volume (m^3)**	**Location**	**Experiment No.**
Ford Falcon	1998	3.8	Adelaide	1
Ford Falcon GL	1997	3.8	Melbourne	2
Holden Commodore VS Calais	1999	4.3	Melbourne	3

Note: See **Appendix V** of Safety Report (Ref.1)

3.4.4 Experimental Methodology – Adelaide

The first experiment was conducted in Adelaide in the presence of two accredited automotive air-conditioning specialists (Ref.3,4). For the purposes of this test, the worst possible leak size was simulated as judged by the specialists. This was achieved by loosening the screwed fitting containing the 'O' ring by one and a quarter turns.

Vernier callipers were used to measure the inside diameters of the fittings to estimate the equivalent leak path size.

Following release of refrigerant into the vehicle, the concentration was measured every minute for the first ten minutes, then every 5 minutes for 30 minutes and then every half hour. The mixing period of the refrigerant within the vehicle was determined.

Photographs demonstrating the equipment setup and leakage rate may be found in **Appendix II**. The following methodology was adopted for measuring the concentration time decay profile of the refrigerant:

Preliminary

1. Air vents in passenger vehicle were placed in closed (recirculating) position.
2. All garage doors were closed to minimise the potential of any wind effects flowing through the garage.
3. Ambient weather conditions were noted.
4. The evaporator (Mitsubishi Sigma 1984), Tx valve and associated hard piping was placed into the vehicle. The remaining components of the air-conditioning system such as the condenser and compressor were located external to the vehicle. Delivery tubing was then passed through the floor pan at the drain lugs which were then re-secured.

5. Gas detection tubing was secured in the rear passenger side and passed through the floor pan drain lug. This tubing was checked to ensure that air flow was permitted.

6. Visual checks were made to ensure that the door and boot were sealed.

7. The gas detector tubing was then hooked into the Foxboro TVA1000 FID and turned on. Background level of hydrocarbon in the car passenger cabin was noted.

Release and Measurement of Tracer Gas

8. The screwed fitting downstream of the Tx valve and leading into the evaporator was slowly cracked open to one and a quarter turns.

9. Swabbing of soap solution at the loosened joint was conducted to visually confirm that a refrigerant leak was occurring.

10. The passenger door was immediately closed and the gas concentration was then recorded at set time intervals.

11. The experiments were recorded until sufficient experimental data had been obtained from each passenger vehicle to allow analysis.

12. The experiment was terminated by opening the car doors and the decay in gas concentration recorded.

13. At the conclusion of the experiment, the soap solution test was again performed to verify that the leak had been continuous.

3.4.5 Experimental Methodology – Melbourne

The experiments conducted in Melbourne were a continuation of the work conducted in Adelaide. Based upon a credible leak rate determined from interviews with accredited automotive mechanics, a length of copper tube (approximately 0.5mm in diameter) was taken and crimped. This was done by an accredited automotive air-conditioning engineer to the desired orifice size and hence leakage rate.

This leakage rate was deemed equivalent to the most credible leak size category of "pinhole" determined from the Safety Report (Ref.1). This leak rate was applied to releases from the thermal expansion (Tx) valve and evaporator.

The refrigerant concentration was measured every minute for the first ten minutes, then every 5 minutes for 30 minutes and then every half hour. The mixing period of the refrigerant within the vehicle was determined.

Experiment 2 was conducted in the presence of a Station Officer from the Fire Investigation and Analysis Department of the Victorian Metropolitan Fire and Emergency Services Board (Ref.5).

Photographs demonstrating the equipment setup and leakage rate may be found in **Appendix II**. The following methodology was adopted for measuring the concentration time decay profile of the refrigerant:

Preliminary

1. Air vents in passenger vehicle were closed.
2. Ambient weather conditions were noted.
3. The ER12 delivery tubing was secured at gear stick level to simulate a release of refrigerant into the car cabin. The tubing was then passed through the floor pan of the drain lugs and re-secured.
4. Gas detection tubing was secured in the rear passenger side and passed through the floor pan drain lug. This tubing was checked that air flow could be permitted.
5. Visual checks were made to ensure that the door and boot were sealed.
6. The ER12 gas bottle was then placed on the digital scales and the delivery line secured to the gas bottle. The initial mass of the gas bottle was noted.
7. The gas detector tubing was then hooked into the HNU Systems DI-101 and it was turned on. Background level of hydrocarbon in the car passenger cabin was noted.

Release and Measurement of Tracer Gas

8. The valve on the ER12 bottle was slowly cracked open. The valve downstream of the bottle on the copper tubing was then opened.
9. Swabbing of soap solution at the end of the copper delivery tube was conducted to visually confirm that a refrigerant leak was occurring.

10. The passenger door was immediately closed and the gas concentration was then recorded at set time intervals.

11. The experiments were recorded until sufficient experimental data had been obtained from each passenger vehicle to allow analysis.

12. The experiment was terminated by opening the car doors and the decay in gas concentration was recorded.

13. At the conclusion of the experiment, the soap solution test was again performed to verify that the leak had been continuous.

14. All vehicles tested were purged with fresh air from the surrounds prior to the commencement of the next experiment.

4. RESULTS AND DISCUSSION

4.1 General

The purpose of this section is to provide results and observations from the following trials involving ER12 refrigerant:

- overcharging of motor vehicle air-conditioning system (**Section 4.2**);
- physical release state from a motor vehicle air-conditioning system (**Section 4.3**);
- ER12 release in a passenger vehicle parked inside a garage (**Section 4.4**).

4.2 Trial 1 - Overcharging of System

4.2.1 Results and Observations

Observations recorded during the course of the air-conditioning system are detailed in **Table 4.1**. Readings of the pressure and temperature of the system at various charge readings are given in **Table 4.2**.

TABLE 4.1
OBSERVATIONS FOR CHARGING TRIAL

Cumulative Charge Mass in System (grams)	Ratio of Charge Mass to Optimum of 200 grams	Comments
60	0.3	outlet temperature reads ambient – no cooling
100	0.5	slight cooling observed
150	0.75	slight cooling observed
200	1.0	optimum outlet temperature achieved
290	1.5	slight increase in outlet temperature
430	2.1	receiver flooded with refrigerant, backpressure increases and outlet temperature increased
600	3.0	backpressure increases and outlet temperature increased
720	3.6	outlet temperature reads near ambient
830	4.2	outlet temperature reads ambient

TABLE 4.2
PRESSURE AND TEMPERATURE VALUES DURING CHARGING

Cumulative Charge Mass in System (grams)	Ratio of Charge Mass to Optimum of 200 grams	Pressure (kPa) and Temperature (°C)Readings			
200	1	P_{low} P_{high}	192 kPa 690 kPa	$T_{ambient}$ $T_{cabin/outlet}$ T_{liquid}	15°C 5°C 23°C
600	3.0	P_{low} P_{high}	220 kPa 896 kPa	$T_{ambient}$ $T_{cabin/outlet}$ T_{liquid}	15°C 6°C 28°C
830	4.2	P_{low} P_{high}	262 kPa 1206 kPa	$T_{ambient}$ $T_{cabin/outlet}$ T_{liquid}	15°C 7°C 35°C

The trial demonstrated that overcharging the system with the ER12 refrigerant past the recommended amount of 220 grams would severely degrade the performance of the system. Depending on the amount overcharged, the cooling efficiency of the system declines dramatically to a point where no cooling can be achieved.

For the purposes of the Safety Study, this trial demonstrated that any overcharging (e.g. human error or scale readings were reading incorrect) into a motor vehicle air-conditioning system should be detected by the accredited automotive mechanics. As part of the procedure following charging, the mechanic must check the outlet temperature to ensure that the system is functioning. This is part of the system check procedure. A high pressure indicated during routine testing of the AC system after charging would also indicate an overcharged system.

4.3 Trial 2 - Physical State of ER12 Release

4.3.1 Release Characteristics

Two hole sizes were used in the assessment that corresponded to leaks inside a passenger cabin. These were catastrophic (equivalent to 1mm) and major (0.1mm) leak sizes. Observations on the physical phase of the release are shown in **Table 4.3**.

These tests were conducted for the air-conditioning system when it was static or in running mode. The tests were duplicated to verify all findings.

TABLE 4.3
PHYSICAL RELEASE CHARACTERISTICS OF ER12

Location of test Points in Air-conditioning System		Observations	
		Leak Size Category	**Phase**
Air-conditioning System On			
A	upstream of Tx valve	catastrophic (1mm) large (0.1mm)	liquid/ two phase vapour
B	downstream of Tx valve	catastrophic (1mm) large (0.1mm)	vapour vapour
C	downstream of evaporator	catastrophic (1mm) large (0.1mm)	vapour vapour
Air-conditioning System Off			
A	upstream of Tx valve	catastrophic (1mm) large (0.1mm)	liquid (<5sec)/ vapour vapour
B	downstream of Tx valve	catastrophic (1mm) large (0.1mm)	vapour vapour
C	downstream of evaporator	catastrophic (1mm) large (0.1mm)	vapour vapour

The following observations are made as a result of the tests:

- With the exception of a catastrophic release upstream of the Tx valve, the release from the air-conditioning system when it was running will result in a continuous vapour phase release. A continuous liquid/ two phase release was observed for a catastrophic release from upstream of the Tx valve. Photographs of the releases are shown in **Appendix III**.

- All releases from the air-conditioning system when it was static were observed to be vapour phase. For the catastrophic release upstream of the Tx valve, there was an initial release of liquid (< 5 seconds) followed by a vapour release. Photographs of the releases are shown in **Appendix III**.

This can be explained as follows:

- When the air-conditioning system is turned off, the refrigerant liquid migrates from the receiver drier throughout the refrigeration system.

- This is achieved since the Tx valve opens up due to a centering device attached to the Tx valve diaphragm which is activated by increased temperature.

- As the refrigerant migrates through the evaporator and pipework, it changes its physical state from liquid to vapour. This transformation is enhanced in high temperature ambient conditions.
- There will be a small amount of refrigerant liquid in the receiver drier at its vapour pressure. However, if there is a leak to atmosphere, the liquid refrigerant "boils off" to a vapour phase.

For the purposes of the Safety Report, a release of refrigerant inside the passenger cabin from the air-conditioning system when the vehicle is parked will be vapour phase. This statement was validated in **Section 4.4** whereby a release of ER12 into the cabin from a large leak size was observed to be vapour phase.

4.3.2 Leak Testing

The following observations are made regarding leak testing of faulty air-conditioning components. Photographs of the damaged equipment are shown in **Appendix III**.

Evaporators

Leaks from the evaporators were very difficult to detect and were evidenced by a slow generation of air bubbles. Upon inspection, the leak sizes were found to be very small pin hole weeps.

Tx Valves

Two common types of Tx valves were examined, the block valve and standard valve. Most valves are fabricated as:

- machined brass block with an inert (non reactive) metal coating; and
- moulded brass fittings with machined threads and internal components.

No fractures or cracks were found on the Tx valves. The leaks from Tx valves were found to be due to alleviation of the joint where 'O' rings are present. The equivalent hole diameter was estimated as approximately 0.1mm or less.

Compressors

Typical leak sources around the compressor were found to be from the face plate and compressor seal. These varied in size from 0.01 to 0.1mm equivalent diameter.

4.4 ER12 Release Results

4.4.1 General Observations

Physical State of Release

The physical state of released refrigerant into the vehicle cabin was observed to be vapour phase. This was verified by the application of a leak detection solution around the cracked joint (during the beginning and conclusion of each experiment) and observing the formation of bubbles.

Mixing Period and Concentration Profile

A review of the ER12 concentration profiles (in the following sections) revealed two distinct phases comprising growth and steady periods. The end of the growth period was recognised when the refrigerant concentration in the passenger vehicle remained near steady (within the tolerance imposed by the accuracy of the analyser).

This phenomena is in line with the predicted steady state model for a continuous release of refrigerant (**Appendix IV**).

In order to determine the release rate, it was assumed that the concentration of the refrigerant was well mixed in the passenger vehicle. The validity of this assumption was verified in two ways:

1. The gas analyser was placed at various locations in the rear of the passenger cabin to monitor the refrigerant concentration.
2. In all experiments, the raw data showed that for the first 10 minutes following release, the concentration fluctuated. Based upon similar experimental work (Ref.2), this has been attributed to the gradual dispersion or diffusion of the material within the bulk air in the passenger cabin to provide a well mixed concentration. After this initial mixing period, the concentration profile provided a steady increase in line with the growth period. (See **Appendix 10** of the Safety Report).

Importantly, it was found that although the refrigerant gas has a molecular weight (51 kg/kmol) heavier than air (29 kg/kmol), a uniform concentration within the passenger compartment will occur within a short period of time.

4.4.2 Experiment 1

This experiment simulated a major leak of refrigerant by loosening the screwed fitting leading into the evaporator. Due to time constraints, the first experiment was only able to be conducted for approximately 2.5 hours. However, the concentration in the cabin was found to reach a near steady value of 1900 ppm. By fitting the raw data to a power law equation, the peak concentration was estimated to be 2000 ppm. The concentration profile for this experiment is shown in **Figure 4.1**.

Using the data given in **Appendix IV**, the average leak rate was estimated to be 1.4 x 10^{-6} kg/s. Measurement of the internal diameters of the screwed fitting equated to an equivalent hole size of < 0.1mm.

The peak concentration was found to be eleven percent (11%) of the Lower Flammability Limit (LFL) of 18500 ppm.

At the conclusion of the experiment, the vehicle doors were opened. As expected, the concentration within the cabin decreased rapidly and dropped to half the peak value within half a minute (30 seconds).

Interestingly, the odourant in the cabin was able to be smelt indicating that a large leak had occurred. Unlike the next set of experiments, this smell was not detected for the "typical" pinhole leaks reflecting the smaller scale of the release.

4.4.3 Experiment 2 and Experiment 3

Experiment 2 and Experiment 3 were conducted over 6.5 and 8.5 hours respectively. The duration of both these experiments were significantly longer than Experiment 1. This was done to observe the likely concentration profile within the passenger cabin for the situation that the vehicle was parked overnight in a garage and a leak occurs.

The concentration profiles for Experiment 2 and Experiment 3 are shown in **Figure 4.2** and **Figure 4.3** respectively. The following observations were made:

- The concentration profile displayed a similar pattern as for the first experiment. That is, the concentration in the passenger vehicle gave a growth and steady phase. This also showed that the leak of refrigerant was continuous.
- For both experiments, the concentration in the cabin reached a final steady value of approximately 18 ppm. Both vehicles used in the study were late models and could be assumed to have fewer leak paths (via seals) than for early models.
- The peak concentration of the refrigerant was found to be 0.1% LFL or three orders of magnitude less than the corresponding LFL.
- No odourant smell was detected in the cabin when the doors were opened indicating the small scale of the leak and hence resulting low concentration.

Pressure and Temperature Effects

The effect of limiting the air exchange between the passenger cabin and the surroundings for a vehicle inside an enclosure was examined in Experiment 2. The first part of the experiment was started in the early afternoon (sunny, slight breeze and 17°C) and the garage door was left open. The steady state concentration reached within the passenger cabin was approximately 15 ppm.

In the late afternoon (elapsed period of three hours), the garage door was closed. The concentration profile (see **Figure 4.2**) showed an increase to 19.4 ppm before settling to a steady state concentration value of 18 ppm. This slight rise in concentration was expected as the air exchange rate is lower in a totally enclosed room than if one side is open to surroundings (Ref. 2). The profile can be explained as follows:

- Following closure of the doors, the ambient temperature in the garage was still higher than the surrounds and as the air exchange rate was lower, the concentration rose.
- As the temperature in the room gradually cooled to ambient the leak rate dropped. This is to be expected since the leak rate is dependent on the vapour pressure of the refrigerant. As the temperature drops, the vapour pressure drops and correspondingly, the release rate also decreases.
- As a result, the system adjusted itself to a new equilibrium and the profile settled down to a new steady state concentration value of 18 ppm. The temperature in the late evening was measured to be 10.7°C.

FIGURE 4.1
EXPERIMENT 1

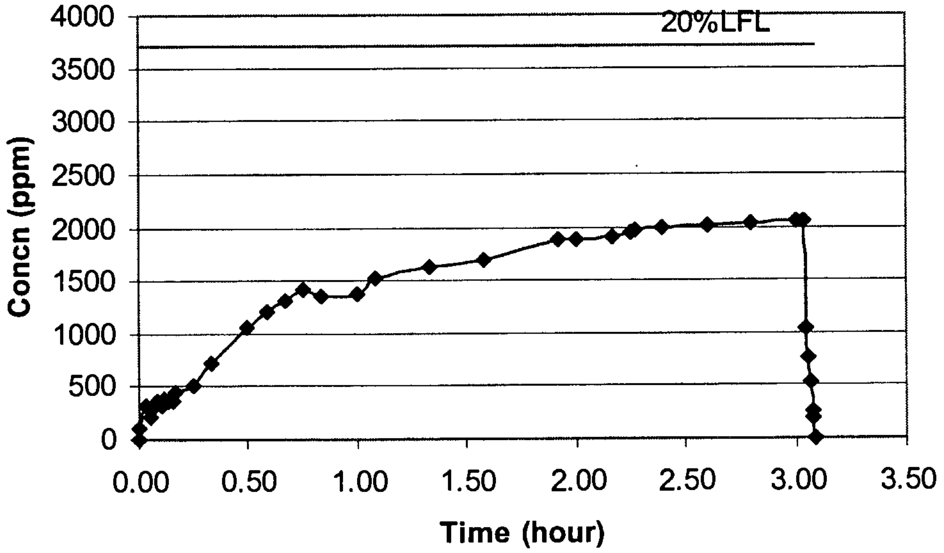


FIGURE 4.2
EXPERIMENT 2

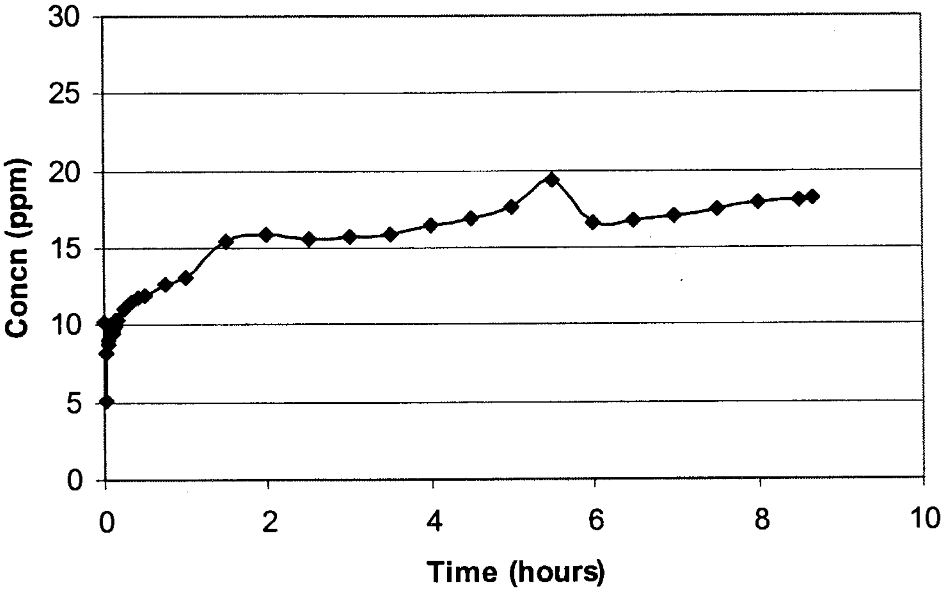
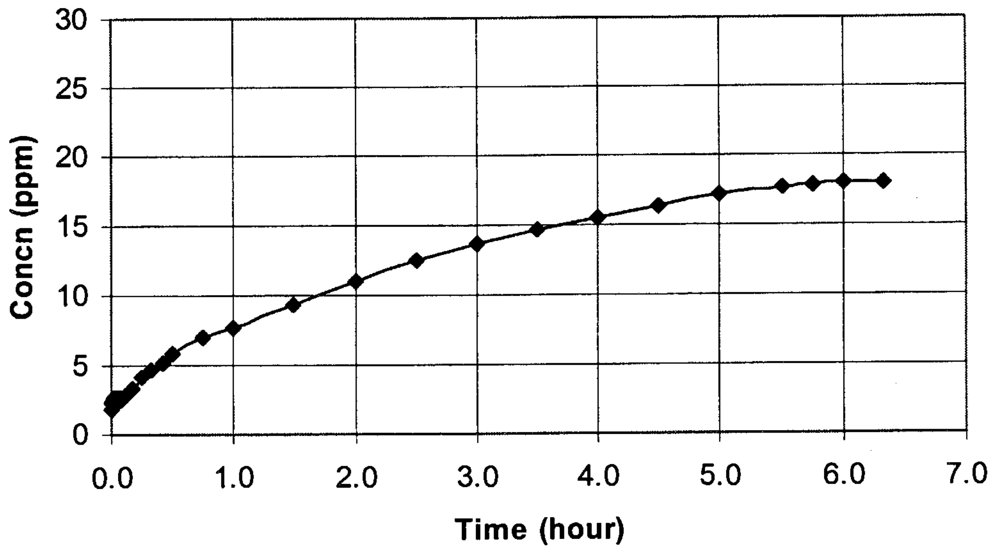


FIGURE 4.3
EXPERIMENT 3



4.4.4 Summary of Results

A summary of the ER12 release experiments is shown in **Table 4.4**. The leak rate was estimated using the methodology described in **Appendix IV**.

TABLE 4.4
SUMMARY OF ER12 RELEASE EXPERIMENTS

Expt No.	Car	Duration	Avg. Ambient Temp (°C)	Peak Value (ppm)	% LFL	Estimated Leak Rate (kg/s)
1	Ford Falcon 1998	1310 to 1530	15.8	2000	11	1.4×10^{-6} (large)
2	Ford Falcon 1997	1350 to 2230	17 (day) 11 (evening)	18	0.1	1.4×10^{-8} (typical)
3	Holden Calais 1999	0845 to 1505	17 (day)	18	0.1	1.4×10^{-8} (typical)

For the purposes of the Safety Report, the experimental results showed that for a typical pinhole leak within the passenger cabin, the refrigerant concentration would be well below the LFL. This supports the claims by workshop personnel (Ref.1) that refrigerant leaks are typically very small and cannot be detected.

Similarly for a "large leak" of refrigerant, the concentration within the cabin would be lower than the LFL and can be detected by smell. Based upon the experiments, all leaks considered in the Safety Report from an air-conditioning system (static mode) would be vapour.

Further, the results also showed that the concentration in the vehicle would reach a peak steady state value even if it was parked overnight in a garage.

5. REFERENCES

1 Granherne Pty Ltd (1999), "Use of Hydrocarbon Refrigerants in Automobile Air-Conditioners, Safety Report", Document No. 80065-BOR-RT-X-500.

2 Granherne Pty Ltd (1999), "Use of Hydrocarbon Refrigerants in Automobile Air-Conditioners, Tracer Gas Studies – Experimental Report", Document No. 80065-BOR-TN-X-700.

3 Mr. Peter Williams, Licence number: 2142, 44 years experience.

4 Mr. Jim Gerazounis , Licence number: 3085, Coolair Automotive, 20 years experience.

5 Mr. Alex Conway, Station Officer, Fire Investigation and Analysis, Victorian Metropolitan Fire and Emergency Services Board.

6 Granherne Pty Ltd (1999): "Boral Energy, Use of ER12 Hydrocarbon Refrigerant in automobile Air-Conditioners, Safety Report", Appendix 10. Document No. 80065-BOR-RT-X-500.

APPENDIX I

CALIBRATION CERTIFICATES FOR GAS ANALYSERS

EnviroRent pty. ltd.

CUSTOMER COPY

CALIBRATION CERTIFICATE FOR FOXBORO TVA 1000A.

ASSET: 0341

P.I.D : Calibrated with 98 ppm isobutylene, and Response Factor set to 1.46 to read direct for Benzene, so that the display shows 67 ppm.
Gas bottle number: 339318

See the table at the back of the Manual for other Response Factor settings.

F.I.D : Calibrated to 100 ppm Methane.
Gas bottle number: 48326

NOTE: Detectors are calibrated to Zero air first.

The above detector was calibrated in accordance with manufacturers specifications. Cylinder certificates are available upon request.

SIGNED: JASON WARD

DATE: 1/6/99

☑ MELBOURNE:
3/14 APOLLO CRT
BLACKBURN 3150
PH: (03)98941808

☐ SYDNEY:
8/20-30 STUBBS ST
SILVERWATER 2141
PH: (02)97480977

☐ BRISBANE:
12B THE CORSO
NORMAN PARK 4170
PH:(07)38995199

☐ PERTH:
3/30-34 ADAMS DRV
WELSHPOOL 6106
PH:(08) 9472 7311

09-06-99

EnviroRent pty. ltd.

CUSTOMER COPY

CALIBRATION CERTIFICATE FOR PHOTO IONISATION DETECTOR.

MAKE: HNU

MODEL: DL 101

ASSET: 0032

Calibration gas species: Iso-butylene.
Calibration gas concentration: 97.3 ppm, balance Zero air.
Gas bottle number: YR 200.

This PID has been referenced to Benzene so that the concentration is displayed as 56 ppm at — span setting.
All PID's are initially zero calibrated.

The above detector was calibrated in accordance with manufacturers specifications. Cylinder certificate is available upon request.

Signed: Stephen Hill

Date: 3/6/99

MELBOURNE:	SYDNEY:	BRISBANE:	PERTH:
3/14 APOLLO CRT	8/20-30 STUBBS ST	12B THE CORSO	3/30-34 ADAMS DRV
BLACKBURN 3150	SILVERWATER 2141	NORMAN PARK 4170	WELSHPOOL 6106
PH: (03)98941808	PH: (02)97480977	PH:(07)38995199	PH:(08) 9472 7311

APPENDIX II

EXPERIMENTAL SET UP

PHOTOGRAPHS

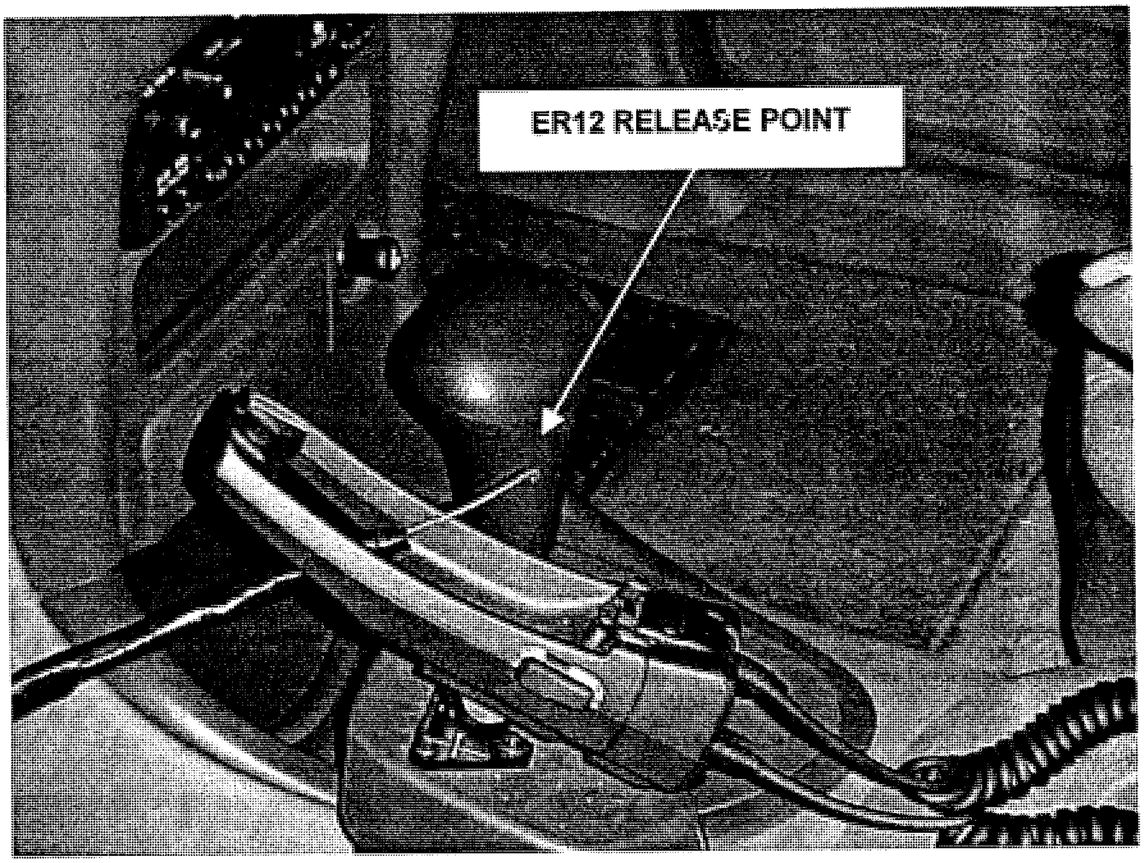


FIGURE AII.1
RELEASE POINT OF ER12 IN CAR

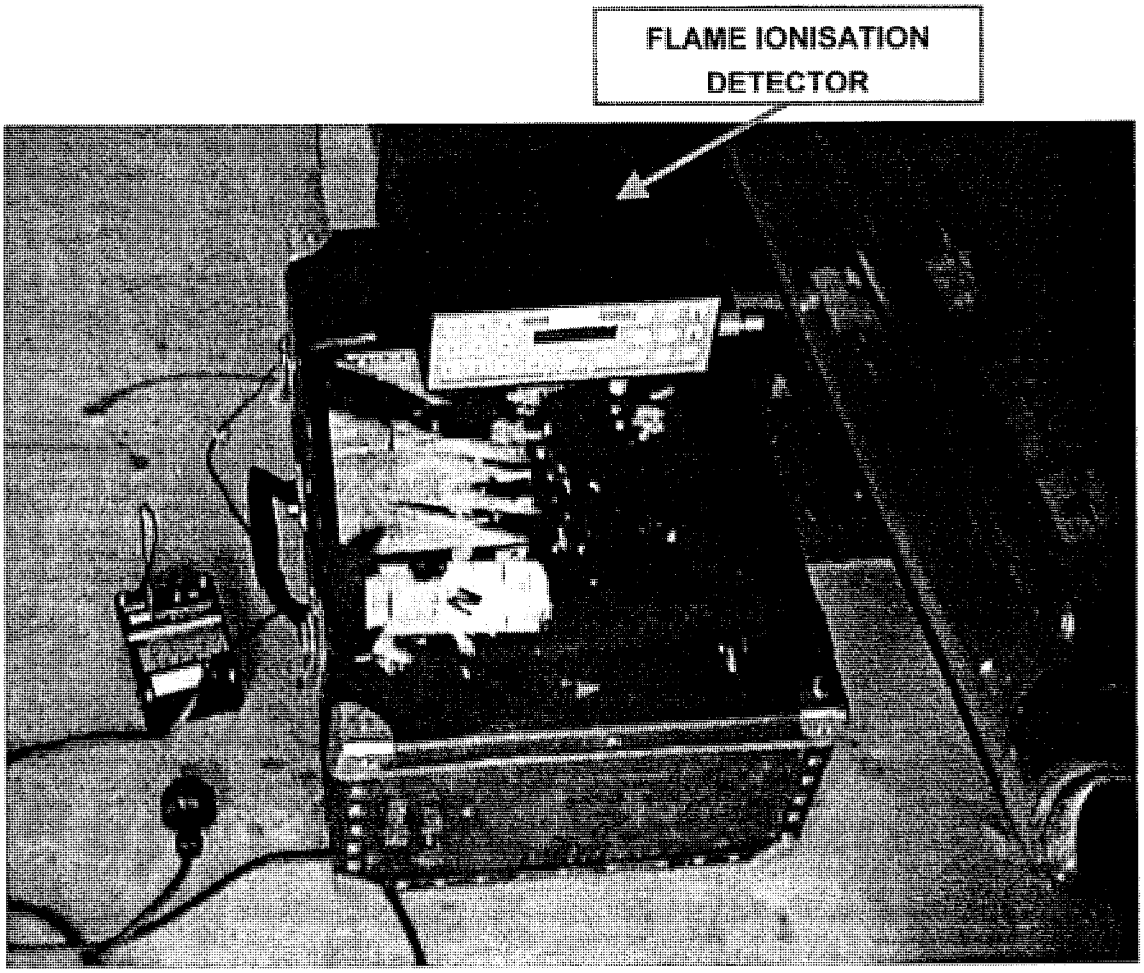


FIGURE AII.2

VIEW OF FLAME IONISATION DETECTOR (FID) BESIDE CAR

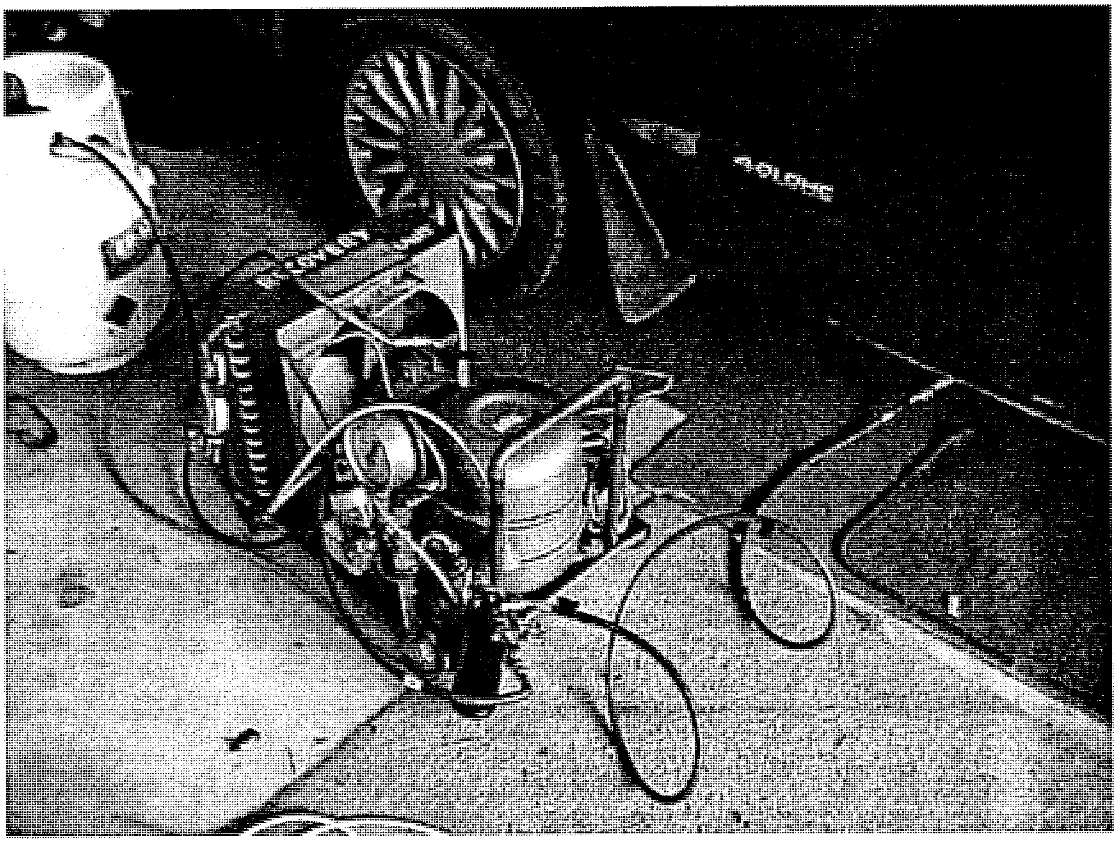


FIGURE AII.3
VIEW OF ER12 DELIVERY RIG

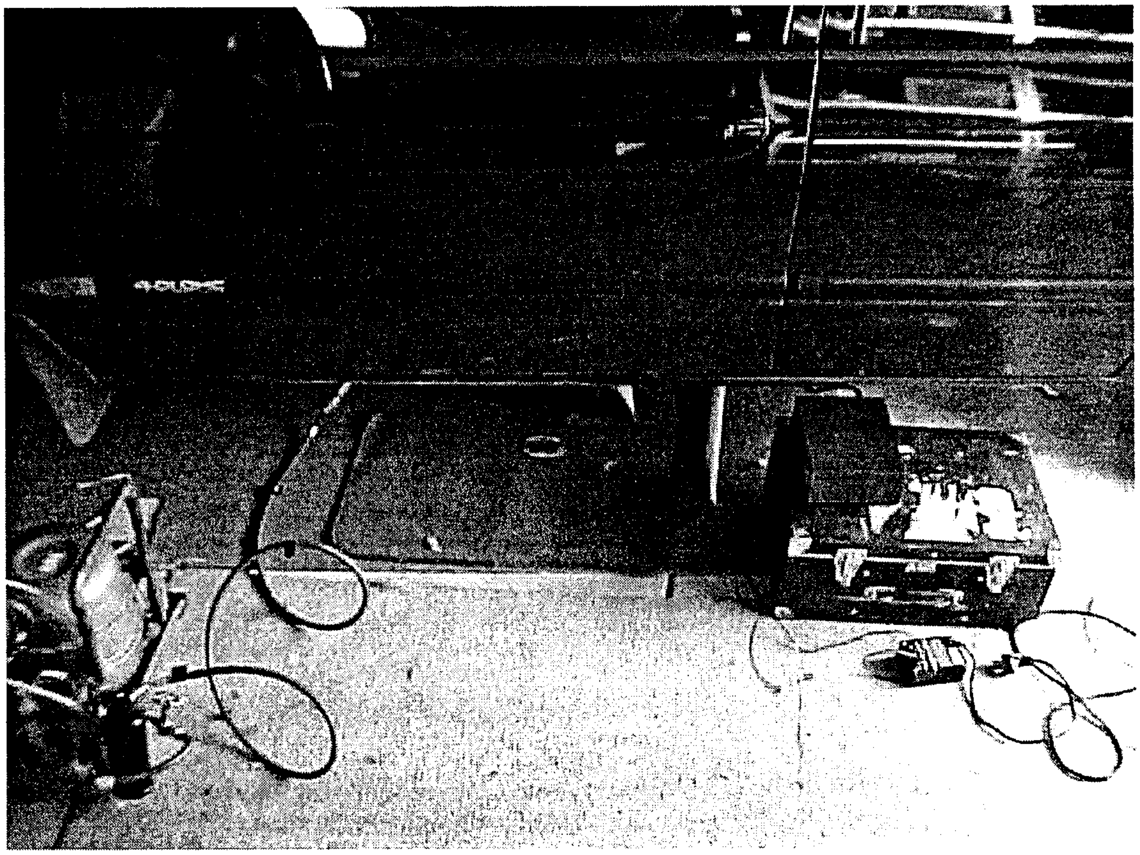


FIGURE AII.4
EQUIPMENT AND CAR SHOWING ENTRY POINTS

FIGURE AII.5
VIEW OF GAS DETECTOR INSIDE CAR

FIGURE AII.6
ER12 CYLINDER ON SCALES

FIGURE AII.7
VIEW OF CAR IN GARAGE

APPENDIX III
PHOTOGRAPHS OF ER12 RELEASES

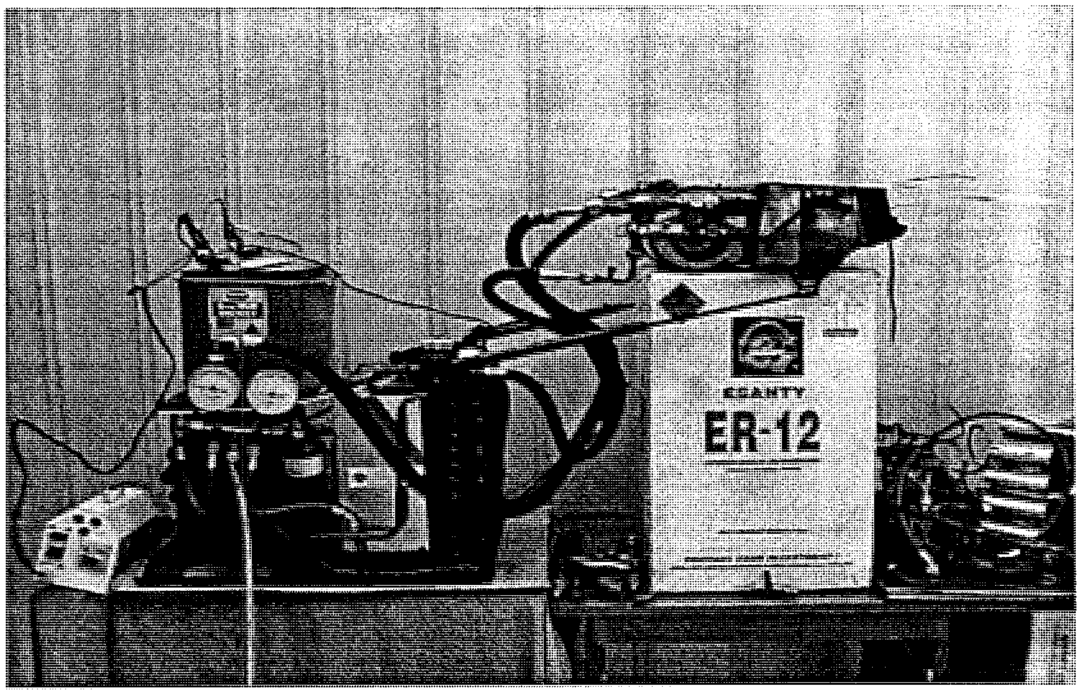


PHOTO AIII.1
AUTOMOTIVE AIR CONDITIONING TEST RIG USED IN EXPERIMENTS

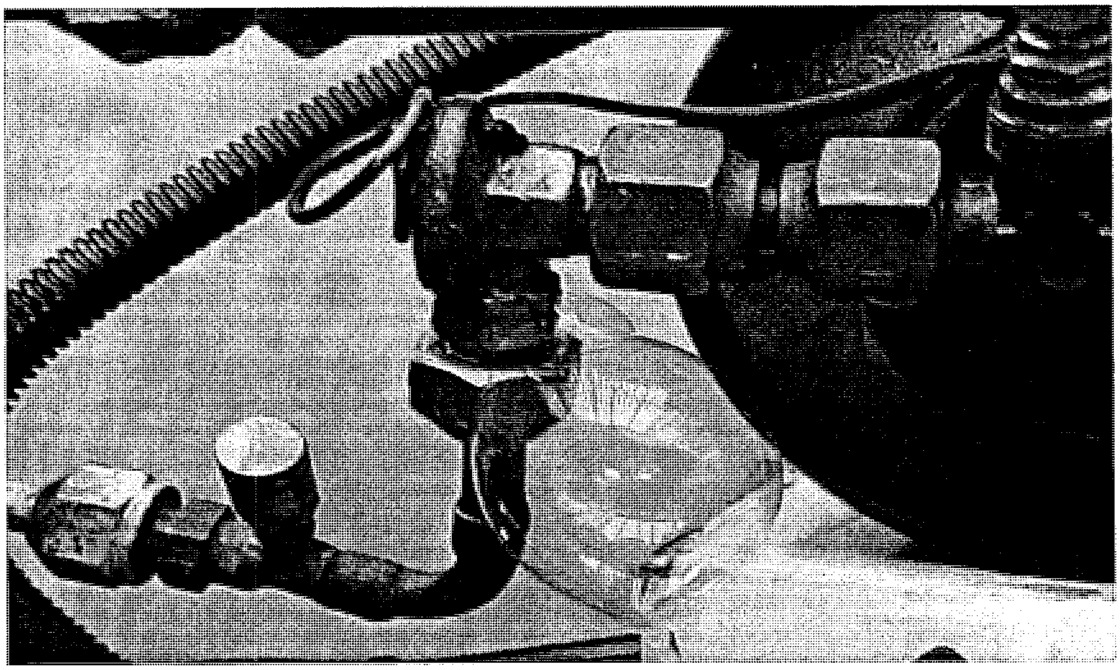


PHOTO AIII.2
VAPOUR LEAK (LARGE) DOWNSTREAM OF Tx VALVE

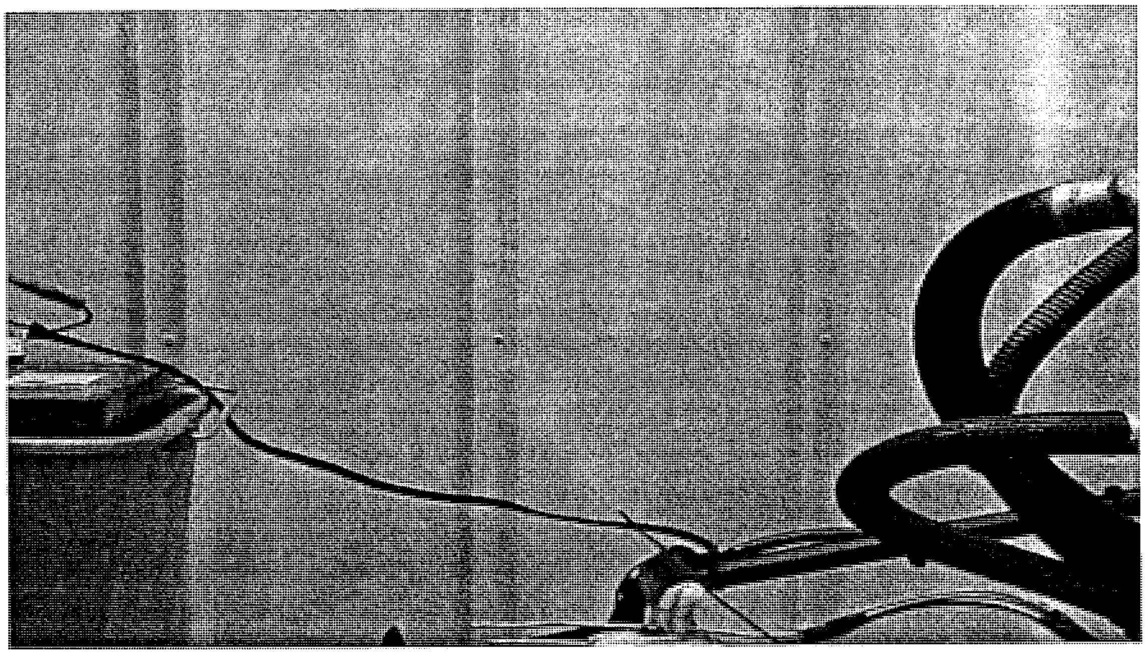


PHOTO AIII.3
TWO PHASE LEAK (<5 SEC, CATASTROPHIC) UPSTREAM OF Tx VALVE

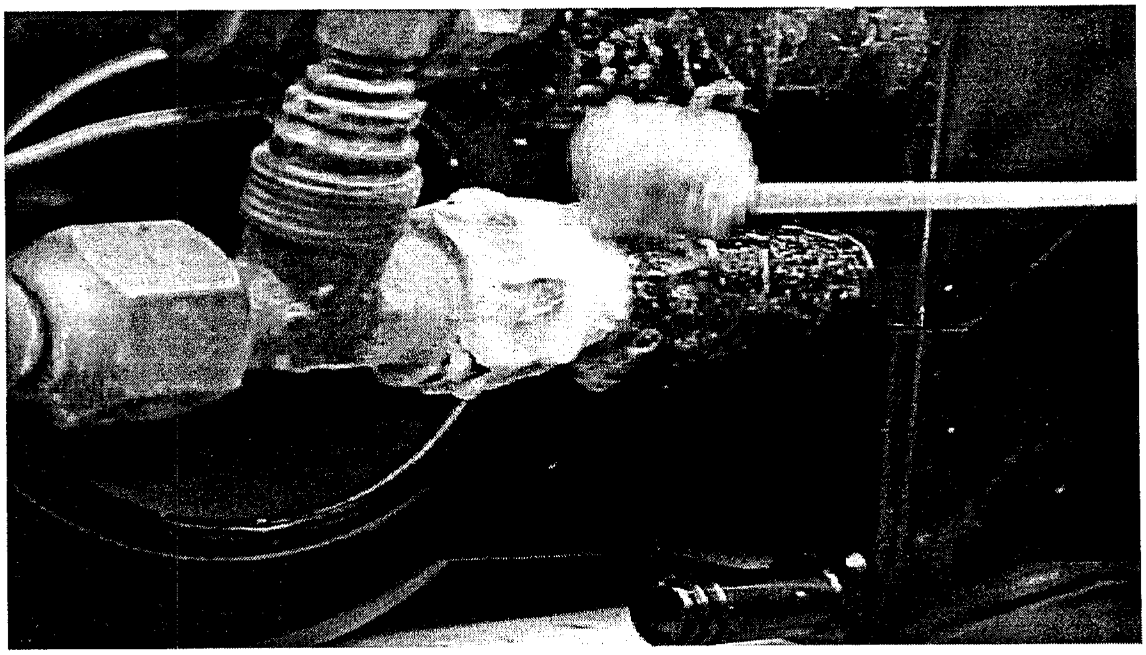


PHOTO AIII.4
VAPOUR LEAK (LARGE) DOWNSTREAM OF EVAPORATOR

APPENDIX IV

CONTINUOUS LEAK MODEL

AIV.1. INTRODUCTION

This Appendix explains the calculation methods and results used to estimate the leak size for the maximum concentrations reached in the experiments i.e. approximately 2000ppm (Experiment 1) and 20ppm (Experiments 2 and 3). The method used is explained in more detail in **Appendix 7** of the main Safety Report.

Section AIV.2 of this Appendix explains briefly the method used and steps taken to calculate the hole size required to give the maximum concentration obtained. **Section AIV.3** gives the results of the calculations.

AIV.2. METHOD

The maximum concentration reached inside the passenger compartment in the experiments in Adelaide (Experiments 2 and 3) was approximately 20ppm. In order to approximate the leak rate that would give such a peak concentration, the model used in **Appendix 7** of the Safety Report to determine concentration of refrigerant in car passenger cabin with recirculating mode was used.

The leak rate was estimated to give a maximum concentration of approximately 20ppm of refrigerant in the car passenger compartment. An air exchange rate of 0.27 m^3/hour was used (Ref.6).

The governing equation was:

$$C = \frac{m}{\nu}(1 - \exp(-\frac{\nu}{V}t))$$

where:

C = concentration of hydrocarbon refrigerant (kg/m^3)

m = leak rate of hydrocarbon refrigerant (kg/s)

t = time (s)

V = volume of car passenger compartment (m^3)

ν = ventilation rate (m^3/s)

AIV.3. RESULTS AND DISCUSSION

The leak rate that gave a maximum concentration of 2000ppm was found to be 3.3E-07 kg/s. The leak rate that gave a maximum concentration of 20ppm was found to be 3.3E-09 kg/s.

The leak rate could then be used to find the approximate hole size in the pipe causing the leak of refrigerant. The Bernouilli equation was used to perform this calculation. The required input data is shown in **Table AIV.1**.

TABLE AIV.1
INPUT DATA FOR HOLE SIZE CALCULATION

Parameter	Value
temperature, K	288
vapour pressure, kPa abs	561
molecular weight, g/mol	51
ratio of specific heats	1.12
gas constant, J/Kmol	8.314
coefficient of discharge	0.8

The results are shown in **Table AIV.2**.

TABLE AIV.2
LEAK RATES AND HOLE SIZES

Expt No.	Max. Concn (ppm)	Leak Rate (kg/s)	Hole Size (mm)
1	2000	1.4E-06	0.0069
2,3	20	1.4E-08	0.0006

APPENDIX 10

TRACER GAS STUDIES – EXPERIMENTAL REPORT

BORAL ENERGY

USE OF HYDROCARBON REFRIGERANTS IN AUTOMOBILE AIR-CONDITIONERS

TRACER GAS STUDIES

EXPERIMENTAL REPORT

DOCUMENT NO:	**80065-BOR-TN-X-700**
REVISION:	**0**
DATE:	**05 September 1999**

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ACN No: 052 291 264

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-	28-06-99	For Internal Document Control	S. Chia B. Gourlay	S. Chia	-
A	05-08-99	Issued for Client Comment	S. Chia B. Gourlay	S. Chia	R. Raman
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Title:
Boral Energy
Use of ER12 Hydrocarbon Refrigerants in Automobile Air-Conditioners
Tracer Gas Studies – Experimental Report

QA Verified: J.Brini		**Date:** 5.9.99

CONTENTS

LIST OF APPENDICES

LIST OF TABLES

ABBREVIATIONS

Abbreviation	Explanation
ACH	air exchange rate
CO_2	carbon dioxide
Expt No.	Experiment Number
g	grams
g/mole	grams per mole
hr	hours
HSE	Health Safety Executive (U.K.)
kg	kilograms
km	kilometres
L	litres
m	metres
m^3	cubic metres
min	minutes
n/a	not applicable
°C	degrees Celsius
ppm	parts per million
s	seconds
V_s	wind speed
W/m^2	Watts per square metre

1. ABSTRACT

A set of fifteen experiments were conducted to determine the characteristic air exchange rate (ACH) of stationary vehicles located in an enclosure and in an open area. A tracer gas method using carbon dioxide was used to determine the concentration versus time profile. Each test was conducted with the air system in the vehicle under closed/ recirculating mode.

Tracer gas was mixed with the bulk air in the passenger vehicle cabin and its concentration was measured as it decayed with time as a consequence of infiltration of air into the vehicle. Complete mixing of the tracer gas within the passenger vehicle cabin was found to occur within 2 to 20 minutes of release. The concentration versus time profile was found to be exponential and the ACH could be calculated by a first order equation. Predicted values of ACH could then be used in modeling the likely refrigerant concentration in a car cabin following a leak.

The trials demonstrated that in the absence of significant wind effects (< 1 m/s), this caused an appreciable effect on ACH from thermal or temperature effects.

In general, for vehicles located in an open area the ACH value increased with increasing ambient temperature and from direct sunlight. Vehicles exposed to direct sunlight exhibited a higher ACH than the same vehicle located in the shade. Further, early model vehicles (by virtue of present leak paths) exhibited a higher ACH value than for late model vehicles. The average ACH value for late model vehicles was found to be 0.7 hr^{-1} whilst early model vehicles yielded a value of 1.1 hr^{-1}. A correlation relating ACH with internal cabin temperature was developed from experimental data.

The ACH values for vehicles inside a well sealed enclosure (with no wind currents) were found to be very similar, on average, 0.3 hr^{-1}. These results showed that the ACH value would be similar regardless of type and age of vehicle.

A rule set was developed for use of ACH values for vehicles located in an enclosure or an open area for risk assessments. A recommendation has been made to repeat these field trials under summer conditions to further examine the dependency of ACH on temperature. It was surmised that under high ambient temperatures, the ACH value should be relatively high. Hence, the use of the present ACH values in risk assessment studies may be considered to be conservative and pessimistic.

2. INTRODUCTION

2.1 General

This technical report has been prepared by Granherne to accompany the Safety Case report (Ref.1) investigating the use of hydrocarbon refrigerant in passenger vehicles. Tracer gas studies were conducted to determine the ACH between stationary passenger vehicles and their surroundings. Field tests considered vehicles positioned within an enclosure and in an open area. The latter was exposed to wind and temperature effects.

The field test results were compared with ACH values derived from previous experiments that were conducted by the U.K. Health and Safety Executive (Ref.2) and the University of Adelaide (Ref.3).

The ACH parameter is a necessary modeling input in estimating the concentration time profile in a passenger vehicle following a leak of refrigerant into the car cabin. This report contains details of the methodology, results and discussion of the tracer gas studies.

2.2 Objectives and Scope of Field Study

2.2.1 Objectives of Study

The objectives of the tracer gas experiments were to:

- determine the concentration time decay profile of tracer gas in a stationary vehicle located (a) inside an enclosure, and (b) in an open area;
- determine the concentration time decay profile for new and old passenger vehicles;
- determine the exchange rate for each passenger vehicle using a first order decay relationship;
- investigate if there are any relationships for exchange rates when passenger vehicle is located inside or outside an enclosure;
- ensure that tests conducted were reproducible; and
- prepare a technical report that can then be used as an input into the Safety Case.

2.2.2 Scope of Study

The experimental work was conducted by Granherne personnel at the Department of Chemical Engineering of the University of Sydney. Trials were conducted from 15 until 18 June 1999. Tracer gas studies were conducted on five (5) different car types.

3. METHODOLOGY

3.1 General

The purpose of this section is to outline the:

- equipment used in the tracer gas studies including the calibration of the gas detector (**Section 3.2**);
- vehicles used in the study (**Section 3.3**); and
- experimental methodology (**Section 3.4**).

3.2 Equipment Used in Study

The equipment that was used in the tracer gas experiments is listed in **Table 3.1**.

TABLE 3.1
EQUIPMENT USED IN THE EXPERIMENTAL WORK

Equipment	Description	Specifications
Fuji ZFP-5 I.R. CO_2 Analyser	Gas detector for carbon dioxide	- non-dispersive infrared ray system - measuring range 0-5000ppm - indication accuracy +/- 10% - response approximately 10s - sampling flow rate ~ 1 L/min
A&D Scales	Scales	30kg by 0.1g
Carbon dioxide	Gas cylinder	Size "D"
WeatherMaster 2000	Weather Station	- air temperature –15 to 50°C, 0.2% accuracy - relative humidity 10 to 90%, 5% accuracy - wind speed 1km/h starting threshold - wind direction 6 degree resolution, accuracy 3% - solar radiation +/- 5%

Each piece of equipment is described below in more detail and its use in the experimental procedure is also described.

3.2.1 Fuji ZFP-5 I.R. CO_2 Analyser

The Fuji carbon dioxide analyser uses infrared methods to analyse the incoming gas stream for carbon dioxide content. The carbon dioxide concentration is reported in parts per million (ppm) within the range of 0 to 5000 ppm.

This instrument was used to measure, at various time steps, the concentration of carbon dioxide inside the car passenger cabin.

The gas analyser was calibrated before hire using nitrogen to determine the zero gas reading. Readings of ambient carbon dioxide levels were also taken at the commencement and finish of the calibration procedure (400 ppm and 395 ppm respectively).

The ambient levels of carbon dioxide in the car passenger compartments at the start of each experiment varied between 420 and 570 ppm. This value was noted for each experiment.

3.2.2 Scales

The digital scales were used to calculate the mass of tracer gas released into the car. The gas cylinder was placed on the scales before the gas release and the weight of the cylinder was noted. The correct amount of gas (approximately 20g) was then released by taking the weight of the cylinder down to a pre-determined value.

3.2.3 Tracer Gas

Carbon dioxide was used as the tracer gas in these studies. It has been used as a tracer gas in many studies especially in determining concentration time decay profiles. The background level of carbon dioxide was noted at the beginning of each experiment in each car.

3.2.4 WeatherMaster 2000

The weather station that was used for the experiments can measure the following parameters:

- temperature;
- relative humidity;
- wind speed;
- wind direction;
- solar radiation; and
- rainfall.

The weather station was used to record the ambient weather conditions each day (Experiments 2 – 15). At the end of each day, collected data from the internal logger was downloaded onto computer for analysis.

3.3 Vehicles Used in Study

Five car types were investigated in the experiments as shown in **Table 3.2**.

TABLE 3.2
CAR TYPES AND VOLUMES

Car Type	Year	Car Passenger Cabin Volume (m^3)	Experiment No.
Toyota Corolla SECA CSX	1986	3.21	1, 3, 4
Ford Laser	1987	3.1	2, 5, 7, 9, 11, 15
Mitsubishi Verada	1998	3.81	6, 10, 14
Honda Civic	1995	2.95	13
Holden Commodore Wagon	1998	6.4	8, 12

The Corolla, Laser and Honda Civic were hatchbacks, the Verada a sedan and the Commodore a wagon. The Commodore, Verada and Honda Civic are significantly newer cars than the Laser and Corolla.

The cars were grouped according to age with the earlier model cars (before 1988) making one group (Laser and Corolla) and the later model cars (after 1988) making the other (Commodore, Verada, Honda Civic).

3.4 Experimental Methodology

The trials were conducted both inside a "garage" and in an open outside area to simulate passenger vehicles parked in a garage and cars parked on the street. The experimental procedure for both scenarios was similar. Photographs of the experimental setup may be found in **Appendix II**.

The following methodology was adopted for measuring the concentration time decay profile:

3.4.1 Preliminary

1. Air vents in passenger vehicle were closed.
2. All garage doors were closed to minimise the potential of any wind effects flowing through the garage.
3. Ambient weather conditions were noted via the weather station.

4. For vehicles in the open area, a thermometer was placed in the car cabin.

5. Tracer gas tubing was secured at gear stick level to simulate a release of refrigerant into the car cabin. The tubing was then passed under the door seal and checked that air flow could be permitted. Visual check was also made that the door was still sealed.

6. Gas detection tubing was secured in the rear to ensure passenger side and passed through the door seal. This tubing was checked that air flow could be permitted. A visual check was made to ensure that the door was still sealed.

7. The gas bottle was then placed on the digital scales and the delivery line secured to the gas bottle. The initial mass of the gas bottle was recorded.

8. The gas detector tubing was then hooked into the Fuji unit and turned on. Background level of carbon dioxide in the car passenger cabin was noted.

3.4.2 Release and Measurement of Tracer Gas

9. A pre-determined amount of gas was then released into the passenger cabin. The release duration and the final mass of the gas bottle were recorded.

10. The tracer gas concentration was then recorded at set time intervals.

11. The experiments were recorded until sufficient experimental data had been obtained from each passenger vehicle to allow calculation of the respiration time.

12. The experiment was terminated by opening the car doors and the decay in tracer concentration was recorded.

13. All vehicles tested were purged with fresh air from the surrounds prior to commencement of the next experiment.

4. RESULTS AND DISCUSSION

4.1 Tracer Gas Results

Granherne conducted a total of fifteen tracer gas experiments. The raw data sets comprising the measured tracer gas concentration at the various time steps and ambient conditions collected by the weather station are shown in **Appendix III** and **Appendix IV** respectively.

A summary of the weather conditions is shown in **Table 4.1**.

TABLE 4.1
SUMMARY OF AMBIENT CONDITIONS OF SURROUNDINGS

Expt No.	Car	Location	Avg Ambient Temp (^{o}C)	Avg Wind Speed (m/s)	Avg Solar Radiation (W/m^2)
1	Corolla	Inside	15.8	n/a	n/a
2	Laser	Inside	14.2	n/a	n/a
6	Verada	Inside	13.8	n/a	n/a
13	Honda Civic	Inside	15.6	n/a	n/a
3	Corolla	Outside	15.3	0.05	231
4	Corolla	Outside	13.4	< 0.01	5.3
5	Laser	Outside	12.0	< 0.01	162
7	Laser	Outside	15.8	0.01	291
8	Commodore	Outside	15.4	< 0.01	5.1
9	Laser	Outside	14.6	< 0.01	3.0
10	Verada	Outside	16.6	0.05	287
11	Laser	Outside	17.3	0.08	286
12	Commodore	Outside	18.2	0.11	268
14	Verada	Outside	18.1	0.08	13.8
15	Laser	Outside	17.8	0.06	258

Note:
n/a denotes not applicable to the experiment

The following observations were made from **Table 4.1**:

- The temperature within the enclosure or "garage" was lower by at least two degrees than the corresponding outside temperature except during the evenings. The temperatures were approximately equal during these periods.
- There was no wind current through the enclosure and it could be assumed to be well sealed.

- The wind speed was almost negligible (< 0.1 m/s) for each day, giving almost still conditions for the outside experiments.

- The solar radiation varied with the time of day and also with the amount of cloud cover present.

The derived air exchange time and ACH from the experimental data is presented in **Table 4.2**. Details are presented in **Appendix IV**.

TABLE 4.2
EXPERIMENTAL RESULTS

Expt No.	Car	Location	Time of Experiment	Air Exchange Time (hour)	Air Exchange Rate (m^3/hr)	Temp (inside car, ^oC)
1	Corolla	Inside	13:40 to 17:40	10.6	0.30	-
2	Laser	Inside	11:00 to 17:30	12.0	0.26	-
6	Verada	Inside	9:50 to 17:10	12.0	0.32	-
13	Honda Civic	Inside	11:40 to 17:40	14.0	0.20	-
3	Corolla	Outside	12:00 to 14:30	2.6	1.2	-
4	Corolla	Outside	14:40 to 17:10	4.3	0.74	-
5	Laser	Outside	8:40 to 11:10	1.7	1.8	-
7	Laser	Outside	11:20 to 14:20	2.3	1.4	-
8	Commodore	Outside	14:45 to 16:55	11.2	0.54	-
9	Laser	Outside	15:12 to 17:42	8.2	0.38	-
10	Verada	Outside	8:35 to 12:27	4.7	0.81	-
11	Laser	Outside	9:25 to 12:55	2.1	1.5	22.3
12	Commodore	Outside	10:30 to 13:50	6.8	0.89	20.6
14	Verada	Outside	13:15 to 17:00	5.4	0.71	-
15	Laser	Outside	14:10 to 17:10	2.7	1.1	19.6

Detailed discussion of the above results is given in the following sections.

4.2 Discussion

4.2.1 Mixing Period

A review of the raw data and corresponding profiles in **Appendix III** displays a gradual decay of tracer gas concentration over time having reached a peak concentration. In order to derive the air exchange rates, it was assumed that the concentration of the tracer gas was well mixed in the passenger vehicle.

The validity of this assumption was verified in two ways:

1. The gas analyser was placed at various locations in the rear of the passenger cabin to monitor the tracer gas concentration.

2. The gas concentration versus time profile as measured by the Fuji revealed that there was a distinct period when the tracer gas was mixing. This was represented by near uniform concentration level.

In all fifteen tests, the raw data showed that for the first 2 to 20 minutes following release, the tracer gas rose to a maximum value that corresponded fairly closely to the predicted peak value. Some fluctuation between the predicted and measured value is expected to occur within the tolerance imposed by the accuracy of the scale.

The following additional observations are made:

- The initial concentration does not influence the respiration parameters calculated, however, it is useful to start close to the target concentration to make sure that the detection systems area operated within their calibrated range.

- The stepped increases and decreases in this initial period have been suggested to be from "slugging" of the tracer gas as it slowly diffused and mixed with the bulk air inside the passenger cabin.

- The raw data showed a jagged plateau whereby the tracer gas concentration was fairly constant within a certain band. This period varied between 2 to 20 minutes and further validated the assumption of a well mixed volume in the passenger compartment.

Therefore it can be seen that a release of tracer gas whose molecular weight (44 g/mole) is heavier than air (29 g/mole) will result in a uniform concentration in a short period of time.

4.2.2 Air Exchange Rates Inside Enclosure

A literature review has found that there has been scarcely any work conducted on determining ACH values for vehicles located inside an enclosure such as a garage. It has been postulated that such ACH values would be lower than those values for vehicles parked in an open area due to the absence of wind effects. The wind effect has the effect of enhancing air exchange between the vehicle and surrounds through pressure effects.

A summary of the air exchange values is reproduced in **Table 4.3** (as taken from **Table 4.2**). The following observations are made from these tables:

- Air exchange times are similar for all inside experiments (10.6 to 14 hours), independent of car type.

- When the car volume is considered, the resulting ACH values are low (< 1 ACH) with an average ACH value of 0.27.

TABLE 4.3
ACH VALUES FOR VEHICLES INSIDE AN ENCLOSURE

Parameter	**Average Value**	**Standard Deviation**
Average air exchange volumetric rate	12.1 m^3/hr	1.4
Air exchange rate (ACH) value	0.27 hr^{-1}	0.051

These values were considered appropriate given that the enclosure was near sealed and had very little wind currents to influence the infiltration rate into a vehicle and hence cause an appreciable exchange of tracer gas with the ambient air.

Further, the tests were conducted in winter and the absence of a high temperature driving force also contributed to the low exchange rates. It is recommended that these trials be repeated under summer conditions to further examine the influence of temperature on ACH in enclosures. It is postulated that the air exchange rate would increase in high temperature conditions.

4.2.3 Air Exchange Rates in Open Area

As no significant effect on wind direction and strength was present during the course of the experiments, the exchange rate between the passenger vehicle cabin and its surrounds was postulated to be dependent on temperature effects.

A summary of the air exchange values is reproduced in **Table 4.4** (as taken from **Table 4.2**).

TABLE 4.4
ACH VALUES FOR VEHICLES IN OPEN AREA

Parameter	**Average Value (hr^{-1})**	**Standard Deviation**
Overall	1.01	0.44
Late model vehicles (> 1988)	0.74	0.15
Early model vehicles (< 1988)	1.17	0.49

The following general observations are made from these tables:

- The ambient temperature for all days was within the range of 12.0°C to 18.4°C. In general, for the outside experiments, the air exchange rate increased for higher ambient temperatures.
- As expected, for the same ambient temperature, the temperature within the passenger vehicle cabin was higher when the vehicle was exposed to direct sunlight than if it was located in the shade. For example, the ACH value was higher for vehicle parked in the sunlight as shown in experiment 11 than when it was in the shade as shown in experiment 9.
- Vehicles displayed a wide variation in ACH values for all outside experiments (1.7 to 11.2 hours).
- Experiments carried out in the early afternoon/ evening experienced longer air exchange times than those conducted earlier in the day. This was readily explained since during the morning experiments vehicles were influenced by direct sunlight and hence experienced higher ACH values. This confirms that the ACH value in the absence of wind is influenced directly by temperature effects.
- This statement was further reinforced by experiments (8, 9, 12) conducted on vehicles parked in shade or early evening exhibited ACH value close to experiments conducted in the enclosure.

Upon further inspection of the results, it was found that there was a clear demarcation in ACH values between late model and early model passenger vehicles. As expected, early model vehicles exhibited a higher ACH value than late model cars due to the presence of pronounced leak paths. Typical leak paths in vehicles are around door seals, opening between cabin and the boot.

4.2.4 Comparison with Previous Studies

Wind Effects

Previous studies have focussed on determining the ACH values for vehicles (with vents in the closed position) parked in an open area. In the U.K. Health Safety Executive (HSE) tests, it was concluded that the ACH rate was primarily influenced by wind effects as no significant temperature difference was noted during the course of the experiments. For a late model vehicle (Renault 21 and Nissan Micra), the HSE found that ACH varies with wind speed (V_s) by $V_s^{1.15}$. This was also confirmed by a study conducted at Adelaide University.

TABLE 4.5
ACH VALUES DOMINATED BY WIND EFFECTS

Wind Speed (V_s) m/s	Air Exchange Rate (ACH) hr^{-1} (HSE)	Air Exchange Rate (ACH) hr^{-1} (Adelaide University)
1	1.1	
1.5	1.6	2.6
2	2.2	
2.5	2.9	
3	3.5	3.2
3.5	4.2	3.7

Temperature Effects

The wind conditions at the time of these trials in winter were observed to be weak varying from 0.01 to 0.11 m/s. Using the HSE correlation, this would give corresponding ACH values of 0.005 hr^{-1} and 0.07 hr^{-1}. These values are lower than those derived from the current trials. Therefore, another mechanism has influenced the ACH rate and this has been attributed to temperature. (Note: The HSE correlation is valid only to wind speeds down to 1 m/s).

Using data collected for vehicles directly influenced by sunlight, a correlation was developed whereby the ACH changed with an increase in temperature. This correlation is valid for a temperature range between 13°C and 22°C (typical Sydney winter conditions) and when there is little wind. If the wind speed is higher than 1 m/s, then the HSE correlation should be used as this becomes the dominant mechanism. A summary is provided in **Table 4.6**.

TABLE 4.6
ACH VALUES DOMINATED BY TEMPERATURE EFFECTS

Ambient Temperature in Cabin °C	Air Exchange Rate (ACH) hr^{-1}
$ACH = 0.158\ T[^\circ C] - 1.993$ $(13 < T < 22,\ V_s < 0.1$ m/s$)$	
13	0.06
15	0.38
17	0.69
19	1.01
21	1.32

4.2.5 Reproducibility of Experiments

The experiments were found to be reproducible in terms of method and results. In particular, experiments 5, 7 and 11 were conducted at similar times of the day and displayed results that were consistent. Hence it was concluded that the trials were conducted under conditions that could be reproducible.

4.3 Safety Case Considerations

4.3.1 General Comments

It was then possible to develop a rule set for ACH values to be used in the Safety Case study of hydrocarbon refrigerant use in passenger vehicles. In terms of the concentration modeling within the cabin, the derived ACH values were treated as conservative and pessimistic as they reflect winter conditions. A recommendation to repeat these trials under summer conditions has been made in this report.

4.3.2 Scenarios to Consider

For the purposes of the study, the Safety Case should consider the likely situations when the passenger vehicle is:

- parked in a garage, and
- parked in an open area.

4.3.3 ACH Values to be used in Assessment

Based upon the field trials conducted in this present study and past work by other institutions, the following ACH values are suggested for use in the Safety Case as presented in **Table 4.7**.

TABLE 4.7
ACH VALUES TO USE IN SAFETY STUDY

Situation	Car Type	Minimum ACH Value (hr^{-1})	Comment
Vehicle parked in enclosure (winter day and evening)	Late Model	0.3	Experimental
	Early Model	0.3	Experimental
Vehicle parked in open area (winter day and evening)	All models	1.0	Experimental/ HSE
	Late Model	0.7	Experimental/ HSE
	Early Model	1.1	Experimental/ HSE

5. CONCLUSIONS

The results and discussion in **Section 4** leads to the following conclusions with regard to the experimental results:

5.1 Mixing Inside Cabin

The experiments have clearly shown that upon release of a gas (carbon dioxide, molecular weight 44 g/mole) that is heavier than air (molecular weight, 29 g/mole), it will be well mixed in the cabin within 2 to 20 minutes.

5.2 ACH Parameter for Vehicle in Enclosure

For the experiments conducted inside the garage enclosure, the air exchange rates were similar for all experiments. The average value was 0.27 m^3/h and the car type did not affect the results significantly. It was concluded that when cars are parked inside an enclosure, the air exchange rate does not vary with the age or "sealing state" of the car.

5.3 ACH Parameter for Vehicle outside Enclosure

The ACH value will vary depending on the age of the car and the temperature inside the car cabin. For the former, early model vehicles (such as the Laser and Corolla used in these tests) had higher exchange rates than late model vehicles (such as the Commodore and Verada used in these tests). It is postulated that this is due to the better sealing of newer cars than older vehicles.

In the absence of, or weak wind effects, temperature was found to be the driving force influencing the ACH. Vehicles exposed to direct sunlight exhibited higher ACH than vehicles parked in the shade. Further in the absence of solar radiation (i.e. early evening), the ACH values approached those values determined for vehicles inside the enclosure. However, as there are some wind effects in the open area, albeit weak, these ACH values were slightly higher than those values in the enclosure.

A correlation has been developed that relates ACH with cabin temperature for a limited range between 13°C and 22°C corresponding to typical Sydney winter days where there is no wind. If wind is present at velocity greater than 1 m/s, the HSE correlation should be used.

A rule set has been provided in this report for ACH values to be used in the Safety Study for estimating the concentration versus time profile following a leak of refrigerant into the car cabin.

5.4 Recommendations

The trials have been conducted during winter when ambient temperatures and wind speeds were low. It is strongly recommended that these field trials be repeated in summer when ambient conditions are higher and temperature effects may be investigated further. It is postulated that the ACH value will be higher for summer than winter conditions. In terms of the Safety Case, this may have an effect on the resulting refrigerant concentration level in the passenger vehicle cabin following a leak.

6. REFERENCES

1 Granherne Pty Ltd (1999), "Use of Hydrocarbon Refrigerants in Automobile Air-Conditioners, Safety Report", Document No. 80065-BOR-RT-X-500.

2 Fletcher, B., Sanders, C.J., (1994), "Air Change Rates in Stationary and Moving Motor Vehicles", Journal of Hazardous Materials, 38, pp 243-256.

3 Crowe, A., (1999), "Measurement of Air Exchange Rate of Stationery Vehicles and Estimation of In-vehicle Exposure", thesis, University of Adelaide.

APPENDIX I

CALIBRATION CERTIFICATE FOR GAS ANALYSER

EnviroRent pty. ltd.

CUSTOMER COPY

CALIBRATION CERTIFICATE FOR FUJI ZFP-5 I.R. CO2 ANALYSER.

ASSET: # 0176

ZERO GAS: N2 ultra-pure
ZERO GAS READING: 0ppm
Gas Bottle Number: ALWA 0443

☑ SPAN CHECK SET: 650 ppm

INITIAL AMBIENT READING
= 400 ppm

FINAL AMBIENT READING
= 395 ppm

2/6/99

☐ MELBOURNE:
3/14 APOLLO CRT
BLACKBURN 3150
PH: (03)98941808

☑ SYDNEY:
8/20-30 STUBBS ST
SILVERWATER 2141
PH: (02)97480977

☐ BRISBANE:
12B THE CORSO
NORMAN PARK 4170
PH:(07)38995199

☐ PERTH:
3/30-34 ADAMS DRV
WELSHPOOL 6106
PH:(08) 9472 7311

APPENDIX II

EXPERIMENTAL SETUP

PHOTOGRAPHS

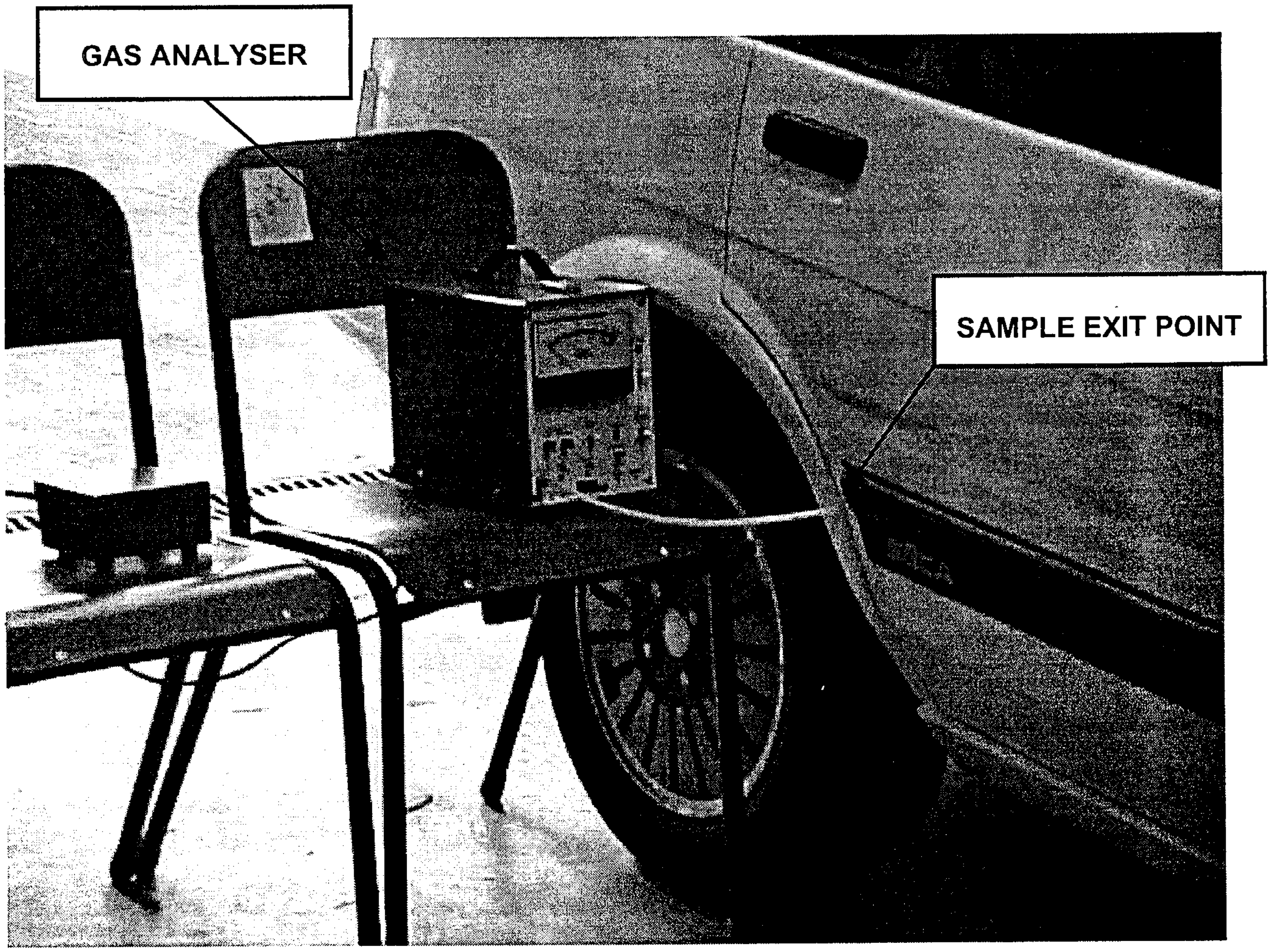


FIGURE AII.1
GAS ANALYSER SHOWING TUBING FROM INSIDE COROLLA

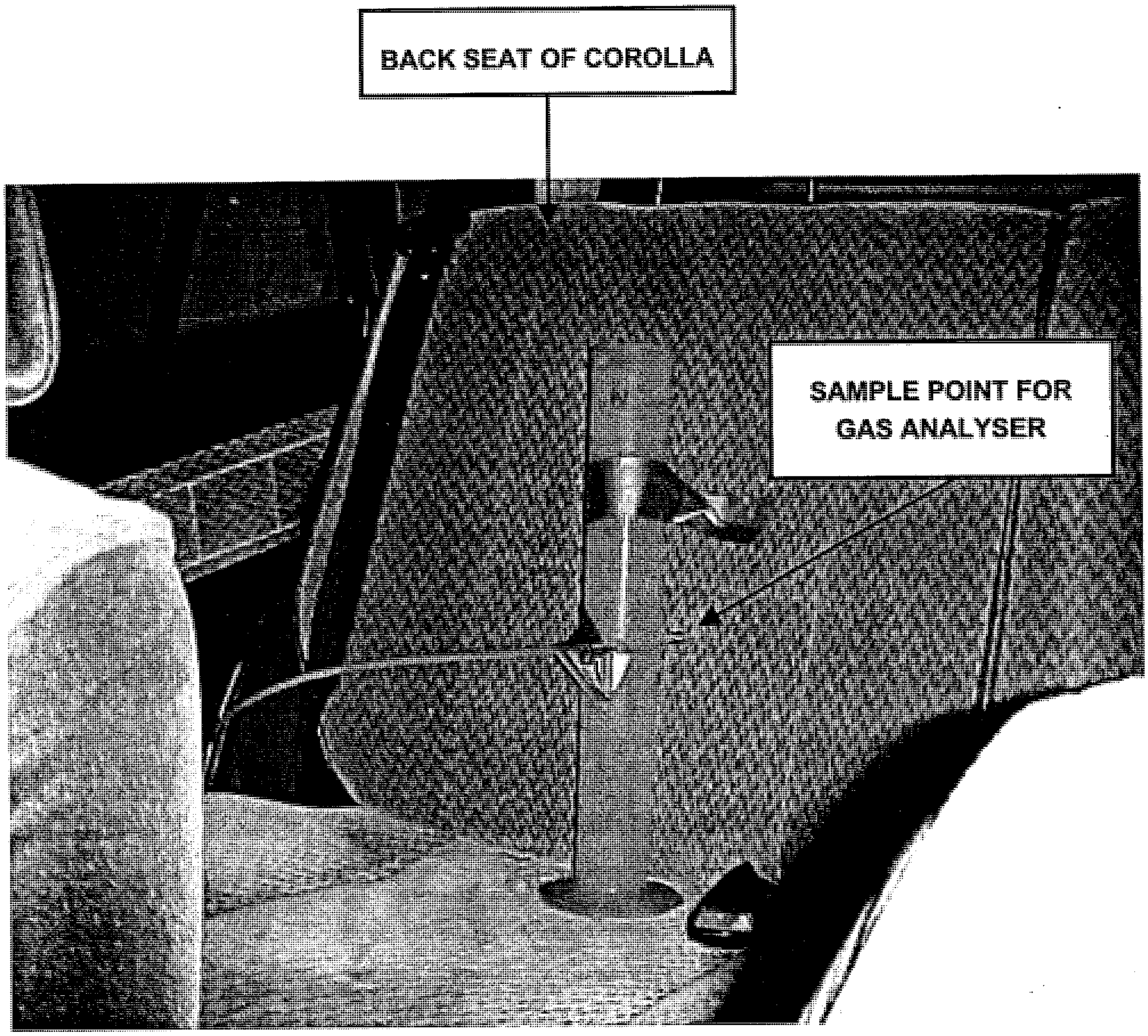


FIGURE AII.2
INSIDE COROLLA SHOWING LOCATION OF GAS ANALYSER TUBING SAMPLE POINT

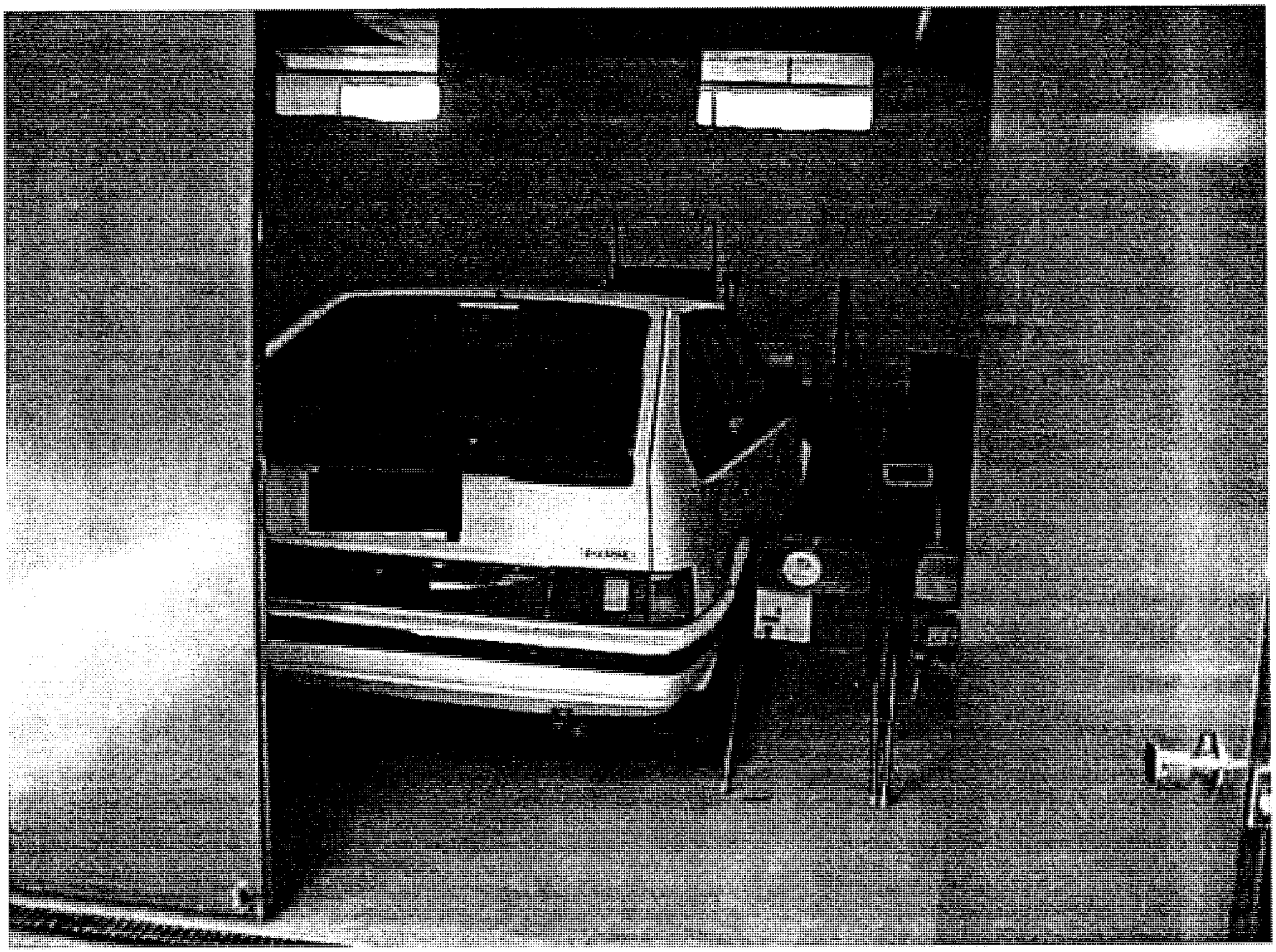


FIGURE AII.3
VIEW OF COROLLA IN "GARAGE"

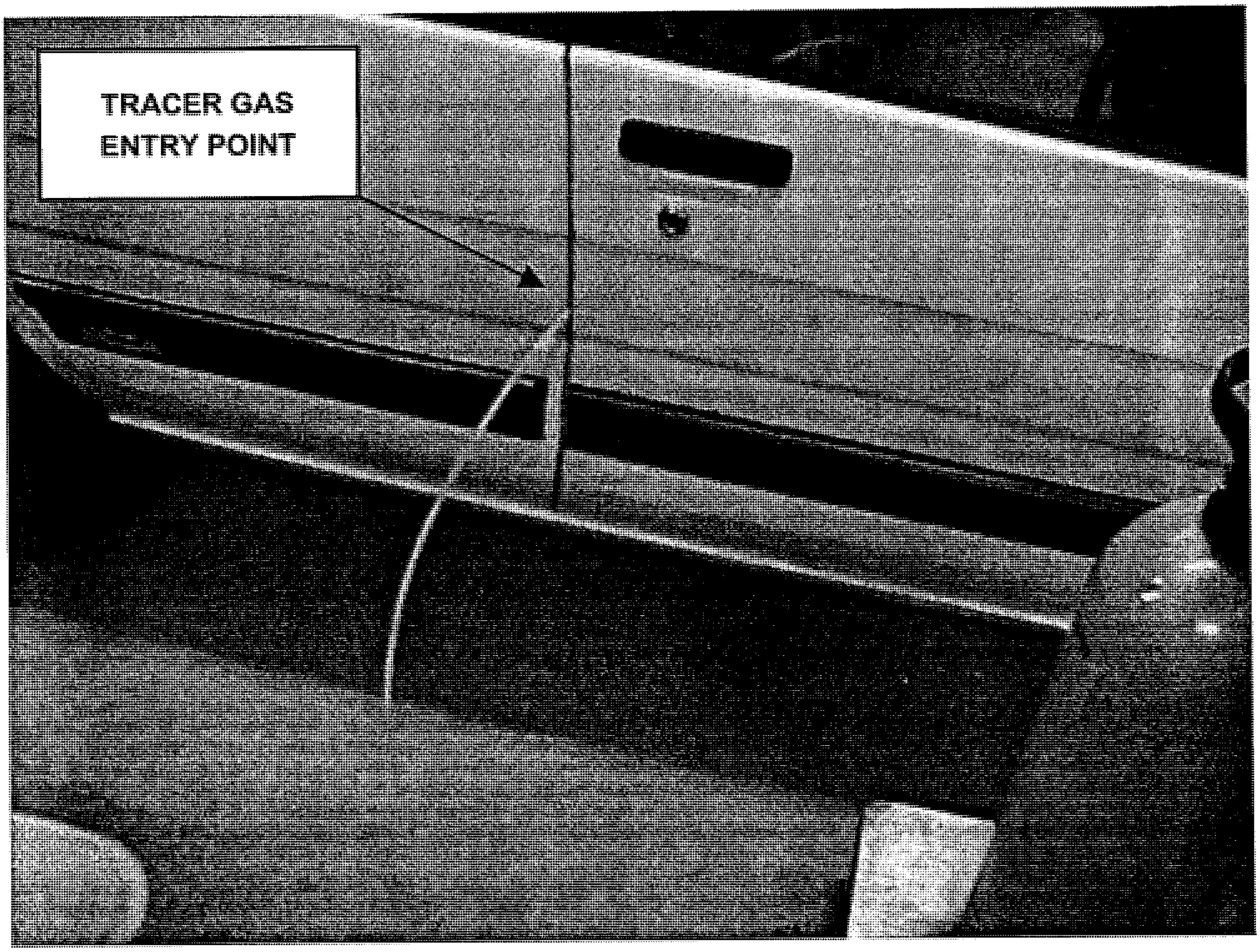


FIGURE AII.4
VIEW OF TRACER GAS TUBING ENTRY POINT TO COROLLA

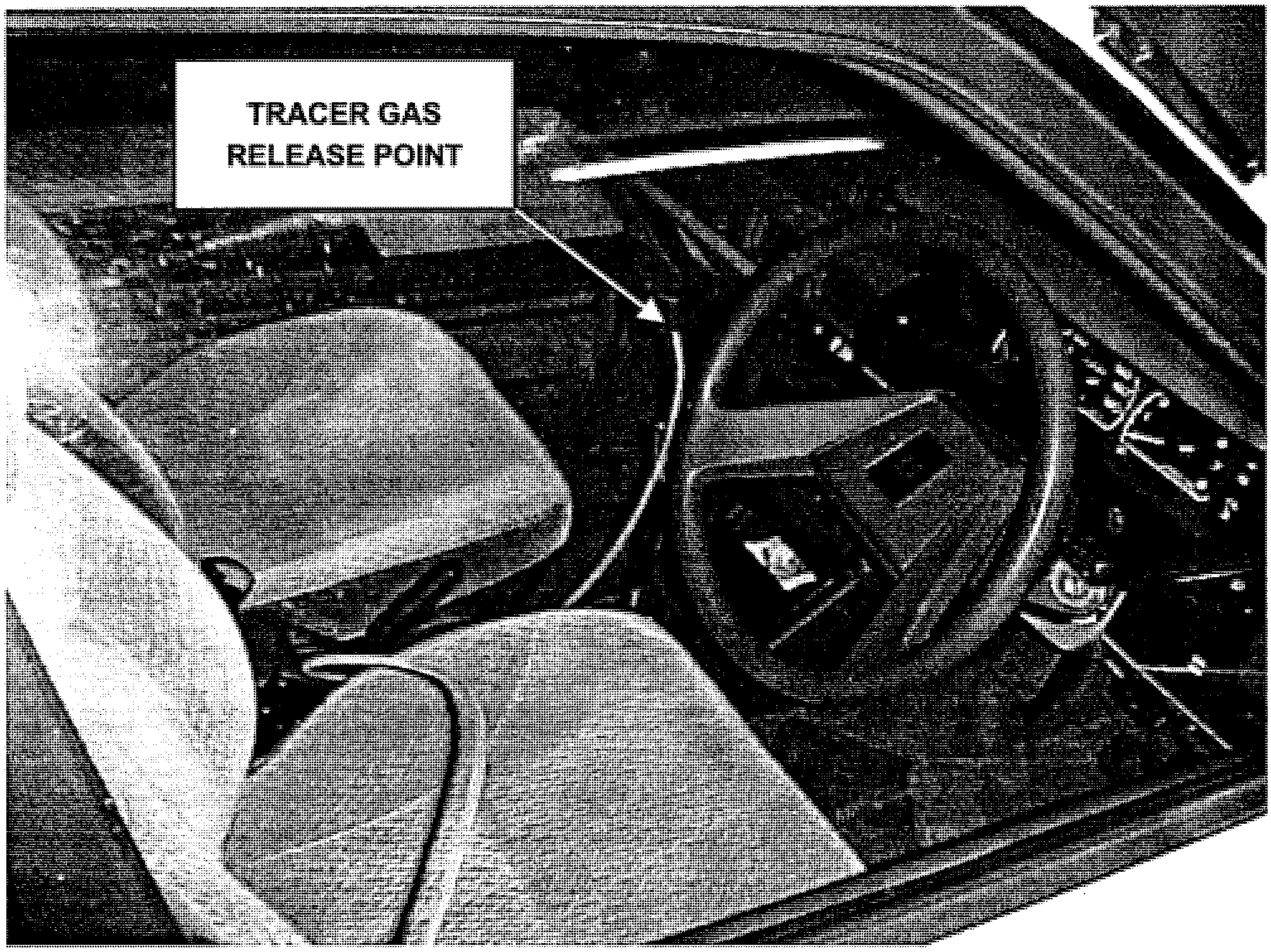


FIGURE AII.5
INSIDE COROLLA SHOWING TRACER GAS EMISSION POINT

FIGURE AII.6
VIEW OF COROLLA FOR OUTSIDE EXPERIMENTS

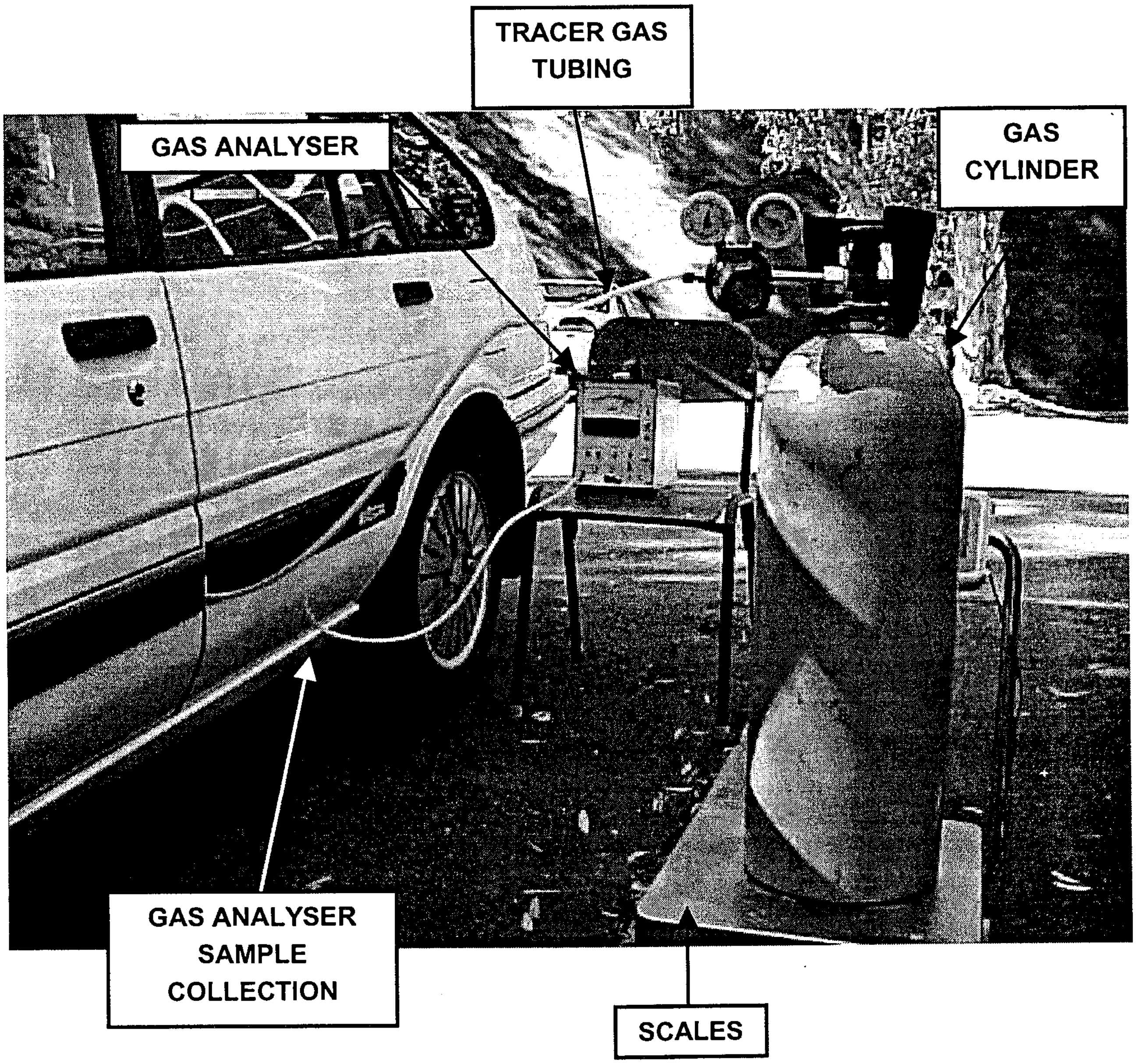


FIGURE AII.7
VIEW OF COROLLA WITH EXPERIMENTAL EQUIPMENT

FIGURE AII.8
VIEW OF WEATHER STATION

APPENDIX III

RAW EXPERIMENTAL DATA

Experiment 1

Car Corolla
Location Inside

Time min	Concn ppm	Temp (inside room) deg C
0	570	16
0.5	570	
1	4000	
1.5	3000	
2	3000	
2.5	2600	
3	2600	
3.5	2500	
4	2950	
4.5	3500	
5	3600	
6	3600	16.4
7	3600	
8	3550	
9	3500	
15	3400	
20	3250	
25	3200	15.8
30	3100	
40	3000	
50	3000	
60	2950	15.8
70	2950	
80	2900	
90	2850	15.7
100	2800	
110	2800	
120	2800	
150	2700	15.5
180	2600	15.6
210	2550	
240	2450	15.2
Doors Opened:		
240.5	2450	
241	2400	
241.5	1700	
242	1400	
242.5	1100	
243	850	
243.5	700	
244	570	

Experiment 2

Car Laser
Location Inside

Time min	Concn ppm	Temp (inside room) deg C
0	470	15.4
0.5	470	
1	470	
2	470	
3	530	
4	700	
5	850	15.6
6	1300	
7	1650	
8	2150	
9	2000	
10	2300	15.2
15	2700	15.2
20	3200	15.2
25	3200	15
30	3100	14.8
40	2950	14.6
50	2900	14.6
60	2800	14.8
90	2750	14.7
120	2600	14.8
150	2500	14.8
180	2400	14.7
210	2300	14.6
240	2200	14.6
270	2150	15.4
300	2100	15.2
330	2000	14.8
360	1900	14.8
390	1850	14.6
Doors Opened:		
390.5	1850	
391	1500	
391.5	1000	
392	750	
392.5	650	

Experiment 3

Car Corolla
Location Outside

Time min	Concn ppm
0	500
0.5	600
1	4600
1.5	3700
2	2900
2.5	3000
3	3000
3.5	3200
4	3400
4.5	3600
5	3650
6	3750
7	3750
8	3700
9	3650
10	3600
15	3350
20	3200
25	3050
30	2950
40	2750
50	2550
60	2400
90	1970
120	1680
150	1550
Doors Opened:	
151	1550
151.5	1500
152	1500
152.5	1450
153	800
153.5	470

Experiment 4

Car Corolla
Location Outside

Time min	Concn ppm
0	450
0.5	450
1	3600
1.5	4200
2	4000
2.5	3150
3	2800
3.5	3400
4	3400
4.5	3350
5	3350
6	3600
7	3900
8	3900
9	3950
10	3900
15	3700
20	3600
25	3500
30	3400
40	3250
50	3100
60	3000
90	2700
120	2500
150	2250
Doors Opened:	
154	2200
154.5	2200
155	1300
155.5	1050
156	550
156.5	500

Experiment 5

Car Laser
Location Outside

Time min	Concn ppm
0	500
0.5	1800
1	4800
1.5	2400
2	3000
2.5	3400
3	3700
3.5	3700
4	3800
4.5	3800
5	3800
6	3750
7	3700
8	3650
9	3600
10	3500
15	3300
20	3000
25	2850
30	2700
40	2450
50	2250
60	2050
90	1580
120	1180
150	900

Experiment 6

Car Verada
Location Inside

Time min	Concn ppm	Temp (inside room) deg C
0	450	12.9
0.5	450	
1	3400	
2	3600	
3	3900	
4	3900	
5	4000	
6	4000	
7	4000	
8	4000	
9	3950	
10	3800	
15	3700	13.4
20	3600	
25	3550	13.5
30	3500	13.4
40	3400	13.5
50	3200	
60	3150	13.6
90	2950	13.6
120	2800	13.6
150	2650	13.9
180	2550	14.1
240	2400	14
270	2350	14.4
308	2300	14.3
342	2250	14.2
370	2200	14.3
400	2150	14.5
430	2120	14.7
440	2100	14.7
Doors Opened:		
440.5	2050	
441	2050	
441.5	1950	
442	1450	
442.5	1350	
443	1200	
443.5	1250	
444	850	
444.5	750	
445	700	

Experiment 7

Car Laser
Location Outside

Time min	Concn ppm
0	450
0.5	8400
2.5	5000
3	5000
3.5	4800
4	4650
4.5	4550
5	4400
6	4350
7	4200
8	4100
9	4000
10	3950
15	3750
20	3600
25	3500
30	3400
40	3250
50	3100
60	2900
90	2200
120	1760
150	1500
180	1280
Doors Opened:	
181	1260
181.5	1250
182	1050
182.5	800
183	580

Experiment 8

Car Commodore
Location Outside

Time min	Concn ppm
0	500
0.5	500
1	2800
1.5	3500
2	3200
2.5	3250
3	3600
3.5	2900
4	2900
4.5	2800
5	2750
6	2650
7	2700
8	2700
9	2700
10	2700
15	2650
20	2600
25	2580
30	2550
45	2500
55	2500
65	2400
90	2350
120	2300
130	2200
Doors Opened:	
131	2200
131.5	2100
132	2050
132.5	1800
133	750
133.5	600

Experiment 9

Car Laser
Location Outside

Time min	Concn ppm
0	500
0.5	500
1	4800
1.5	2300
2	1600
2.5	2000
3	2400
3.5	2600
4	3100
4.5	3100
5	3600
6	3600
7	3450
8	3400
9	3500
10	3500
16	3550
20	3500
25	3450
30	3350
40	3200
50	3150
60	3050
90	2900
120	2800
150	2700
Doors Opened:	
151	2700
151.5	1850
152	2100
152.5	1900
153	1700
153.5	1600
154	1000
154.5	800
155	700

Experiment 10

Car Verada
Location Outside

Time min	Concn ppm
0	450
1.5	3150
2	3650
2.5	4200
3	4150
3.5	3950
4	3900
4.5	3900
5	3900
6	3800
7	3750
8	3700
9	3650
10	3650
15	3500
20	3400
25	3350
30	3250
40	3100
50	3000
62	2850
90	2500
120	2300
152	2100
191	1900
232	1800
Doors Opened:	
234	1800
234.5	1150
235	600

Experiment 11

Car Laser
Location Outside

Time min	Concn ppm	Temp (in car) deg C
0	450	
0.5		
1		
1.5		
2		
2.5		
3		
3.5		
4	5000	
4.5	4950	
5	4850	19
6	4700	
7		
8		
9	4400	
10	4300	21
15	3950	22.5
21	3700	24
25	3550	24
30	3400	23.5
40	3250	22.5
50	2900	23
60	2700	22
92	2200	21
120	1700	23.5
152	1380	22
180	1100	21
210	850	23
Doors Opened:		
210.5	850	
211	800	
211.5	600	

Experiment 12

Car Commodore
Location Outside

Time min	Concn ppm	Temp (in car) deg C
0	420	20.5
0.5	420	
1	1400	
1.5	2600	
2	1900	
2.5	2100	
3	2300	
3.5	3200	
4	3400	
4.5	3550	
5	3700	20.5
6	3450	
7	3500	
8	3350	
9	3250	
10	3250	20.5
15	2800	
20	2750	20.5
25	2700	
30	2700	20.5
40	2600	20.5
50	2500	22
60	2450	22
90	2250	21
120	2100	20
150	2000	20
183	1850	20
201	1750	20
Doors Opened:		
202	1750	
202.5	1500	
203	500	

Experiment 13

Car Honda Civic
Location Inside

Time min	Concn ppm	Temp (inside room) deg C
0	450	15.3
1	600	
2	2200	
3	2600	
4	3600	
5	3600	15.7
6	3700	
7	3700	
8	3600	
9	3500	
10	3600	15.7
15	3400	15.6
22	3200	
25	3150	15.5
30	3200	15.6
40	3100	15.7
52	2950	15.5
60	2850	15.4
90	2700	15.5
123	2650	15.4
172	2550	15.4
212	2400	15.5
250	2300	15.6
280	2250	15.6
310	2200	15.7
340	2150	15.8
360	2050	15.5
Doors Opened:		
360	2050	
360.5	2050	
361	1900	
361.5	1550	
362	1650	
362.5	1550	
363	1000	
363.5	1200	
364	800	
364.5	600	

Experiment 14

Car Verada
Location Outside

Time min	Concn ppm
0	450
0.5	4500
1	5000
4	4650
4.5	4500
5	4400
6	4300
7	4300
8	4250
9	4150
10	4050
15	3850
21	3650
25	3500
31	3450
46	3200
50	3150
66	3000
90	2800
120	2600
150	2450
180	2300
210	2150
225	2100
Doors Opened:	
225	2100
225.5	1500
226	750
226.6	550

Experiment 15

Car Laser
Location Outside

Time min	Concn ppm	Temp (in car) deg C
0	400	22
1	2800	
1.5	2400	
2	3000	
2.5	3300	
3	4000	
3.5	3700	
4	3950	
4.5	3900	
5	3850	21.5
6	3800	
7	3750	
8	3700	
10	3700	21
15	3600	21
20	3500	20.5
25	3400	20.5
30	3200	20
40	2950	20
50	2700	19.5
60	2500	19
90	2200	18.5
120	1850	18
150	1550	17
180	1300	16
Doors Opened:		
180	1300	
180.5	1050	
181	650	

APPENDIX IV

WEATHER DATA

Weather Data for 16 June 1999

Time	Air Temp degC	Wind Speed km/h	Wind Dirn deg	Solar Radn W/m^2	Rel. Hum. %
10:30	12.5	0.2	138	49	47.3
10:40	12.7	0.1	54	87	46.7
10:50	12.9	0	132	55	46.4
11:00	13.1	0.1	180	60	46.1
11:10	13.2	0.3	174	65	45.7
11:20	13.4	0.1	210	157	45.5
11:30	13.7	0.2	90	300	44.7
11:40	14.2	0.2	138	701	43.6
11:50	15	0.3	150	707	41.5
12:00	15.7	0.2	198	712	39.8
12:10	16	0.3	114	711	38.1
12:20	16.3	0.1	114	706	37.4
12:30	16.6	0.2	30	699	36.8
12:40	16.6	0.2	150	559	36.6
12:50	16.1	0.2	162	59	37.5
13:00	15.5	0.3	120	51	38.4
13:10	15	0.2	168	43	39.7
13:20	14.8	0.4	132	33	41.1
13:30	14.6	0.2	258	29	41.5
13:40	14.6	0.3	186	27	41.9
13:50	14.6	0.1	90	30	42.2
14:00	14.5	0.1	102	11	42.5
14:10	14.5	0.2	156	6	42.4
14:20	14.5	0.1	150	6	42.7
14:30	14.4	0.1	240	9	43.1
14:40	14.4	0	258	7	43.4
14:50	14.3	0.2	168	9	43.2
15:00	14.2	0	132	8	43
15:10	14.1	0	300	12	43.9
15:20	14	0	90	10	43.9
15:30	13.9	0	342	6	44.2
15:40	13.7	0	300	4	44.9
15:50	13.6	0	108	3	45
16:00	13.4	0	102	0	45.2
16:10	13.3	0	204	5	45.8
16:20	13.1	0	162	14	46.7
16:30	12.9	0.1	132	6	47.6
16:40	12.7	0	126	0	48.3
16:50	12.4	0	90	0	49.3
17:00	12.2	0	222	0	49.7
17:10	12	0	138	0	49.9
17:20	11.8	0	78	0	50.3
avg	14.07	0.12	156.9	141.8	43.65
max	16.6	0.4	342	712	50.3
min	11.8	0	30	0	36.6

Weather Data for 17 June 1999

Time	Air Temp degC	Wind Speed km/h	Wind Dirn deg	Solar Radn W/m^2	Rel. Hum. %
8:30:00	11.5	0	306	99	49.2
8:40:00	11.3	0	144	271	47.1
8:50:00	11.6	0	162	313	47
9:00:00	11.7	0	156	352	46.4
9:10:00	12	0.1	66	359	45.7
9:20:00	12.1	0	132	139	46
9:30:00	12.2	0	168	114	45.9
9:40:00	12	0	114	158	45.8
9:50:00	11.7	0	96	343	46.4
10:00:00	11.9	0	84	181	46.9
10:10:00	12	0.1	132	50	46.2
10:20:00	11.9	0	120	38	46.7
10:30:00	11.8	0.2	144	45	46.7
10:40:00	12	0	144	63	47.1
10:50:00	12.2	0	180	54	47.1
11:00:00	12.4	0.1	120	65	46.6
11:10:00	12.5	0	72	54	46.5
11:20:00	12.7	0	144	169	46.2
11:30:00	13.1	0	54	324	46.1
11:40:00	14	0.1	156	698	44.9
11:50:00	15.1	0	168	701	42
12:00:00	15.9	0	90	704	39.9
12:10:00	16.4	0	96	702	38.6
12:20:00	16.8	0.1	306	698	37.6
12:30:00	17.3	0.1	96	689	37.3
12:40:00	17.1	0	204	513	37.1
12:50:00	16.7	0.2	330	60	38.6
13:00:00	16.4	0	294	50	39.9
13:10:00	16.2	0	24	41	40.8
13:20:00	16.1	0.1	312	36	41.2
13:30:00	16.1	0	126	24	41.6
13:40:00	16.1	0.3	96	25	41.8
13:50:00	16.1	0	294	20	41.8
14:00:00	16.1	0	114	34	42
14:10:00	16.2	0.1	60	33	42.1
14:20:00	16.2	0	222	5	42
14:30:00	16.2	0	72	4	42.1
14:40:00	16.1	0.1	102	9	42.3
14:50:00	16.1	0	168	4	42.3
15:00:00	15.9	0	252	11	42.3
15:10:00	15.8	0.1	6	6	42.8
15:20:00	15.8	0	126	6	42.8
15:30:00	15.7	0	318	4	43.8
15:40:00	15.6	0	36	3	44.3
15:50:00	15.4	0	108	4	44.9
16:00:00	15.3	0	36	6	45.3
16:10:00	15.1	0	96	7	45.7
16:20:00	15	0	48	9	46.1
16:30:00	14.8	0	78	3	45.3
16:40:00	14.6	0	90	0	45.9
16:50:00	14.3	0	90	0	47.2
17:00:00	14	0	90	0	48.8

Weather Data for 17 June 1999 (continued)

Time	Air Temp degC	Wind Speed km/h	Wind Dirn deg	Solar Radn W/m^2	Rel. Hum. %
17:10:00	13.6	0	90	0	50.4
17:20:00	13.3	0	90	0	51.9
17:30:00	12.9	0	90	0	53.3
17:40:00	12.6	0	90	0	54.8
avg	14.31	0.03	135.75	148.21	44.59
max	17.3	0.3	330	704	54.8
min	11.3	0	6	0	37.1

Weather Data for 18 June 1999

Time	Air Temp degC	Wind Speed km/h	Wind Dirn deg	Solar Radn W/m^2	Rel. Hum. %
8:20:00	12.6	0	96	68	55.1
8:30:00	13.3	0	6	224	53.5
8:40:00	14.2	0	60	259	52.5
8:50:00	14.8	0.2	72	294	51.1
9:00:00	15.2	0	36	331	50.2
9:10:00	16	0	48	347	48.7
9:20:00	16.6	0	108	168	47.1
9:30:00	16.7	0.1	60	160	46.5
9:40:00	16.6	0.1	114	178	46.7
9:50:00	16.4	0	0	118	47
10:00:00	15.9	0	60	114	48.2
10:10:00	15.8	0.1	288	89	49.5
10:20:00	15.8	0.1	30	55	49.3
10:30:00	15.6	0	48	51	50.3
10:40:00	15.5	0	6	55	51.8
10:50:00	15.6	0	60	66	51
11:00:00	15.7	0	66	70	49.4
11:10:00	15.9	0	54	94	48.3
11:20:00	16.6	0.2	96	202	47
11:30:00	17.1	0.1	30	286	44.6
11:40:00	17.8	0.4	120	675	42.5
11:50:00	18.6	0.3	168	672	40.8
12:00:00	19.2	0.5	168	668	39.5
12:10:00	19.8	0.5	174	669	38.2
12:20:00	20.1	0.6	174	668	37.2
12:30:00	20.2	1.3	78	659	36.7
12:40:00	20.1	1.2	174	511	36.7
12:50:00	19.8	1	354	61	36.8
13:00:00	19.5	0.3	36	54	36.6
13:10:00	19.1	0.2	282	47	37.2
13:20:00	19	0.5	222	35	37.3
13:30:00	18.8	0.4	0	27	36.6
13:40:00	18.7	0.6	198	24	36.9
13:50:00	18.6	0.5	294	26	37.1
14:00:00	18.5	0.4	276	26	37
14:10:00	18.5	0.1	342	19	37.2
14:20:00	18.5	0.4	348	24	36.8

Weather Data for 18 June 1999 (continued)

Time	Air Temp degC	Wind Speed km/h	Wind Dirn deg	Solar Radn W/m^2	Rel. Hum. %
14:30:00	18.5	0.1	36	10	37.4
14:40:00	18.5	0.4	318	10	37
14:50:00	18.4	0.1	306	6	36.6
15:00:00	18.4	0.4	354	12	37
15:10:00	18.3	0.2	300	3	37.4
15:20:00	18.1	0.1	354	6	38.1
15:30:00	18	0.1	342	6	38.7
15:40:00	17.8	0.3	66	4	39.1
15:50:00	17.8	0.3	312	12	39.3
16:00:00	17.8	0.5	258	15	39.1
16:10:00	17.6	0.4	354	19	38.8
16:20:00	17.4	0.3	0	1	39.3
16:30:00	17.2	0.1	258	0	39.7
16:40:00	16.9	0.1	336	0	40.6
16:50:00	16.6	0.1	36	0	41.8
17:00:00	16.3	0.1	318	0	42.8
avg	17.36	0.26	164.04	154.68	42.48
max	20.2	1.3	354	675	55.1
min	12.6	0	0	0	36.6

APPENDIX 11

IGNITION SOURCES AND PROBABILITIES

TABLE OF CONTENTS

A11.1. INTRODUCTION

A11.1.1 Purpose

This section plays an important part in the Safety Case submission. A fire or explosion inside a passenger vehicle may only occur if a flammable mixture is present in the required concentration range **and** an ignition source is available. The latter is the focus of this appendix.

Analysis of potential leak scenarios has been discussed in **Part III** of the main report and in **Appendix 7**.

A11.1.2 Objectives of this Appendix

The objectives of this Appendix were to:

- identify potential ignition sources present in a passenger vehicle;
- measure the electrical parameters (by way of voltage and current readings, inductance and stored energy) of identified sources;
- determine if the identified ignition source is of sufficient strength to cause an ignition of flammable hydrocarbon mixture with regards to AS 2380.7i "Intrinsic Safety" (Ref.1); and
- develop a rule set for ignition probabilities for input into the risk assessment.

A11.1.3 Scope of Appendix

The scope of this appendix covered electrical systems associated with a typical passenger vehicle. It is recognised that there may be some variations in electrical systems from one vehicle manufacturer to another. This appendix is intended to identify electrical systems that are common to all cars (e.g. central door locking, interior light).

For the testing, a range of components was selected from cars, which would be typical for private vehicle use, ranging from four-cylinder to eight-cylinder cars.

A11.2. DESCRIPTION OF CAR ELECTRICAL SYSTEMS

A11.2.1 Introduction

For the purposes of this assessment, electrical systems associated with a passenger vehicle may be divided into two areas:

- Engine Electrical System, and
- Chassis Electrical System (including passenger cabin).

A11.2.2 Engine Electrical System

The electrical systems include ignition, charging and starting components related to the car engine. Of interest in this study is the charging system (i.e. alternator) and starting system.

The starting system generally consists of battery, starter motor, starter solenoid and the electrical circuits connecting the components. Of interest here is the starter motor/ solenoid assembly. When the ignition key is turned to the "START" position, the starter solenoid is actuated through the starter control circuit. The starter solenoid then engages the starter motor. To crank the engine, it is the battery that supplies the electrical energy to the starter motor.

Typically, a reading of nine volts or more, with the starter motor turning at normal cranking speed is achieved.

The alternator and starting motor systems are all located in the engine bay.

A11.2.3 Chassis Electrical System

The electrical system in a typical passenger vehicle is a 12 volt, negative ground type from a lead/ acid type battery. This battery is charged by the alternator when the engine is running, supplies power for the lights and all electrical accessories (e.g. radio).

A typical electrical circuit consists of electrical components such as switches, relays, motors, fuses, fusible links or circuit breakers related to that component and the wiring and electrical connectors that link the component to both the battery and chassis.

Electrical problems usually arise from loose or corroded connections, a blown fuse, a melted fusible link or a bad relay. All components must be properly grounded.

A11.3. IDENTIFICATION OF POTENTIAL IGNITION SOURCES

A11.3.1 Identification

A review of passenger vehicle electrical systems was undertaken to identify areas where a potential ignition source existed. As given previously, the ignition source must be capable of generating sufficient energy to ignite a hydrocarbon mixture that is in the flammable concentration range. It is expected that the most likely source of potential ignition is arcing of electrical switches and relays on closing and opening. Another possible source is electrical motors fitted with carbon bushes which have the potential for spark generation. Ignition sources not associated with the normal operation of equipment in the vehicle (such as cigarettes and matches) can also result in ignition. However a report by Arthur D Little for the US Department of Energy (Ref.2) contains the results of a series of experiments conducted with ignition of non-inert refrigerants. It was found that only high energy ignition sources could cause ignition and not lit cigarettes or in-car cigarette lighters.

The potential for spark generation is dependent on the following factors:

- the size of current running through the component;
- the amount of inductance in the circuit. High inductance circuits (such as relay coils, motor windings, transformer windings) can generate high voltages at contacts when switches are operated, which can in turn lead to arcing;
- the degree of sealing of electrical contacts from the atmosphere; and
- the amount of wear and dirt on components which can reduce the voltage at which arcing can occur.

Arcing can also occur as a result of failures such as electrical shorting. The probability of ignition depends on the likelihood of a short occurring after a refrigerant leak has occurred and is still in the flammable range. The methodology undertaken was to assess the ignition potential from normal operations of electrical equipment.

A11.3.2 Car Cabin

In a modern car, a range of typical switches, relays and motors inside a passenger vehicle cabin are summarised in **Table A11.1**. These are typical of the range of components expected. **Figure A11.1** shows a typical layout for a power window system and **Figure A11.2** shows a layout for a power door lock system.

TABLE A11.1
ELECTRICAL COMPONENTS INSIDE A PASSENGER VEHICLE CABIN

Electrical System	**Components**
Combination on steering column	- wiper/ washer switch - headlight dimmer switch - light control switch - turn signal switch
Ignition assembly	- ignition switch
Cruise control assembly	- cruise control switch
Power window assembly	- power window motor - power window switch - master switch
Central door locking assembly	- door lock motor - door unlock detection switch - master switch - front passenger door lock manual switch
External rear view mirror assembly	- mirror adjustment switch
Radio assembly	- radio fuse
Others	- rear window defogger switch - interior light - stop light switch

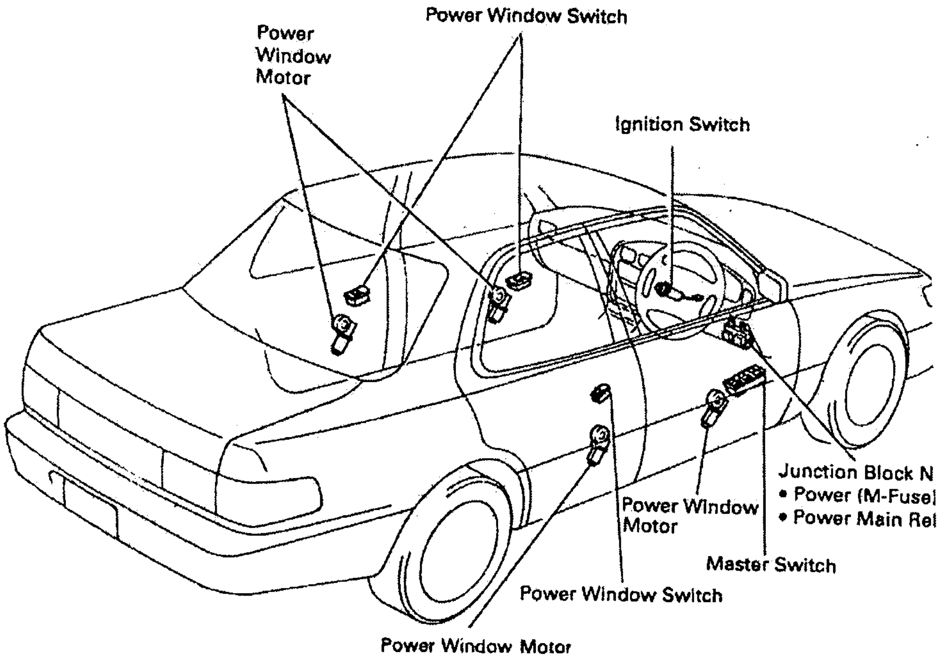


FIGURE A11.1
POWER WINDOW SYSTEM COMPONENT LAYOUT

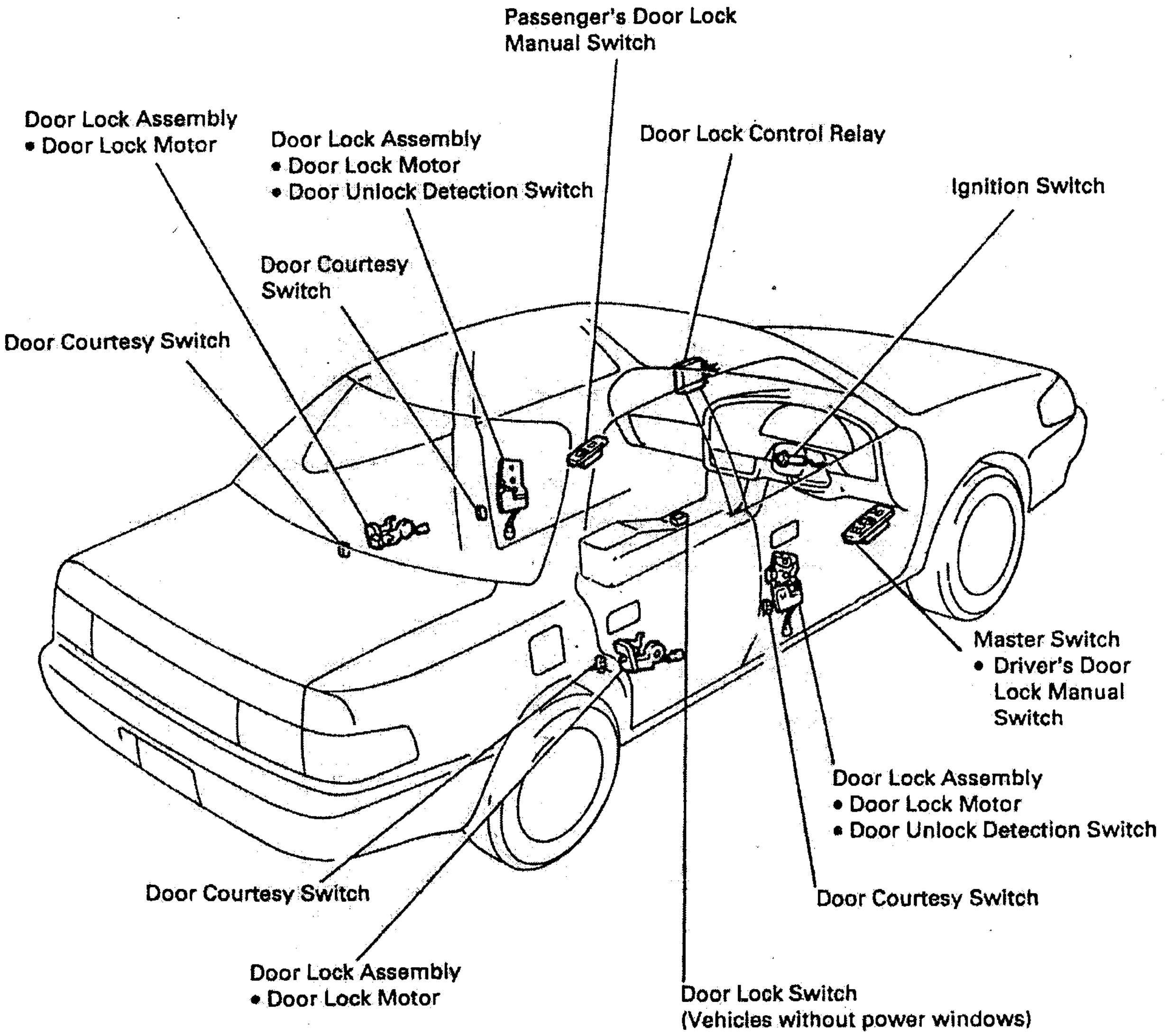


FIGURE A11.2
POWER DOOR LOCK SYSTEM COMPONENT LAYOUT

A11.3.3 Engine Bay

In a modern car, the location of typical switches, relays and motors inside the engine bay of a passenger vehicle is summarised in **Table A11.2**.

TABLE A11.2
ELECTRICAL COMPONENTS INSIDE PASSENGER VEHICLE ENGINE BAY

Electrical System	**Components**
Windshield wiper system	- windshield wiper motor
Horn system	- horn relay
Engine system	- ignition coil (primary) - ignition coil (secondary) - alternator/ generator - starter motor - starter motor solenoid
Others	- brake fluid level warning switch - neutral start switch - cruise control actuator - air-conditioning clutch - pressure switches - relays - fuses - headlights, etc.

A11.3.4 Others

Although not part of a passenger vehicle electrical system, other potential areas of concern are those with hot surfaces shown in **Table A11.3**.

TABLE A11.3
HOT SURFACES OF A PASSENGER VEHICLE

Location	**Components**
Passenger Vehicle Cabin	- none identified
Passenger Vehicle Engine Bay	- engine block (in operation) - exhaust manifold - radiator (upper section)

A11.4. EVALUATION OF POTENTIAL IGNITION SOURCES

A11.4.1 Voltage and Current Measurements

An initial assessment was made to determine voltage and current values from operation of electrical equipment. Based upon the reviews given in the earlier sections of this Appendix, a representative sub set of components from **Table A11.1** and **Table A11.2** was taken. This is shown in **Table A11.4**.

In order to measure the current and voltage associated with each component, a qualified autoelectrician was commissioned to undertake these readings. Testing was conducted on 5 May 1999 by Eastern Valley Automotive, MVRIC licence number 25148.

A11.4.1.1 Methodology

Rather than assess all potential electrical equipment which could be installed in vehicles, the approach taken was to determine the minimum ignition current from Appendix A of AS 2380.7 "Intrinsic Safety i" and compare this value with current values measured for a typical range of electrical equipment. In an initial set of tests, the testing was limited to obtaining the readings of voltage and current. As the refrigerant is predominantly propane, the curves for equipment classified to Group IIA in Appendix A of AS 2380.7 were used to determine the minimum ignition current.

It was assumed that circuits were either resistive (those that have an inductance less than 1 milliHenry)) or inductive (those that have an inductance greater than 1 milliHenry) . Figure A2 of AS 2380.7 gives the minimum ignition current for resistive circuits and Figure A5 for inductive circuits. Most cars currently operate with batteries of 12 Volts. For conservatism a battery voltage of 16 Volts was assumed, although the voltage could not reach this high in normal operation. This is the maximum voltage for a fully charged battery. The minimum ignition current is then about 4.5 amps for resistive circuits. To determine the minimum ignition current for inductive circuits, it was necessary to determine the inductance of the circuits considered. This was undertaken as described in **Section A11.4.2** below.

The methodology used for screening out a potential source was as follows:

For resistive circuits:

1. For the given maximum voltage (taken as 16 volts for a fully charged battery), from Figure A.1 provided in AS 2380.7i "Intrinsic Safety" (Ref.1), determine the minimum ignition current to ignite a mixture of propane and air (Group IIA material).

2. Measure the current across the selected resistive circuit. This was carried out by a licensed auto-electrician in a range of cars.

3. If the measured current in Step 2 is less than the minimum ignition current required as calculated in Step 1, then screen out the component as a potential ignition source.

For inductive circuits:

4. Measure the inductance of the selected component. This was carried out by Unisearch Limited, the consulting arm of the University of NSW (report prepared by Associate Professor T.R.Blackburn (Ref.3).

5. For the rated current of the component, obtain the inductance that would provide the minimum ignition energy for Group IIA material, from Figure A.5 of Ref.1. This is given for a 24V supply. Adjust this inductance value for a 16V supply, to give the same ignition energy, using the relationship $E=0.5\ LI^2$. This step assumes constant resistance and hence uses the relationship $I = V/R$.

6. If the measured current in Step 2 is less than the minimum ignition current required as calculated in Step 1, screen out the component as a potential ignition source.

7. If the inductance measured in Step 3 is less than that calculated in Step 5, then screen out the component as a potential ignition source.

A11.4.1.2 Results of Voltage/ Current Measurements

Table A11.4 details the measured voltage and current values associated with each component. The assessment of the components against the criteria of Ref.1 is discussed further after the inductance of circuits is determined in **Section A11.4.1**.

TABLE A11.4
MEASURED VALUES

Component	Measured Values	
	Voltage (V)	Current (A)
Passenger Vehicle Cabin		
Power window motor	12	3
Power windows switch	12	0.5
Ignition switch	12	0.5
Interior light	12	1
Central door lock motor	12	1.5
Fan motor	12	10
Passenger Vehicle Engine Bay		
Windscreen wiper	12	5
Starter motor	12	120
Ignition coil (primary)	12	3
Ignition coil (secondary)	12	3
Starter motor solenoid	12	4
Alternator	12	0

A11.4.2 Inductance Measurements

To determine typical values of inductance, Unisearch Ltd of the University of New South Wales were commissioned to undertake measurements of a range of typical electrical components. The following components were obtained from used spare parts dealers:

i Window winder motor:
Bosch: Germany, for a Commodore VB SL/E
Rated at 12 volts, 3 amps.

ii A/C Fan motor:
Harrison, GM: New York, for a Commodore VB SL/E
Rated at 12 volts, 10 amps (this is likely the full A/C rated current, not the fan only).

iii Central door lock motor:
by JIBECO, Japan: for Skyline, Series 1
Rated at 12 volts, 1.5 amps.

iv Windscreen wiper motor:
Lucas Australia: for Commodore VC.
Rated at 12 volts, 5 amps.

v Ignition coil:
Bosch Australia: for Telstar
Rated at 12 volts, 3 amps primary winding current.

vi Starter motor:
No obvious manufacturer identification on the unit.
Rating details supplied were: 12 volts, 4 amps solenoid and 120 amps cranking current.

In addition, the starter motors for the following vehicles were tested in situ:

- Toyota Corolla (1986);
- Mitsubishi Verada (1998); and
- Holden Commodore (1998).

The inductance values were measured with an AIM bridge used in series mode with 1 kHz frequency. The inductance measurement accuracy was checked with a number of standard inductors within the range of values measured.

The uncertainty of the measurements was estimated to be better than 4%.

The measured inductance values are given in **Table A11.5**. The corresponding energy stored in the inductance, based on the rated current is also given, using the equation $E = 0.5\ L\ I^2$ (Joules).

TABLE A11.5
MEASUREMENT OF COMPONENT INDUCTANCE

Component	Rated Current (amps)	Measured inductance (milliHenry)	Stored Energy (Joule, based on rated current)	Resistive Circuit (Inductance <1mH)	Minimum Igniting Current (amps)	Evaluation
Cabin Equipment						
Window winder	3	0.450	0.002	Yes	4.5	Rated current less than minimum igniting current.
Fan motor	10	0.308	0.016	Yes	4.5	Rated current exceeds minimum igniting current.
Door lock motor	1.5	1.60	0.002	No	0.65	Rated current less than minimum igniting current.
Engine Bay Equipment						
Windscreen wiper motor	5	1.92	0.024	No	0.6	Rated current exceeds minimum igniting current. Unlikely to be operated at the same time as a significant leak.
Ignition coil: Primary	3	5.00	0.023	No	0.35	Rated current exceeds minimum igniting current.
Ignition coil: Secondary	-	38,800	< 0.023	No	Offscale, <20mA	Stored energy in coil secondary depends on primary stored energy. The energy transfer efficiency will be less than 100%.
Starter motor: Solenoid	4	0.5	0.004	Yes	4.5	Rated current exceeds minimum igniting current. Unlikely to be operated at the same time as a significant leak as occupants would detect leak.
Starter motor: Cranking motor	120	1.2	8.7	No	0.75	Rated current exceeds minimum igniting current. Unlikely to be operated at the same time as a significant leak.

Table A11.6 summarises the inductance values for the starter motors measured in situ for the sample cars. No details of the current ratings of these items were available, however it is expected that the current ratings will be similar and that the stored energy values will be similar.

TABLE A11.6
MEASUREMENT OF IN-SITU STARTER MOTOR INDUCTANCE (CRANKING MOTOR)

Component	**Measured inductance (milliHenry)**	**Comments**
Toyota Corolla	1.7	-
Mitsubishi Magna	0.94	-
Toyota Corolla	1.27	-

A11.4.3 Evaluation of Stored Energy in Inductive Components

A report for the US Bureau of Mines (Ref.4) gives the minimum spark ignition energy of propane in air as 0.26 mJ (2.6E4-5). Therefore, the components in **Table A11.5** will have a higher stored energy than the minimum spark energy required for ignition of a refrigerant leak. However, the potential for ignition will be reduced for the following reasons:

- Not all stored energy will be converted to spark energy as electrical equipment are designed to minimise the generation of sparks under normal operating conditions.
- The amount of intrinsic protection provided by equipment casings (i.e. central door lock sealed unit) is not taken into account.

A11.4.3.1 Evaluation Against AS2380.7

There are some components in the vehicle cabin, which according to the methodology of AS2380.7i (Ref.1) could potentially be an ignition source. The likelihood of these components resulting in ignition will depend on the level of intrinsic protection. It would be conservative to assume that there could potentially be some components used which would have little intrinsic protection as a range of components from different manufacturers could be used. Some protection from ignition would be provided by panelling as well, but the ignition potential is not readily assessable. Of particular concern is the ventilation fan motor, as it has a high current (about 10 amps) and would be normally in service when the air-conditioning is in service. However, if the fan is running a flammable mixture would not be generated in the vehicle cabin.

The central door locking mechanism has the stored energy that exceeded the minimum ignition energy for ER12. However, this circuit is essentially behind panelling and, even though not electrically sealed, i.e. is not directly exposed to the vapour-air mixture, unless the unit was damaged, or shorting occurred at the time of operation, releasing a high-energy ignition source. The unit is typically housed in a strong plastic casing.

There is also equipment in the engine bay which has the potential for ignition, but in this case a leak of refrigerant would have to occur in the engine bay and there would be protection from fires to passengers in the vehicle cabin.

A11.4.3.2 Ventilation Fan Speed Control Resistance

Heat produced from resistance has also been identified as another potential ignition source. The most likely source is the ventilation fan control unit that has a stepped series of resistors which are operated to control the speed of the fan motor. To determine the likelihood of ignition, a number of texts and manuals were referenced and figures on resistance values obtained.

One text (Ref. 5) gives figures of about 2Ω (ohms) for a typical car. The power lost due to resistance can be obtained by the formula $E = V^2/R$ where V is the voltage across the resistor and R the resistance. Assuming a conservative value of 16V across the resistor, this gives a power of 128 Watts. Given that the ignition temperature of propane is 466°C, the potential for ignition can be disregarded as the resistor will not reach this temperature.

A11.4.3.3 Conclusions

A preliminary assessment was made using AS 2380.7i (Ref.1) to determine the stored energy in resistive and inductive circuits of the electrical components in automobiles. It was found that some circuits would have sufficient stored energy to ignite a flammable mixture of hydrocarbon refrigerant according to AS 2380.7i (Ref.1). Of these, only the central door lock motor is likely to be operated when the vehicle is parked.

The stored energy does not mean automatic ignition, as there should be a fault in the electrical component to release a part of this energy towards ignition of a potential hydrocarbon refrigerant-air mixture.

The ignition probabilities used in the safety assessment is given in **Table AII.7**. Further details are given in **Appendix 12**.

TABLE AII.7
IGNITION VALUES USED IN STUDY

Ignition	Value Used in Study
Immediate ignition probability due to intrinsic failures (car moving)	0.01
Delayed ignition probability due to intrinsic failures (car moving)	0.01
Immediate ignition probability due to intrinsic failures (car stationary)	0.001
Delayed ignition probability due to intrinsic failures (car stationary)	0.001

A11.5. REFERENCES

1 Standards Australia (1987): AS 2380.7i – 1987, "Intrinsic Safety".

2 Arthur D Little (1995): "Risk Assessment of Flammable Refrigerants, Part 3: Car Air Conditioning", Cambridge.

3 T.R. Blackburn (1999): "Inductance Measurements on Automotive Electrical Components", Unisearch Limited, The University of New South Wales, Sydney.

4 J.M. Kuchta (1985): "Investigation of Fire and Explosion Accidents in the Chemical, Mining and Fuel-Related Industries – A Manual", US Department of the Interior, Bureau of Mines, Bulletin 680.

5 James E. Duffy: "Modern Automotive Mechanics", Goodheart-Willcox Company, South Holland, Illinois.

APPENDIX 12

FAILURE RATE DATA (DATA COLLECTION SURVEY)

TABLE OF CONTENTS

A12.1. INTRODUCTION

A12.1.1 General

This Appendix contains the rationale for the development of the rule sets for leak sizes used in the Safety Study as well as the associated frequency data. Granherne coordinated an extensive literature review with the following organisations including:

- UNSW Research and Professional Information Delivery (RAPID) Services.
- Newtek Pty Limited.
- Boral Energy.
- Boral Esanty.

A considerable amount of information is available in the literature on automobile air-conditioning systems. However, the focus of this literature has been under the broad headings of air-conditioning systems, refrigerant replacements to CFC, retrofitting, components associated with air-conditioning.

Little data was available in the public arena on parameters useful for a safety assessment. These parameters include risk assessments, quantification of leaks from air-conditioning systems as well as leak frequency data and failure modes of components. Other important parameters included car ventilation rates, vehicle volumes and air exchange rates.

There were very few reliable databases containing this information. Agencies such as the Federal Office of Road Safety and Standards Australia were contacted but no information was available. In addition, Granherne directly approached the car manufacturers and air-conditioning specialists such as General Motors Holden, Ford Australia and Air International. However due to confidentiality issues, information was not made available to Granherne.

Databases that did exist were related to numbers of registered vehicles and distribution of new vehicles in Australia and by state.

Therefore, it was necessary to obtain the required data for the Safety Report directly from the field in the form of surveys. This appendix outlines the survey results and their interpretation as well as the data analysis performed to obtain the required frequency values.

A12.1.2 Purpose

The purpose of this Appendix is to outline the methodology, results and derivation of leak frequency rule sets used in the Safety Study.

A12.1.3 Objectives

The objectives of this Appendix were to:

- provide results from the field surveys;
- provide discussion from interviewed accredited automotive mechanics on the results in relation to faulty equipment and their failure modes;
- undertake a parts count of a typical air-conditioning system;
- provide a rule set for leak sizes to be used in the Safety Study; and
- develop the frequency database to be used in the Safety Study.

Note:

1. A comprehensive failure modes and effects analysis (FMEA) study of a vehicle air-conditioning system has been included in **Appendix 2**.

A12.2. FIELD SURVEYS

A12.2.1 Introduction

Field surveys were carried out during January and June 1999 in Melbourne, Adelaide, Perth and Brisbane of motor vehicle repairers to collect data for frequency analysis in this report. The survey took the form of a questionnaire that was filled in during face-to-face interviews with accredited automotive mechanics in their workshop areas.

These cities were chosen for the following reasons:

- Both HCFC and HC products have been in use in South Australia, Western Australia and Victoria. Victoria has been using hydrocarbon refrigerants for a minimum of four years.
- Workshops in South Australia, Western Australia and Victoria were chosen as they had experience in both HCFC and HC products.
- Workshops in Queensland were chosen to gain experience of air-conditioning systems operating in high humidity conditions.

A total of 68 surveys were conducted. This was considered a reasonable sample population to derive statistically meaningful results. The survey distribution is given in **Table A12.1**.

TABLE A12.1
SURVEY DISTRIBUTION

State	No. of Surveys	Type of Refrigerant
Queensland (Brisbane)	12	HCFC
South Australia (Adelaide) and Western Australia (Perth)	19	HCFC/ HC
Victoria (Melbourne)	37	HCFC/ HC
TOTAL	**68**	

The survey's questions were developed to collect data from which leak frequencies could be calculated for the risk analysis section of this report. The leak size and source were particular objects of interest in the survey and detailed questions in this regard were asked. The survey sheet used is shown as **Figure A12.1**.

Melbourne

The survey was carried out in Melbourne in January 1999. Selected raw data is shown in **Table A12.2**. The results shown are those used in the subsequent calculations and data analysis for calculation of frequencies.

The MVAC repairers surveyed in Melbourne serviced vehicles with HFC or HC refrigerants.

A follow up survey was conducted in June 1999 with selected workshops to further refine the leak frequency of air-conditioning system components located in the vehicle cabin. These components were the thermal expansion valve (Tx) and evaporator.

Brisbane

Newtek Pty Ltd carried out the survey in Brisbane on Granherne's behalf during February 1999.

Twelve workshops were surveyed for data collection in this area. All the workshops serviced vehicles with HFC refrigerant only. The raw data is shown in **Table A12.3**.

Adelaide and Perth

The survey was carried out in Adelaide and Perth in April 1999 by Granherne. Nineteen workshops were surveyed for data collection.

The workshops serviced vehicles with HFC or HC refrigerants. The survey results are summarised in **Table A12.4**.

A follow up survey was conducted in June 1999 with selected workshops to further refine the leak frequency of air-conditioning system components located in the vehicle cabin. These components were the thermal expansion valve (Tx) and evaporator.

FIGURE A12.1
SURVEY QUESTIONNAIRE FORMAT

Date:	
Name of Company/ Repairer:	
Address:	
Name of Contact:	

1	How many cars are serviced here each day or per week?						
							/day or /week
2	How many days/weeks per year are you open? (ie: Mon-Sat, except Public Hols? etc)						
3	How many car air-conditioning systems are serviced per day or per week? (as for Qn 1)						
							/day or /week
4	How many of those car air-conditioning systems are recharged with refrigerant?						
							/day or /week
5	What type of refrigerant is used (%)?						
	HCFC	HC	CFC	Other			
6	What types of leaks occur in the car air-conditioning system (%)?						
	Pinhole	Small	Rupture	Other			
7	How many AC systems are damaged and in need of mechanical repair (%)?						
8	Where are they damaged (%)?						
	evaporator	condenser	compressor	TX valve	pipework	receiver drier	other

Other questions:

9	If there is damage to the AC system, what is the extent, the cause, the effects, the potential of leakage? etc.
10	How do you think pinhole/ small leaks occur?
11	Have you ever heard of explosions/ fires in cars due to air-conditioning refrigerant leaks?
12	Do new systems leak less than older designs?
13	Are systems designed for R134a? Are systems changed over to HC after repair or refilled with R134a?
14	Can you estimate an average leak rate on a yearly basis?

TABLE A12.2
MELBOURNE SURVEY RESULTS

No.	No. cars serviced / week	No. days open/ week	No. AC systems serviced / week	Leak Type (%)			Leak Source (%)								
				Pinhole	Small	Large	Evap	Cond	Comp	Tx	Pipework	Receiver / drier	O-rings	Seals	Other
1	66	6	66				15	15			15		40	15	
2	20	5	20												
3	36	6	36												
4	66	5.5	22					10	5	5		5	75		
5	44	5.5	44	90			10				30		30	30	
6	30	6	12		50		16	16		17	17	17		17	
7	100	6	100						20				80		
8	9	5.5	9				40				30				30
9	40	6	1	90				25	25	25		25			
10	25	5	3	90			30	30		10			30		
11	40	5.5	25		95	5		50	25		25				
12	37	5	12	9	90	1		50			50				
13	45	6	3.5	80	20			34	33			33			
14	45	6	35	45	45	10		30	30	20		10	10		
15	25	6	12		100		50	50							
16	25	5.5	24				25	25	25		25				
17	35	5.5	35	40				80			20				
18	55	6	3.5	90				30	30		40				
19	22	6	9	100			30	30	10	10	10	10			
20	75	5.5	50	80	20			20			80				
21	125	5	38	60	40										
22		5	25	50	50				45	10	45				
23	30	5	2	90	10		45				45				

TABLE A12.2
MELBOURNE SURVEY RESULTS

No.	No. cars serviced / week	No. days open/ week	No. AC systems serviced / week	Leak Type (%)			Leak Source (%)								
				Pinhole	Small	Large	Evap	Cond	Comp	Tx	Pipework	Receiver / drier	O-rings	Seals	Other
24	20	5	20	90			40		40			20			
25	83	5.5	83				20	20			30		30		
26	50	5	10												
27	50	5	8												
28	165	5.5	65				30	30					40		
29	6	5													
30	20	5	10	90				40		30	30				
31	45	5	15		100								100		
32		5	12				15	60				15		20	
33	12	5.5	12	50	50						50		50		
34	20	5	3				40				30		30		
35	20	5.5	20				25	25	25		25				
36	480	6	240	50	50		20	20	20			20	20		
37	55	6	30	50	25	25	33	33			34				

TABLE A12.3
BRISBANE SURVEY RESULTS

No.	No. cars serviced / week	No. days open/ week	No. AC systems serviced / week	Leak Type (%)			Leak Source (%)								
				Pinhole	Small	Large	Evap	Cond	Comp	Tx	Pipework	Receiver / drier	O-rings	Seals	Other
1	10	6	10	45	45	10		100							
2	40	5.5	40		80	20		80			10	10			
3	40	5	40	10	80	4		100							
4	22	5.5	18					100							
5	25	5.5	12	8	90	2									
6	23	5.5	23	20	80										
7	40	5.5	15	3	95	2									
8	60	5.5	60	2	92	3									
9	60	5.5	60	20	70	10		60	30		10				
10	42	5.5	42	25	60	2		100							
11	33	5.5	17	10	80	2									
12	50	5	15	2	95	2		90				10			

TABLE A12.4
ADELAIDE/ PERTH SURVEY RESULTS

No.	No. cars serviced / week	No. days open/ week	No. AC systems serviced / week	Leak Type (%)			Leak Source (%)								
				Pinhole	Small	Large	Evap	Cond	Comp	Tx	Pipework	Receiver / drier	O-rings	Seals	Other
1	25	7	25												
2	60	6	22	80	20			20	10				70		
3	55	5.5	11	90		10	30						70		
4	33	6	18	90	5	5	5	10	5				60	20	
5	100	5		80	15	5	10	20							70
6	20	5	3	85	10	5	10	20					70		
7	100	6	90	98	2		1	4					95		
8	60	5	5	99	1		5	5	5				85		
9	20	6	2	90	5	5		10	10				80		
10	60	6	12	90	10			15			15		70		
11	50	5	5	20	60	10	10	10	10	10			60		
12	60	6	18	90	9	1	2	5	5	5	10	10			
13	36	6	18	90	10			30	10				60		
14	25	5	15	85	10	5	10	30	20	10		30			65
15	24	6	24	75	15	10		20	10				70		
16	60	6	6	89	10	1		20					80		
17	60	6	18	90	10			30	20				50		
18	150	6	72	90	10			15	10		25		50		
19	108	6	60	90	8	2	5	5	5	5	10		70		

A12.2.2 Results

The raw data was then distributed to provide the following:

- Proportion of total vehicles serviced that have air-conditioning,
- Leak size distribution,
- Leak location distribution.

Statistical methods were also employed to demonstrate that the raw data sets were compatible and related to each other. The results are given in **Table A12.5** through to **Table A12.7** as well as shown in graphical form in **Figure A12.2** through to **Figure A12.4**.

TABLE A12.5
VEHICLES SERVICED BY SURVEYED WORKSHOPS

No.	Parameter	Value
1	Total number of vehicles repaired in surveyed workshops	3502 per week
2	Number of vehicles serviced with air-conditioning systems	1832 per week
3	Percentage of vehicles with air-conditioning systems	52.3

TABLE A12.6
LEAK SIZE DISTRIBUTION

Survey Location	Leak Type from Air-conditioning System		
	Pinhole	Large	Catastrophic
Melbourne	57%	39%	4%
Brisbane	13%	82%	5%
Adelaide	84%	12%	4%
Average	51%	44%	4%

TABLE A12.7
LEAK LOCATION DISTRIBUTION

Survey Location	Air-conditioning System								
	Evap.	Tx valve	'O' Ring	Compr. unit	Seals	Hoses	Cond.	Drier	Other
Melbourne	12.5	4.6	16.8	11.3	3.5	19	23.9	5.3	3.0
Brisbane	0	0	0	4.3	0	2.9	90.0	2.9	0
Adelaide	4.9	1.7	57.8	6.7	1.1	3.3	14.9	2.2	7.4
Average	5.8	2.1	24.9	7.4	1.5	8.3	42.9	3.5	3.5

FIGURE A12.2
LEAK SIZE DISTRIBUTION IN ENTIRE AIR-CONDITIONING SYSTEM (ENGINE BAY AND PASSENGER CABIN)

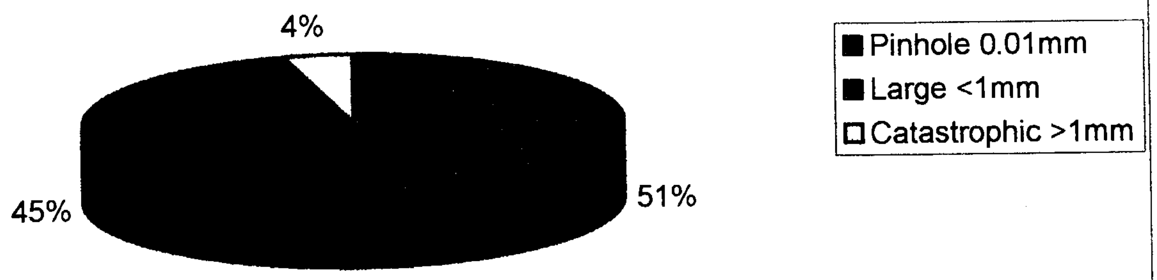


FIGURE A12.3
DISTRIBUTION OF LEAK LOCATIONS IN ENTIRE AIR-CONDITIONING SYSTEM

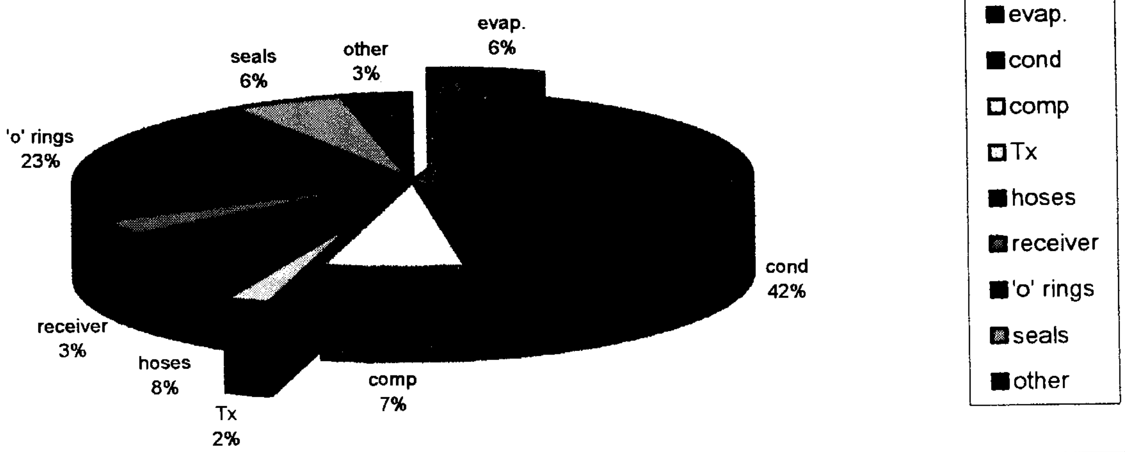
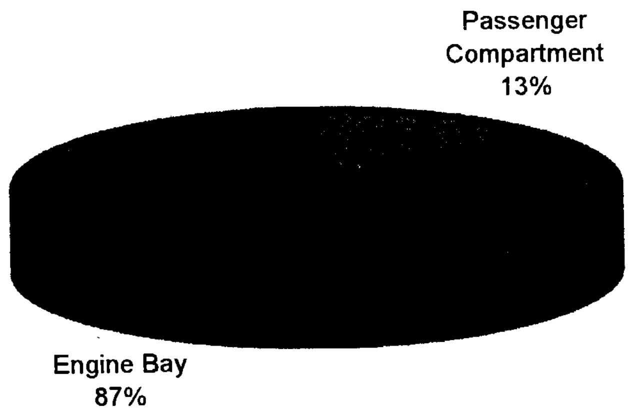


FIGURE A12.4
DISTRIBUTION OF LEAK SOURCES IN ENGINE BAY AND PASSENGER CABIN



A12.2.3 Discussion

The following comments are made with regards to the above results:

- All survey locations provided consistent values in terms of leak sizes.
- Survey results for Brisbane displayed a higher tendency for leaks arising from condensers followed by hoses and driers. All these components are located in the engine bay.
- Approximately 52% of all vehicles are fitted with air-conditioning systems. This value compares favourably with a statistic published by NSW Motor Vehicle Repair Industry Council of 50% (Ref.1).
- The majority of leaks fell between the leak classification of "pinhole" and "large".
- 44% of all leaks were defined as "pinhole". As given in **Section A12.3**, a pinhole leak was defined by the accredited automotive mechanics as a leak that occurs over "a period of 3-6 months".
- 52% of all leaks were defined as "large". As given in **Section A12.3**, a large leak typically occurs in the engine bay where air-conditioning system components are typically moving or exposed to vibration and corrosion. Failure modes are discussed in **Section A12.3**.
- Of the vehicles fitted with air-conditioning and assuming that the thermal expansion (Tx) valve is located inside the firewall, approximately 14%[1] have exhibited a leak inside the cabin. A detailed parts count is given in **Section A12.5**.

Section A12.6 details the leak frequencies developed for components inside a passenger vehicle cabin.

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[1] Conservatively assuming that the Tx valve is located inside the passenger cabin, approximately 2 'O' rings (**Section A12.5**) are present. This represents 25% of the overall number of 'O' rings. Thus the total percentage of leaks inside a cabin is equal to the sum of evaporator, Tx valve and its 'O' ring fittings. This value is estimated to be 14% (2%+6%+0.25(23%)).

A12.3. FAILURE MODES AND LEAK SIZES OF SYSTEM

A12.3.1 Introduction

The purpose of this section is to outline the failure modes of air-conditioning system components as gathered from the workshop surveys. In addition, comments regarding the typical leakage rate and leak size are given. The rule sets for leak size distribution are also provided. Finally comments are made regarding incidents involving ER12. This section is intended to supplement the FMEA study given in **Appendix 2**.

A12.3.2 Failure Modes of Components

This section summarises comments made by workshops regarding failure modes of motor vehicle air-conditioning systems. On average, each workshop had 10 years experience in automotive air-conditioning systems. This collectively represents more than 680 years of experience.

The survey focused more on causes of leaks in the air-conditioning components rather than issues relating to performance characteristics. A summary of the comments is presented in **Table A12.8**.

A12.3.3 Summary of Leak Size Rule Sets

Following from the workshop surveys and FMEA study, it was necessary to develop a rule set for leak sizes for the engine bay and passenger compartment. Based upon observations and discussions, the leak sizes for components inside the passenger cabin were found to be at least an order of magnitude lower than for the engine bay. This arises since:

- there are no moving air-conditioning components,
- components experience minimal vibration within the passenger cabin, and
- the evaporator is enclosed in a casing.

For the purposes of the Safety Study, the rule sets used in the analysis are given in **Table A12.9**.

TABLE A12.8
FAILURE MODES OF AIR-CONDITIONING COMPONENTS

No	Component	Typical Causes of Leak	Typical Leak Size	Detection of Leak	Comments
1	Evaporator (inside passenger cabin)	- corrosion	- pinhole and nearly undetectable (0.01mm and leak over period of weeks/ months) - some weeping (< 0.1mm – for an Australian manufactured vehicles) - workshops dismissed rupture scenarios	- dye testing - pressure testing - oil stain (“tell tale”) - drain hole in evaporator housing unit (for large leaks)	- very difficult to detect - majority of leaks are so small can only go by “tell tale” oil stains - pressure still held for months (3 or more) - the evaporators of some popular Australian manufactured vehicles are particularly susceptible to leakage
2	Piping/ hoses (engine bay)	- abrasion and thinning against engine bay - heat stress from pipe touching hot surfaces - vibration (engine bay) - corrosion	- fine cracks - split pipework - blown hoses	- pressure testing	- blown hoses can occur frequently in the engine bay - cracks in piping depends on age (1 in 10 year leak)

TABLE A12.8
FAILURE MODES OF AIR-CONDITIONING COMPONENTS

No	Component	Typical Causes of Leak	Typical Leak Size	Detection of Leak	Comments
3	'O' rings (engine bay and passenger cabin)	- incorrect installation ('O' ring rolled not placed on properly) - incorrect installation ('O' ring squeezed too hard and becomes flat) - AC not used frequently with seals drying out	- fine cracks in 'O' ring - pinhole size (loss over days for Tx valve 'O' rings)	- by oil residue - by pressure testing	- 'O' ring leak quite susceptible for vehicles with Tx valve located in engine bay - 'O' rings in Japanese vehicles last for 5 years or more - hydrocarbon refrigerant is compatible with seals (cf R134a)
4	Tx Valve (engine bay and passenger cabin)	- defective unit from new (very rare)	- cracks in unit less than 1mm equivalent diameter - Tx valve units do not generally leak only fittings	- by oil residue - by pressure testing - by dye testing	- majority of workshops reported 9/10 times leaks from Tx valves are 'O' rings - rare as Tx valve bodies are made from brass
5	Condenser (engine bay)	- stone chips - acid from squashed insects	- start off as minor leaks	- visual oil stains - dye testing - pressure testing	- susceptible component of system
6	Compressor (engine bay)	- loss of oil and gas in system	- very small seal leaks (0.1mm and up)	- pressure testing - dye testing - oil stain	- hydrocarbon refrigerant is compatible with MVAC compressor units - susceptible component of system

TABLE A12.9
LEAK SIZE RULE SETS USED IN SAFETY STUDY

Location	**Leak Category**	**Equivalent Leak Size (mm)**
Engine Bay	Catastrophic	12 (vapour line) 8 (liquid line)
	Large	1
	Typical	0.1
Passenger Cabin	Catastrophic	1
	Large	0.1
	Typical	0.01

A12.4. INCIDENTS INVOLVING ER12

A12.4.1 Introduction

A prime objective of the workshop surveys and reviews was to determine if there had been any incidents in terms of release, ignition and fire from the use of the refrigerant, ER12.

Granherne found there have been no reported fire incidents in Australia or problems associated with the use of ER12 in automobiles.

A12.4.2 Incidents in the Workshops

As given in Question 11 of the survey form **Figure A12.1**, Granherne found that most workshops had not observed or heard of any fires or explosions resulting from the use of the refrigerant product.

The assessors did note that some workshops had “heard” from industry of service garages experiencing explosions and fires. However, upon further questioning, no reliable reference or source could be produced. These stories could only be classified as unsubstantiated.

Those workshops that did use hydrocarbon refrigerant were questioned on venting practices. Given that the workshops are typically large open garages with good venting, buildup of released refrigerant was not considered to be a major issue. Further the amount of gas released (up to 300 grams) was considered to be minor.

Some workshops reported experiencing a leak of refrigerant during charging which was directed across a running engine. However, no ignition occurred. One workshop reported igniting a release during charging and a small fire occurred over a short period of time. The flame was likened to the shape from a cigarette lighter and could be extinguished by blowing across it.

Use of ER12 in Vehicles

Granherne through Boral Esanty could not gather any evidence of vehicles experiencing a fire or explosion from the use of hydrocarbon refrigerant. This includes vehicles currently using the ER12 product.

During the course of the study, Granherne was only able to source one documented case where a vehicle using ER12 refrigerant had been involved in an accident. No fire or explosion resulted from this crash of which details are provided below.

Details of the crash were as follows:

- The vehicles involved in the collision were a Ford Panelvan and a late model Holden Vectra.
- The Holden Vectra was fitted with an air-conditioning system. The system was charged with approximately 250 - 270 grams of ER12 refrigerant.
- The accident occurred in Victoria (Grange Road, Toorak 11/5/99 8:16 am) where the panel van failed to give way at a stop sign.
- The Holden Vectra was involved in a front on collision at approximately 40-50 km/hr.
- The impact was described as heavy and caused substantial damage to both vehicles.
- In particular, the Holden Vectra suffered the following damage: - radiator, bumper bar, R/H headlight, R/H guard, bonnet, and a number of other parts including the AC condenser, AC Receiver Drier, AC and Engine fans, AC hoses and pipework.
- The condenser was ruptured and a total loss of refrigerant occurred. The driver reported the refrigerant appeared as a white cloud that very quickly dissipated. There was no ignition, and no explosion nor fire.

Photographs of the damaged Holden Vectra are given in **Figure A12.5** and **Figure A12.6**.

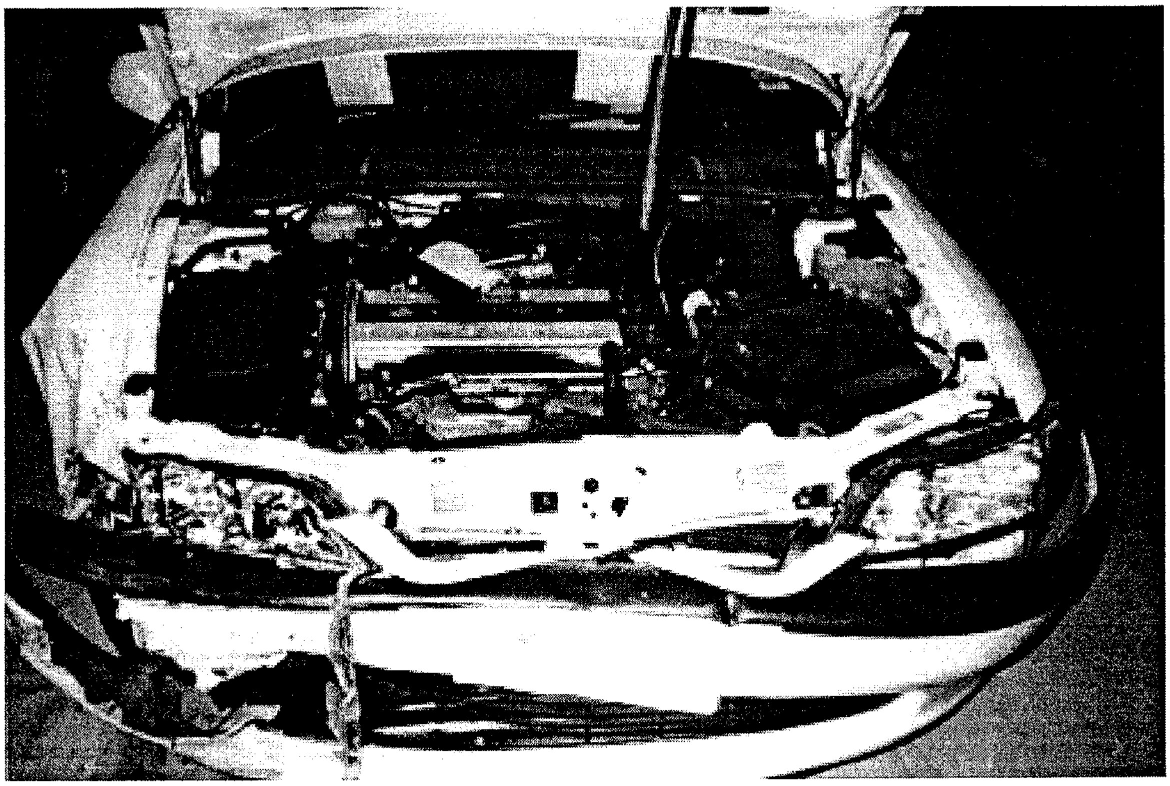


FIGURE A12.5
PHOTOGRAPH OF DAMAGED VEHICLE – 1

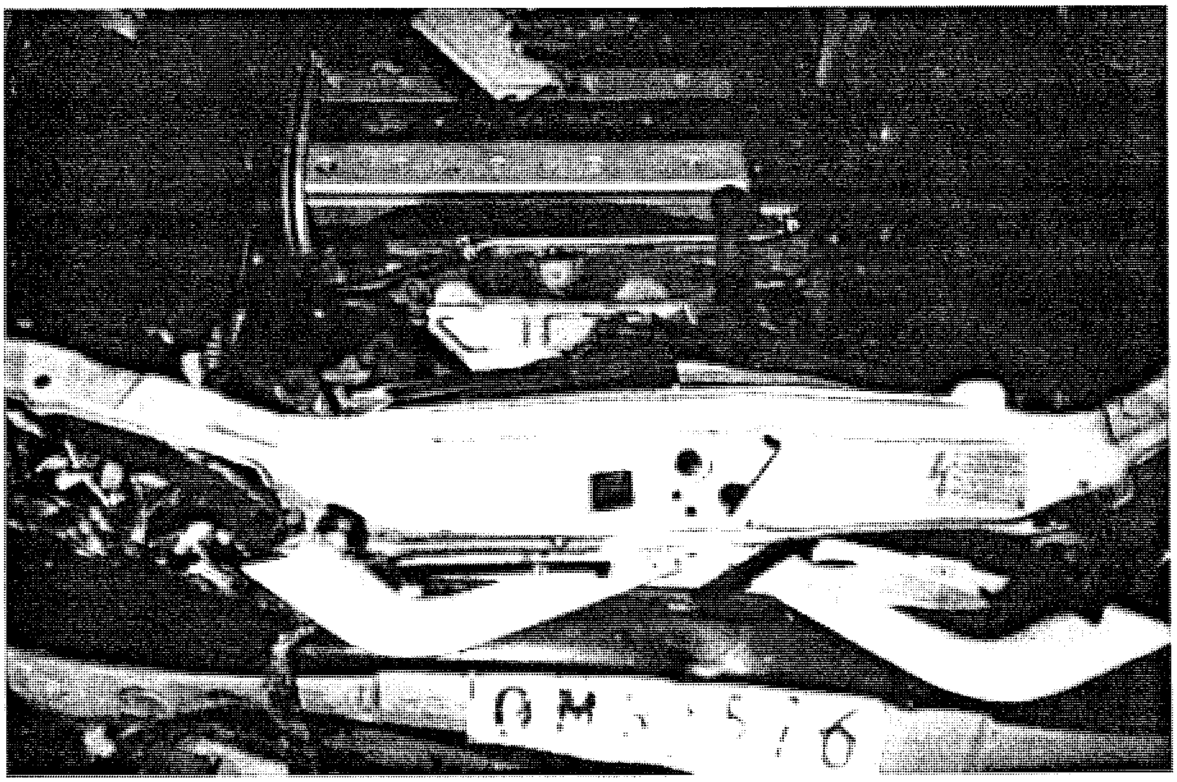


FIGURE A12.6
PHOTOGRAPH OF DAMAGED VEHICLE – 2

A12.5. PARTS COUNT OF AIR-CONDITIONING SYSTEM

A12.5.1 Introduction

The purpose of this section is to undertake a parts count of a typical vehicle air-conditioning system. This data is then used in determining the leak frequency from components located inside the passenger cabin.

Emphasis has been placed on the passenger cabin since incidents involving a leak of refrigerant in the engine bay have been shown not to affect occupant(s) of the passenger cabin.

A12.5.2 Parts Count

A drawing of the basic components of the air-conditioning system is given in **Figure A12.7**. A schematic of this air-conditioning system is given in **Figure A12.8**.

A summary of the parts count of fittings is shown in **Table A12.10** and **Table A12.11**. A reference to each component listed in the table is provided in **Figure A12.8**.

TABLE A12.10
PARTS COUNT OF FITTINGS IN A TYPICAL AIR-CONDITIONING SYSTEM

Air-conditioning System		Fitting Type	Number of Fittings	Ref. in Fig. A12.8
From	To			
Compressor	-	Seal on suction and discharge lines	2	A, B
Compressor	Condenser	'O' ring seal and screwed fitting	2	C, D
Condenser	-	None – seamless with no welded elbows	n/a	
Condenser	Receiver/ Drier	'O' ring seal and screwed fitting	1	E
Receiver/ Drier	Expansion valve	'O' ring seal and screwed fitting	1	F
Expansion valve	-	'O' ring seal and screwed fitting (or flared joint) upstream and downstream	2	G, H
Expansion valve	Evaporator	None – seamless with no welded elbows	n/a	
Evaporator	Compressor	'O' ring seal and screwed fitting	2	I, J

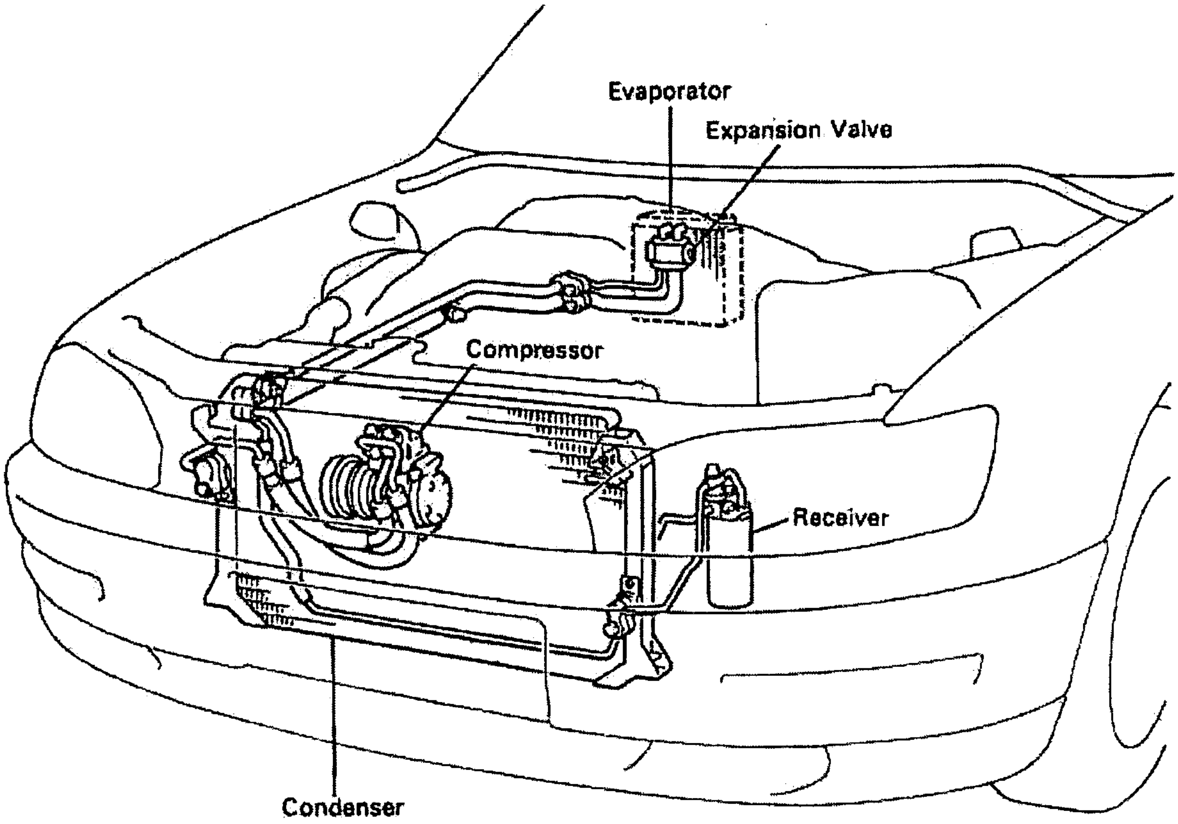
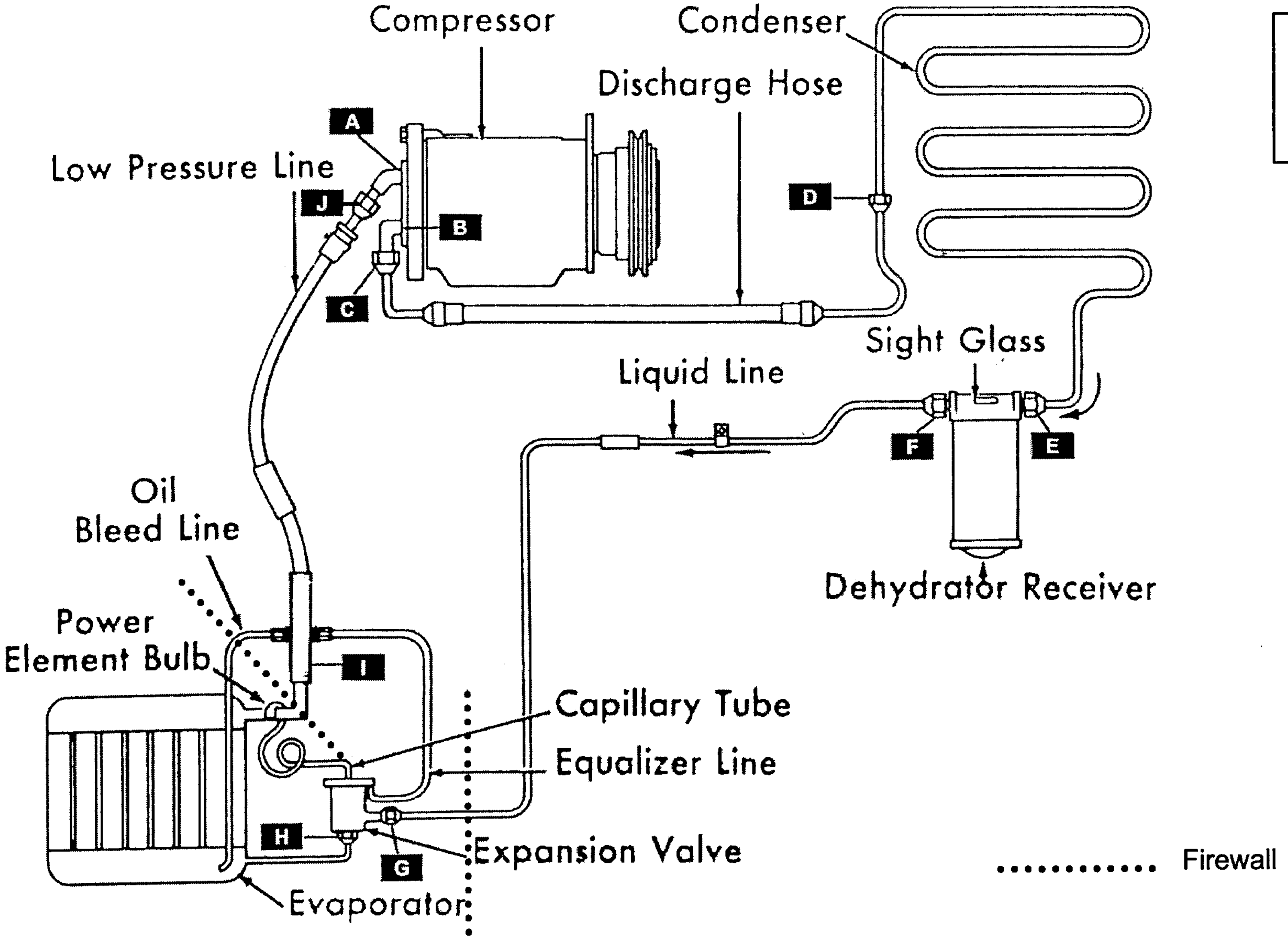


FIGURE A12.7
DRAWING OF TYPICAL VEHICLE REFRIGERATION SYSTEM

FIGURE A12.8
SCHEMATIC OF TYPICAL VEHICLE REFRIGERATION SYSTEM



Using **Table A12.10**, the distribution of the fittings within the vehicle may be done as shown in **Table A12.11**.

As shown in the previous drawings, the location of the various components of the air-conditioning system may be conveniently divided between the engine bay and passenger cabin. These two areas are separated by the firewall.

In discussion with workshops, it was found that Tx valves might be present in either the engine bay or passenger cabin. In general, General Motors Holden and Ford vehicles have their Tx valves in the engine bay whilst most popular Japanese makes have the valves positioned in the passenger compartment.

Conservatively assuming that the thermal expansion valve is located inside the passenger cabin, the number of fittings (and hence potential leak sources) is two or 25% of the total 'O' ring fittings.

TABLE A12.11
DISTRIBUTION OF 'O' RING FITTINGS

Location	**Number of 'O' Ring Fittings**	**% of Total**
Engine Bay	6 (locations C, D, E, F, I, J on **Figure A12.8**)	75
Cabin	2 (locations G, H)	25
Total	8	100

A12.6. FREQUENCY USED IN SAFETY STUDY

A12.6.1 Base Frequencies

The base frequency values for the Safety Study were determined from the survey data obtained from the workshops (**Section A12.2**). Only evaporator and Tx valve base failure frequencies were calculated as they are the only two components that can fail and cause a leak into the passenger compartment of a car. The base frequencies are shown in **Table A12.12**.

TABLE A12.12
BASE FREQUENCY VALUES

Component	Base Frequency Value	Justification
Evaporator	0.00191 evaporator failures /car-year	A range of evaporator leak frequencies per year was obtained from the survey data (0 to 750/year). These values were then used to obtain the evaporator failures/ car-year using the number of cars with air-conditioning repaired by each workshop to do the calculation. The base frequency is an average of these results.
Tx valve fittings	0.043 Tx valve failures /car-year	Similarly, a range of Tx valve leak frequencies per year was obtained from survey data (0.2 to 12/year) and these were used to calculate the Tx valve failures /car-year. The base frequency is an average of these results.

A leak frequency for each leak category (typical, large, catastrophic) was required for use in the risk calculations. The values selected are shown in **Table A12.13**. These values were calculated by distributing the base frequencies given in **Table A12.12** as follows:

Typical (0.01mm)	90% base frequency
Large (0.1mm)	9% base frequency
Catastrophic (1mm)	1% base frequency

Over a total of 46,950 car years there were no 1mm evaporator failures. Using a binomial distribution, the failure frequency for a 1mm leak can be predicted with a 50% confidence limit as:

$$= 1 - (1 - 0.5)^{1/46950}$$
$$= 1.5\text{E} - 05 / \text{car} - \text{year}$$

This value is in close agreement with the value for this category given in **Table A12.13** (1.91E-05/ car-year, for a 1mm evaporator failure).

TABLE A12.13
LEAK FREQUENCY DISTRIBUTION

Component	Leak Category	Leak Size (mm)	Leak Frequency (/ car-year)
Intrinsic			
Evaporator	Typical	0.01	1.72E-03
	Large	0.1	1.72E-04
	Catastrophic	1	1.91E-05
Tx valve	Typical	0.01	3.87E-02
	Large	0.1	3.87E-03
	Catastrophic	1	4.3E-04
Collision			
AC system	Catastrophic	1	1.78E-03 [1]

Note: 1. Ref. 2

A12.6.2 Probabilities Used in Assessment

The probabilities used in the assessment for calculation of the leak frequency and frequency of fire/ explosion due to ignition of the leak are given in **Table A12.14**.

TABLE A12.14
PROBABILITIES USED IN ASSESSMENT

Probability Description	Value	Sensitivity Range	Reference/ Justification
Tx valve inside passenger cabin	0.6	-	Fords and Holdens have Tx valve outside cabin, from **Table A12.15** these make up approximately 40% of Australian new cars sold in 1998, therefore approximately 60% of cars have Tx valve inside passenger cabin.
Overcharged system with refrigerant	0.09	-	Ref.3 gives this value for "fairly simple task performed rapidly or given scant attention".
Moving car	1.8/24 = 0.075	6/24 = 0.25	1.8 hours per person per day are spent in a car on average (Ref.4). Ref.5 gives average mileage per week for cab drivers as 1300 to 3200 km/week; for casual drivers 80-400 km/week. These mileages were averaged to give the sensitivity range shown.
Stationary car	0.925	0.75	Moving car probabilities were subtracted from one to give stationary car probabilities.
Parked inside	0.5	0.7	Estimate
Small car	0.5	-	VFACTS database (Ref. 6)
Medium car	0.1	-	VFACTS database (Ref. 6)
Fresh air vents closed	0.5	-	Estimate
AC on	0.4	0.6	Estimate. 0.25 value from Coldic 1997.
AC off	0.6	0.4	Estimate
Leak in engine bay due to collision	0.99	-	ADL 1995, Ref. 2
Leak in cabin due to collision	0.01	-	ADL 1995, Ref. 2
Ignition			
Immediate ignition probability due to intrinsic failures (car moving)	0.01	-	ADL 1995, Ref. 2
Delayed ignition probability due to intrinsic failures (car moving)	0.01	-	ADL 1995, Ref. 2
Immediate ignition probability due to intrinsic failures (car stationary)	0.001	-	ADL 1995, Ref. 2
Delayed ignition probability due to intrinsic failures (car stationary)	0.001	-	ADL 1995, Ref. 2
Immediate ignition probability due to collision	0.03	-	ADL 1995, Ref. 2
Delayed ignition probability due to collision	0.01	-	ADL 1995, Ref. 2
Ignition probability in the cabin	0.05	-	ADL 1995, Ref. 2
Evaporator damage resulting from collision	0.05	-	ADL 1991, Ref. 7

A12.6.3 Cars Registered in Australia

The numbers of cars sold new in Australia in 1998 was used to determine the proportion of the most popular makes: Ford, Holden, Mitsubishi and Toyota on the road. It was assumed that the new cars sold in 1998 are representative of all cars on the road. The values are shown in **Table A12.15**.

TABLE A12.15
CARS SOLD NEW IN 1998 IN AUSTRALIA

Car Type	% New Sold in Australia in 1998[1]
Ford	18
Holden	20.5
Mitsubishi	10.9
Toyota	15.3
Other	35.2

Note: 1. VFACTS Database, Ref.6.

It can be seen from **Table A12.15** that the proportion of Ford and Holden cars on the road in Australia can be estimated as approximately 40% of all cars. As Fords and Holdens have their Tx valves on the outside of the passenger cabin, while the majority of other makes have the Tx valve inside the passenger cabin, it was assumed for the purposes of this assessment that 40% of all cars have the Tx valve in the engine bay.

Data for the total number of registered cars in Australia was obtained from the Australian Bureau of Statistics. It was estimated that 50% of Australian cars have air-conditioning installed (Ref.1). This data is presented in **Table A12.16**.

TABLE A12.16
TOTAL CARS REGISTERED IN AUSTRALIA

Year	Passenger Vehicles	Campervans	Light Commercial Vehicles	Total	Total with AC
1995	8 628 806	31 835	1 527 212	10 187 853	5 093 927
1996	8 989 136	32 339	1 601 641	10 623 116	5 311 558
1997	9 206 236	33 291	1 632 219	10 871 746	5 435 873
1999[1]	-	-	-	11 600 000	5 800 000

Note: 1. Extrapolation of given data used to estimate the 1999 values.

Serious injury/ fatal crash data was obtained from the Federal Office of Road Safety and is shown in **Table A12.17**.

TABLE A12.17
FATAL/ SERIOUS INJURY CRASH DATA

Year	Number of Fatal/ Serious Injury Crashes	% Total Cars on Road
1992	18 550	0.2
1993	18 901	0.2
1994	19 270	0.2
1995	19 622	0.2
1996	19 280	0.2

A12.6.4 INITIATING FREQUENCIES FOR EVENT TREES

The frequency data given in **Table A12.13** and **Table A12.14** was used in the calculation of the final risk values for the Safety Assessment using event trees. The details of these event tree calculations are given in **Appendix 16**. **Table A12.18** shows the initiating frequencies used for each event.

A sample calculation is given for a small car, 1mm leak (Events 6,8,12):

Initiating Frequency = [(freq. evap. leak 1mm) + (freq. Tx leak 1mm) * (prob. Tx inside cabin) * (prob. Ford)] * (prob. small car)

= (1.91E-05 + 4.3E-04 * 0.6 * 0.1) * 0.5

= 2.25E-05 pa

TABLE A12.18
INITIATING EVENT FREQUENCIES FOR RISK ASSESSMENT

Event Numbers	Event Description	Initiating Frequency / car-year	Method
6, 8, 12	Small car, 1mm leak	2.25E-05	Sum of evaporator and Tx (adjusted to account only for Tx inside the vehicle) leak frequencies for 1mm leak, multiplied by small car percentage
8	Medium/ large car, 1mm leak	2.25E-05	Sum of evaporator and Tx (adjusted to account only for Tx inside the vehicle) leak frequencies for 1mm leak, multiplied by medium and large car percentage
12	Small car, 0.1mm leak	2.02E-04	Sum of evaporator and Tx (adjusted to account only for Tx inside the vehicle) leak frequencies for 0.1mm leak, multiplied by small car percentage
18	Medium car, 1mm leak	4.49E-06	Sum of evaporator and Tx (adjusted to account only for Tx inside the vehicle) leak frequencies for 1mm leak, multiplied by medium car percentage
19	Small car, 1mm leak	2.25E-05	Sum of evaporator and Tx (adjusted to account only for Tx inside the vehicle) leak frequencies for 1mm leak, multiplied by small car percentage
20	Collision	8.90E-05	Leak frequency from AC due to collision multiplied by probability of evaporator damage due to collision

A12.7. REFERENCES

1 NSW Motor Vehicle Repair Industry Association (1996): "Briefing Paper: Alternatives to CFC as Refrigerants in Motor Vehicle Air-Conditioners – Hydrocarbons compared to R134a", Sydney, January.

2 Arthur D. Little (1995): "Risk Assessment of Flammable Refrigerants, Part 3: Car Air-conditioning".

3 Williams, J.C., "A data based method for assessing and reducing Human Error", Proceedings of IEEE 4th Conference on Human Factors in Power Plants, Monterey, California, 1988.

4 Crowe, A. (1999): "Measurement of Air Exchange Rate of Stationary Vehicles and Estimation of In-Vehicle Exposure", Thesis, University of Adelaide.

5 "Retrofitting fleet A/Cs with HFC-134a refrigerant", *Automotive Engineering*, March 1994, pp. 49-51.

6 VFACTS Database(1998): "New Passenger Vehicle Sales by Size, Australia", December.

7 Arthur D. Little (1991): "Non-Inert Refrigerant Study for Automotive Applications – Final Report", Prepared for the US Department of Energy, Office of Transportation Technology, November.

APPENDIX 13

FAILURE RATE DATA (OTHERS)

TABLE OF CONTENTS

A13.1. INTRODUCTION

A13.1.1 General

As outlined in **Appendix 12**, an extensive literature review was conducted in the public arena on air-conditioning systems. Despite the many publications on the subject matter, limited data was available regarding risk assessments and in particular, estimation of leak frequencies.

Very little data was available in the public arena on parameters useful for a Safety Assessment. These parameters include risk assessments, quantification of leaks from air-conditioning systems as well as leak frequency data and failure modes of components. Other important parameters included car ventilation rates, vehicle volumes and air exchange rates.

A13.1.2 Purpose

The purpose of this appendix is to summarise any previous published frequency data relevant for this study.

A13.1.3 Data Sources

Granherne was able to source three published reports related to risk assessment studies and frequency analysis of automobile air-conditioning systems. These data sources are summarised in this appendix:

1. Arthur D. Little Ltd (1995): "Risk Assessment of Flammable Refrigerants" (Ref.1).

2. Arthur D. Little Ltd (1991): "Non-Inert Refrigerant Study for Automotive Applications – Final Report" (Ref.2).

3. Denis Clodic (1997): "Zero Leaks – Limiting Emissions of Refrigerants" (Ref.3).

Each of these reports is addressed separately to give the information contained within it. The data is then summarised for comparison with the data generated by Granherne through the survey work conducted and shown in **Appendix 12**.

Arthur D. Little (ADL) Limited is a US based consulting firm specialising in areas of technical safety and risk management. ADL has conducted two studies on hydrocarbon refrigerant prepared for Calor Gas Limited (1995) and the US Department of Energy (1991). The former study was an independent risk assessment study of Calor Gas hydrocarbon refrigerant products in the application of refrigerated road transport vehicles and automobile air-conditioning systems. The product marketed by Calor Gas is of similar composition to ER12 refrigerant.

The latter study for the US Department of Energy focused on a comparative study between refrigerants in terms of performance. The report also contained a risk assessment of vehicle collisions and experimental data.

Denis Clodic is deputy director of the Centre for Energy Studies of Ecole des Mines de Paris. He is a member of ASHRAE and a member of the United Nations Environment Programme (UNEP) Technical Option Committee (TOC) on Refrigeration under the Technical and Economics Assessment Panel (TEAP) of the Montreal Protocol.

Under ASHRAE, the document focussed on estimating the typical leak rate and frequency from various uses of refrigerants from industrial to vehicle air-conditioning systems. For the vehicle assessment, the author has investigated potential leak sources from the various air-conditioning components.

A13.2. LEAK FREQUENCY DATA

A13.2.1 Arthur D. Little, 1995

A review of the Calor Gas Risk Assessment study revealed the following ADL findings:

Consequence Analysis

- Most leaks that occur from a motor vehicle air-conditioning system are in the engine bay.
- Engine compartment leaks if ignited will have negligible effects in terms of consequences such as explosion.
- Unlikely that leaks in the engine bay will be ignited by hot surfaces (i.e. engine running).
- ADL laboratory tests showed that a vehicle lighter and lit cigarette had insufficient energy to ignite a hydrocarbon mixture.
- Consequence analysis conducted by ADL was recognised as being **conservative** and concentrated on catastrophic releases. The study did not provide a failure modes and effects analysis. It also very conservatively assumed that all leaks were continuous whilst in reality, depressuring occurs thus lowering the leak rate.
- Nevertheless, the explosion assessment for ignited catastrophic releases demonstrated that passengers in the cabin would be exposed to very small overpressures that would decay almost to zero. The bulkhead and dashboard would absorb much of the energy. This injury potential to personnel was minimal.
- Flashfires in the cabin from ignited catastrophic releases would cause very minor burns to the driver and passenger.

Frequency and Risk Analysis

- The total frequency of fires/ explosions that can cause harm to people from ignited CARE refrigerant was estimated to be 3.05E-07 per car per year.
- It was concluded that the use of hydrocarbon refrigerant would have negligible or very small increase in public risk.

- Based upon UK statistics, the probability of leak due to collision was calculated as 1.78E-03 per year of air-conditioning equipped car. ADL has estimated that 99% of leaks resulting from a collision will occur in the engine bay and 1% in the passenger cabin.
- The frequency of a leak rate for a passenger vehicle was estimated from refrigerated road transport systems to be 8.4E-03 per car per year. ADL has estimated that 98% of intrinsic leaks will occur in the engine bay and 2% in the passenger cabin.
- The ignition probabilities for a vehicle involved in a collision with hydrocarbon refrigerant was taken to be 3% for immediate ignition and 1% for delayed ignition.
- The ignition probabilities from a leak of hydrocarbon refrigerant due to intrinsic failure was taken to be 1% for immediate ignition and 1% for delayed ignition.

A13.2.2 Arthur D. Little, 1991

A review of the US Department of Energy study revealed the following ADL findings:

Consequence Analysis

- Most leaks that occur from a motor vehicle air-conditioning system are in the engine bay.
- Jet mixing and dispersion will limit the formation of a flammable mixture in the engine bay and hence ignition potential is very low. Thus any generated explosion overpressure is very low (<< 1psi) due to the open venting at the bottom of the engine compartment.
- Potential ignition sources in the engine bay would be broken battery cables.
- Only 1.5% of crashes result in deformations greater than 6 inches in the vicinity of the A-pillar and instrument panels and the evaporator is typically located at least 12 inches inboard of the passenger side door.
- Considerable deformation and dislocation of the evaporator can occur without causing refrigerant leaks. ADL assigned a probability of 5% for leakage for accidents. Thus full rupture of an evaporator in the event of a crash is considered by ADL to be very low. Laboratory tests demonstrated that the evaporator requires significant force on a typical impaling punch before any leakage occurs.

- Any explosion in the passenger compartment is unlikely to cause injury to passengers as relief would be provided by the windows blowing out.

Frequency and Risk Analysis

- The total frequency of fires that can cause harm to people from ignited hydrocarbon refrigerant was estimated to be 3.50E-07 per car per year and is very low. This assessment was based upon conservative assumptions.
- No credible ignition sources are known for the passenger compartment, and assigned a 5% probability although this value is thought to be very high.
- The frequency of a fire in the engine bay resulting from an ignition of hydrocarbon refrigerant is of the order of 14 to 50E-06 per car per year.
- No databases were available in the United States relating specifically to fires from vehicle accidents.

A13.2.3 Denis Clodic, 1997

By comparison with the ADL risk assessment studies, the ASHRAE publication focussed on estimating the likely emission rates from an air-conditioning system. These were the result of intrinsic failures of the system. Some research was also done in crash or collision situations.

Failure Modes

- Air-conditioning systems do not experience major leaks.
- Losses from an air-conditioning system are due to fugitive emissions (mostly due to hose permeation).
- Hoses in the engine bay in the AC system are made of rubber or plastic, are porous and introduce an intrinsic level of leakage due to permeability.
- Full loss of charge principally occurs from traffic accidents.

Leakage Rates

- The US EPA conducted leak tests of air-conditioning systems using R12 and found the following:
    - average emission rate of refrigerant from the system due to pipe leaks was 0.36 kg/year per vehicle, half of which was fugitive emissions that were not located by leak detectors with a 1g/year sensitivity, and

  - significantly higher level of fugitive emissions can be expected from a system that is operating and one that is not operating.

  This confirms that the intrinsic leak rate is very small (and can be equated to leak category of "pinhole", as used in the present Safety Study).

- Losses from hoses when the air-conditioning system is off and running have been estimated to be a total of 0.88 kg/year.

Frequency and Risk Analysis

- In service company statistics, condenser tubing ruptures due to accidents represent about 10% to 15% of causes of all AC system services. Other ruptures can occur, especially at the crimp on metal fittings of rubber hoses. This confirms ADL findings that a high percentage of air-conditioning system leaks occur in the engine bay following an accident.
- In the United States, the average running time of an automobile air-conditioning system is estimated to be 120 to 200 hours for an average annual travel distance of 24,000 kilometres with an average driving time of 800 hours.

A13.2.4 Summary

Table A13.1 summarises the leak frequencies used in previous studies.

TABLE A13.1
SUMMARY OF DATA USED IN PREVIOUS STUDIES

Parameter	Description	Value	Reference
Frequencies	Intrinsic leak from air-conditioning system (all components)	8.40E-03 per car per year	ADL 1995
	Leak from air-conditioning system due to collision	1.78E-03 per car per year	ADL 1995
	Fire frequency resulting from ignition of intrinsic leak causing injury	3.05E-07 per car per year	ADL 1995
	Fire frequency resulting from ignition of leak due to collision causing injury	3.50E-07 per car per year	ADL 1991
	Fire frequency resulting from ignition of leak	14-50E-06 per car per year	ADL 1991
Leak Probabilities	Probability of leak in engine bay due to intrinsic leak	0.98	ADL 1995
	Probability of leak in cabin due to intrinsic leak	0.02	ADL 1995
	Probability of leak in engine bay due to collision	0.99	ADL 1995
	Probability of leak in cabin due to collision	0.01	ADL 1995
Ignition Probabilities	Immediate ignition probability due to intrinsic failures	0.01	ADL 1995
	Delayed ignition probability due to intrinsic failures	0.01	ADL 1995
	Immediate ignition probability due to collision	0.03	ADL 1995
	Delayed ignition probability due to collision	0.01	ADL 1995
	Ignition probability in the cabin	0.05	ADL 1991
Others	Probability of evaporator damage resulting from collision	0.05	ADL 1991
	Probability of condenser rupture due to collision	0.15	Clodic 1997
	Probability that air-conditioning system is operating during the year (US figures)	0.25	Clodic 1997

A13.3. REFERENCES

1 Arthur D. Little (1991), "Non-Inert Refrigerant Study for Automotive Applications, Final Report".

2 Arthur D. Little (1995), "Risk Assessment of Flammable Refrigerants, Part 3: Car Air-conditioning".

3 Clodic, D. (1997), "Zero Leaks, Limiting Emissions of Refrigerants".

APPENDIX 14

CORRESPONDENCE AND CONSULTATIONS

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A14.1. INTRODUCTION

A14.1.1 Purpose

The purpose of this Appendix is to outline concerns and issues raised by commercial organisations, motorists associations and government departments regarding the use of ER12 hydrocarbon refrigerant.

A14.1.2 Scope

Concerns and issues were gathered from interviews held with the following organisations located in Victoria, South Australia and Western Australia where hydrocarbon refrigerant is used in passenger vehicles:

Distributors

- Bursons (Marketing Manager, distributors of ER12 in Melbourne).
- Motor Traders (Marketing Manager, distributors of ER12 in Adelaide).

Motorists Associations

- SA Royal Automobile Association (Adelaide Head Office).
- The Royal Automobile Club of WA (Perth Head Office).

Government Departments

- Department of Mines and Energy Queensland (Chief Gas Examiner, Brisbane).
- WA Department of Energy (Chief Gas Examiner, Perth).
- TransAdelaide (St. Agnes Depot).

A14.1.3 General

In order to identify issues and concerns regarding the use of ER12 hydrocarbon refrigerant in vehicles, Granherne undertook the following:

- Failure Modes and Effects Analysis (FMEA, **Appendix 2**);
- Hazard Identification (HAZID, **Appendix 3**);
- Workshop Surveys (**Appendix 12**); and
- Consultations.

This Appendix presents findings from consultations with:

- distributors of ER12 product;

- motorists associations; and
- government bodies and departments.

For the purposes of the study, consultations were limited to organisations located in Victoria, South Australia and Western Australia. This was done as hydrocarbon refrigerant products including ER12 are used in these states.

A14.2. CONSULTATIONS

A14.2.1 Introduction

The following tables summarise the issues regarding hydrocarbon refrigerant which were discussed with distributors, motorists associations and government departments. Both distributors interviewed initially had concerns regarding flammability issues with the product. However, upon internal reviews and discussions with Boral Energy, they were satisfied that the product did not pose a risk to workshops or end-users (i.e. motorists).

This was also the view held by a South Australian public transport section who undertook an internal safety and health risk assessment. They concluded that the risk of using ER12 product in their bus fleet was minimal and acceptable.

Motorists associations were non-committal towards the use of hydrocarbon refrigerant. Both organisations believed that the ER12 product would be accepted if the risk to the driver was proven to be acceptable.

A14.2.1.1 Distributors

A summary of the main comments from the distributors is shown in **Table A14.1**.

A14.2.1.2 Motorists Associations

A summary of the main comments from the distributors is shown in **Table A14.2**.

A14.2.1.3 Government

A summary of the main comments from government bodies and departments is shown in **Table A14.3**.

TABLE A14.1
COMMENTS FROM DISTRIBUTORS

Distributor	Issue/ Concern	Comments
Bursons (Melbourne, Victoria)	ER12 Gas Bottles	- Product has been sold since October 1995 - No leaking cylinders - No damaged cylinders - Of the 8,000 units sold only one faulty unit (internal valve passing– not a safety issue)
	Packaging/ Labelling	- Packaging and labelling of product was done in consultation with the Victorian Dangerous Goods inspector
	Fire Events	- Unaware of fire incidents involving ER12 - False rumours of fires and explosions in workshops. When investigated by Bursons revealed no evidence
Motor Traders (Adelaide, South Australia)	ER12 Gas Bottles	- Product has been sold since October 1998 - No leaking cylinders - No damaged cylinders - Of the 400 units sold only one faulty unit (internal dip tube – not a safety issue)
	Fire Events	- No reported incidents from workshops using the product
	Packaging	- Could be enhanced by placing “charge charts” into box prior to sealing
	Public Risk	- Group Manager believed that product has an acceptable risk to the public due to minor quantity used - Risk is comparable to that of vehicle containing 60 litres of LPG or petrol - Product is more environmentally friendly than current refrigerants

TABLE A14.2
COMMENTS FROM MOTORISTS ASSOCIATIONS

Distributor	**Issue/ Concern**	**Comments**
Royal Automobile Association of SA, Inc. (RAA)	Public Risk	- RAA has no formal commitment to the use of hydrocarbon refrigerant - Safety Report needs to determine risk involved with the flammability of the product - Safety Report needs to determine if risk from product to the public (i.e. motorist) is acceptable
	Fire Events	- RAA had not heard of any proven fire incidents involving product
	Others	- RAA views that product will currently fill the lower end of the market - Safety Case should highlight performance characteristics of the product
The Royal Automobile Club of WA Inc. (RAC)	Workshop Risk	- Safety Report should investigate the handling of a hydrocarbon product at workshop level - Safety Report should comment on the level of training provided to workshops on product handling and use
	Public Risk	- Safety Report should investigate the situation of a vehicle parked overnight
	Others	- Safety Case should provide a statement whether the refrigerant can be used in existing vehicle air-conditioning systems - Recognised that the product is more environmentally friendly than current refrigerants - Safety Case needs to explain mixing of refrigerant in cabin following a leak

TABLE A14.3
COMMENTS FROM STATE GOVERNMENT DEPARTMENTS

Distributor	Issue/ Concern	Comments
Western Australian Department of Energy	Public Risk	- Safety Report needs to determine the risk to the public and acknowledge whether it is safe for use or not - Safety Report needs to determine if risk from product to the public (ie motorist) is acceptable
	Fire Events	- Department had not heard of any proven fire incidents involving product - Safety Report needs to investigate potential ignition sources - Safety Report needs to discuss how refrigerant leak is dissipated
	Others	- Department has issued a position paper on the use of hydrocarbon refrigerants - Motor Traders Association in WA is in agreement with Departments position
TransAdelaide (St. Agnes Depot)	Public Risk	- An internal risk management study was undertaken on product use - Risk was found to be acceptable to driver and public
	Others	- At least 100 buses use the product for driver comfort - Maintenance downtime has decreased significantly (greater than 80%) from use of product
Department of Mines and Energy (DME) Queensland		- The concerns raised by the QLD DME have been addressed throughout the Safety Study (see **Section 1.4** of the main report)

APPENDIX 15

APPROVAL REQUIREMENTS FOR QUEENSLAND

The approval requirement in Queensland for use of hydrocarbon refrigerants in automobile air-conditioners consists of obtaining an approval under Section 4(c) of Regulation 108A, Queensland Gas Regulation Act 1989. The approval authority is the Chief Gas Examiner.

Section 4(c):

> *As an alternative to 4(a) and 4(b) above, approval may be sought from the Chief Gas Examiner for a particular installation or class of installation.*
>
> *Applications for such approval must be supported by a full and comprehensive safety report.*
>
> *The report must include an assessment of hazard and risk in all phases of the life cycle of the refrigeration or air-conditioning system including installation, maintenance, use, decommissioning, disposal and obsolescence. The assessment of hazard and risk must include at least the following-*
>
> - *an assessment of the effect on the safety and reliability of the refrigeration or air-conditioning system and its components that a change of refrigerant may have;*
> - *identification of all hazards associated with each life cycle phase listed above. Appropriate hazard identification models such as Hazard and Operability Study (HAZOP), Failure Modes and Effects Analysis (FMEA), Fault Tree Analysis and Event Tree Analysis must be used;*
> - *an analysis of such hazards in terms of their consequences and their likelihood of occurrence;*
> - *assessment of the vulnerability of people who could be affected by an incident involving the refrigeration or air-conditioning system;*
> - *consideration of the controls and other factors that could be implemented to mitigate the hazard and risk to all phases of the life cycle. The decision to accept or reject any control measure should be justified;*
> - *assessment and qualification of risk for each life cycle phase. The risk must be presented as a comparison with the original design. Where a finite population is known, an estimate of the likely number of injuries and fatalities per year should be presented. The assessment should consider qualitative as well as quantitative outputs of the analysis. In particular this must include environmental risk, avoidable risk and societal risk.*

All information and data sources must be referenced, the results of testing presented and all assumptions clearly stated.

The installation of flammable hydrocarbon gas in a refrigeration or air-conditioning system must comply with Technical Standard 2 above and one other Technical Standard listed above.

TRAINING FOR WORKERS IN THE USE OF THE GASES IN REFRIGERATION OR AIR-CONDITIONING

From 31 December 1995, all persons involved in the commissioning, installation, service, repair, maintenance or de-commissioning of refrigeration or air-conditioning systems using flammable hydrocarbon gases must be licensed under the Gas Act. Training courses will be introduced which will provide the safety training necessary to work with these gases. Persons currently working with these gases may apply for a licence at any time and will be assessed in terms of their knowledge and experience.

SAFE OPERATION OF REFRIGERATION OR AIR-CONDITIONING WORKSHOPS IN WHICH THE GASES ARE USED

From 31 December 1995, all workshops at which the commissioning, installation, service, repair, maintenance or de-commissioning of air-conditioning or refrigeration systems using flammable hydrocarbon gases will be carried out must conform to Australian Standard AS 2746-1985 "Australian Gas Vehicles Workshops Code", Clauses 2.3(b), (c), (d) and Clause 2.4, and must be equipped with an electronic gas leak detector.

Areas where flammable hydrocarbon gases are stored or used are classified as hazardous areas in accordance with Australian Standard AS 2430 Part 1 –1997 and Part 3-1991 "Classification of Hazardous Areas" and must conform to the requirements of Australian Standards dealing with installations in hazardous areas. They must also conform to Australian Standard AS 1596-1989 "Storage and Handling of LP Gas".

SIGNS, SAFETY NOTICES AND CERTIFICATON THAT MUST BE DISPLAYED OR PROVIDED

From the date of commencement of the Approval, where flammable hydrocarbon gas is used in a refrigeration or air-conditioning system, a clearly marked data plate must be fitted indicating that the refrigeration or air-conditioning system contains flammable gas. The data plate shall be affixed to the installation in such a position that it will be easily observed by any person carrying out work on the system or any associated equipment.

In workshops, where work is being carried out with flammable hydrocarbon gases, "No Smoking" signs as described in AS 1319-1994 must be displayed.

Licensed persons supplying flammable hydrocarbon gas to an installation shall provide to the owner of that installation a certificate stating the work has been carried out in accordance with the requirements of the Gas Act and the Regulations. This certificate is required to contain –

- *the name and address of the owner of the installation;*
- *the type of installation;*
- *the quantity of flammable hydrocarbon gas used;*
- *the certificate stated above;*
- *the name, licence number and signature of the licensed person.*

A copy of the certificate is to be retained by the licensed person and be made available to a gas examiner on request.

A table listing the DME requirements has been provided in the main report (**Table 1.2**) with the appropriate cross-references.

APPENDIX 16

RISK ASSESSMENT

TABLE OF CONTENTS

A16.1. INTRODUCTION

This Appendix details the methodology, calculations and results of the risk assessment part of the Safety Study. The risk assessment was performed using event trees which are shown in the following sections. The frequencies and probabilities used in the calculations were taken from the data presented in **Appendix 12** and **Appendix 13**.

The incident scenarios that were analysed were those carried forward from the consequence analysis as listed in **Appendix 7**. Incidents were chosen for further analysis based on whether they had the potential to cause a concentration of ER12 in the passenger cabin greater than 50% LFL.

A16.2. METHODOLOGY

A16.2.1 Incident Scenarios Carried Forward for Risk Assessment

The incidents carried forward for risk analysis are shown in **Table A16.1**. No engine bay releases were carried forward because they were shown not to affect the passenger cabin (**Appendix 8**).

TABLE A16.1
PASSENGER CABIN INCIDENTS CARRIED FORWARD FOR ANALYSIS

ID No.	No.	Vehicle Status	Car Type	Vent Status	AC Status	Hole Size (mm)	Concn > 50% LFL
N-1	6	Moving	Small	Closed	On	1	Yes
N-7	8	Moving	All	Closed	Off	1	Yes
N-4	12	Stationary (inside)	Small	Closed	Off	0.1, 1	Yes
N-8	18	Overcharged	Medium	Closed	Off	1	Yes
N-8	19	Overcharged	Small	Closed	On/ Off	1	Yes
N-3	20	Collision	All	-	-	-	Yes

Note: ID No. refers to the numbering of incidents in **Appendix 3**.

Each of these incidents was analysed separately to give the various outcome frequencies. The outcomes used in this study following a release of ER12 refrigerant were:

- Diffuse fire (due to immediate ignition of ER12 refrigerant).
- Flashfire/ explosion (due to delayed ignition of ER12 refrigerant).
- No effect to passenger (due to safe dispersion of ER12 refrigerant).

The individual event frequencies could then be summed for each car type (small, medium, large) and for each incident outcome (diffuse fire, flashfire/ explosion, no effect).

A16.2.2 Event Tree Analysis

Event Tree Analysis (ETA) is applied when an incident scenario can result in a variety of consequences. For this Safety Study, ETA identifies and evaluates potential accident outcomes that might result following a leak of ER12 refrigerant, normally called an initiating event. ETA is an inducting reasoning technique which is used to study the ultimate frequency and consequences of events, working from cause to effect. Event trees are logic diagrams showing the alternative ways in which a system can fail after a given initial event.

An ETA is a development of an incident from the initiating event through to the consequences resulting from the circumstances or state of the vehicle at the time of the event.

The probabilities of stated conditions were obtained from survey data and past risk assessment studies.

A16.2.2.1 Base Case and Sensitivity Analyses

The following case studies were investigated in the Safety Study as given in **Table 16.2**.

TABLE 16.2
CASE STUDIES INVESTIGATED IN SAFETY STUDY

Case Study	Description	Variable	Justification
Base	Risk values calculated based upon values given in **Appendix 12** and **Appendix 13**	-	-
Sensitivity 1	Stationary (Incident 12)	The probability of a car being parked in the open was changed from 0.5 to 0.7	It was postulated that in Queensland, or in sub-tropical conditions, cars are parked more commonly in carports or in the open rather than garages. Carports are classed for the purposes of air exchange rates as being in the open air
Sensitivity 2	Moving (Incident 6, 8)	The probability that a car would be moving was changed from 0.075 to 0.25	6 hours per day was seen as a reasonable average upper bound for the number of hours per day a car is moving due to occupations such as Taxi driving where a person is in a moving car for their working day
Sensitivity 3	Moving (Incident 6, 8)	The probability that the AC is on was changed from 0.4 to 0.6	In QLD, it was postulated that the air-conditioning system in a car may be on for up to 60% of the year due to the higher temperatures experienced there
Sensitivity 4	Stationary (Incident 6, 8, 12)	The probability of ignition was changed from 0.001 to 0.01	Although the number of ignition sources present in a stationary vehicle (engine off) is considerably less than when the vehicle is in operation, assumed ignition probability is the same for all modes

A16.3. CALCULATIONS AND RESULTS

A16.3.1 Introduction

Each event tree for the Base Case is presented in this section to show the calculation of all incident frequencies. The base frequencies and probabilities used in the event trees were taken from **Table A12.13** and **Table A12.14**, in **Appendix 12**.

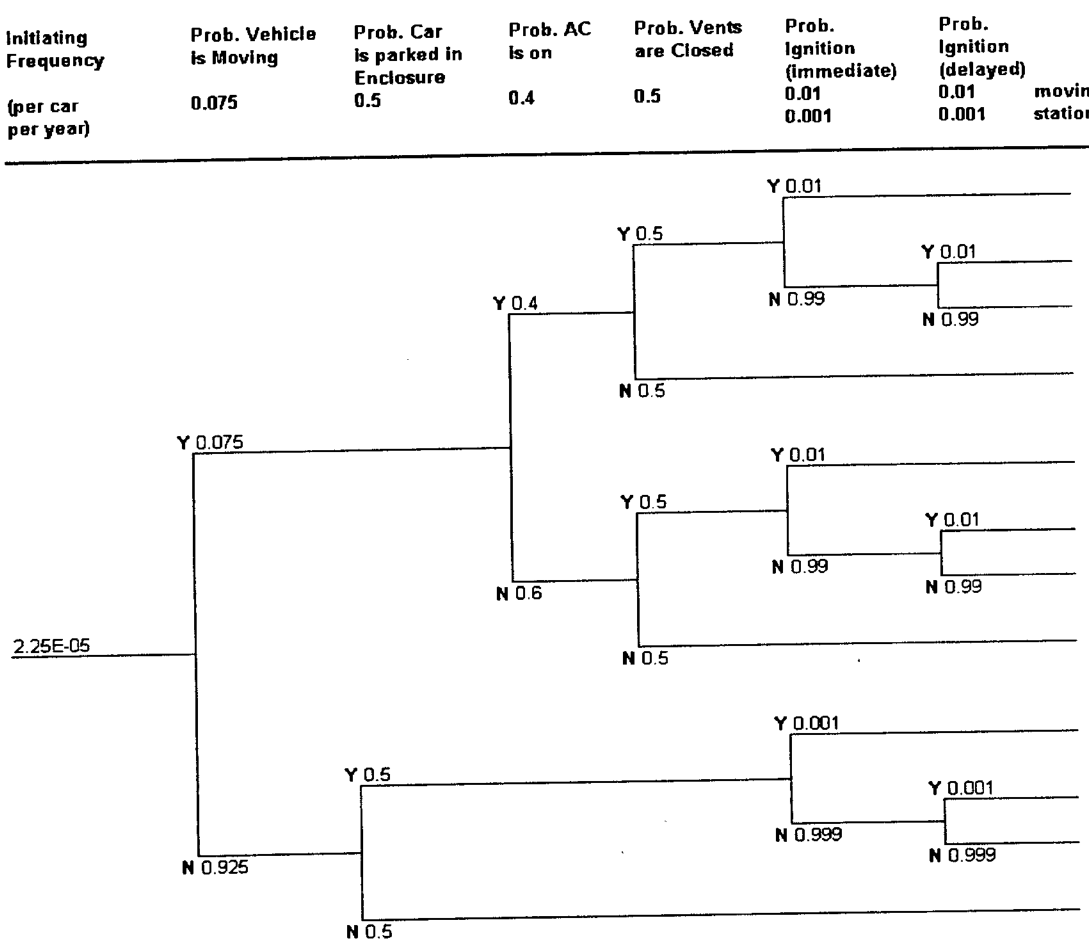
Two sensitivity cases were also undertaken to allow for some variation in incident probabilities. The changes made to the Base Case figures are given and the results of the event trees shown.

A16.3.2 Base Case Event Trees

The results of the Base Case Event Trees are shown in **Table A16.3**.

TABLE A16.3
BASE CASE RESULTS

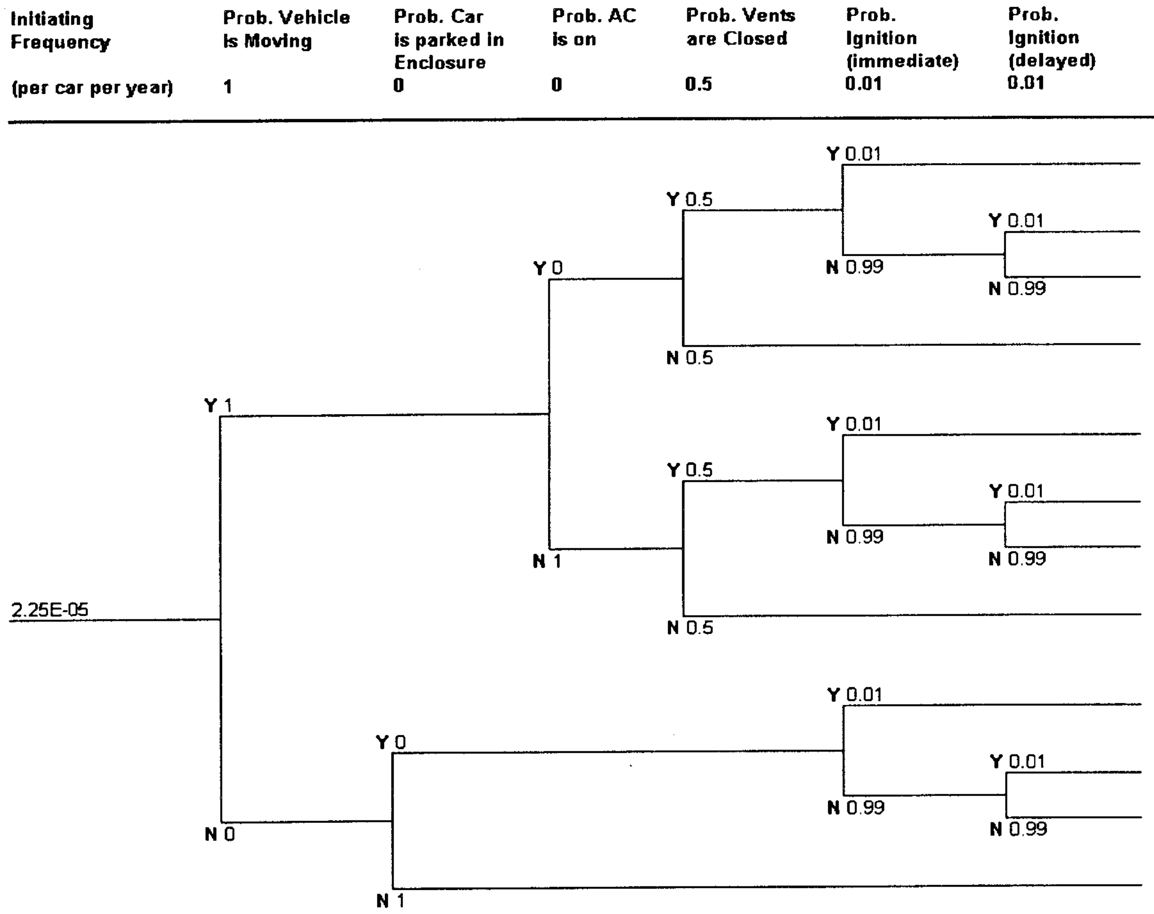
Event No.	Event Description	Outcome (/ car-year)								
		Diffuse Fire			Flashfire/ Explosion			No Effect/ Safe Dispersion		
		S	M	L	S	M	L	S	M	L
6	Small car, moving, vents closed, AC on, 1mm leak	3.4E-09	-	-	3.3E-09	-	-	6.7E-07	-	-
8	All cars, moving, vents closed, AC off, 1mm leak	5.1E-09	2.3E-08	9.0E-08	5.0E-09	2.2E-08	9.0E-08	1.0E-06	4.5E-06	1.8E-05
12	Small car, stationary, inside, 0.1 and 1mm leak	1.1E-07	-	-	1.1E-07	-	-	2.2E-04	-	-
18	Medium car, overcharged, AC off, 1mm leak	-	1.2E-09	-	-		-	-	4.0E-07	-
19	Small car, overcharged, AC off, 1mm leak	6.1E-09	-	-	6.0E-09	-	-	1.6E-06	-	-
Sub-Total		1.3E-07	2.4E-08	9.0E-08	1.3E-07	2.2E-08	9.0E-08	2.3E-04	4.9E-06	1.8E-05
20	Collision	2.7E-08			4.3E-09			8.9E-05		
Total		2.7E-07			2.4E-07			3.4E-04		



Outcome		Event 6	Event 12	Event 8
diffuse fire at source	3.37E-09	3.37E-09		
flashfire/ explosion in cabin	3.33E-09	3.33E-09		
no injury to persons in cabin	3.30E-07	3.30E-07		
no injury to persons in cabin	3.37E-07	3.37E-07		
diffuse fire at source	5.05E-09			5.05E-09
flashfire/ explosion in cabin	5.00E-09			5.00E-09
no injury to persons in cabin	4.95E-07			4.95E-07
no injury to persons in cabin	5.05E-07			5.05E-07
diffuse fire at source	1.04E-08		1.04E-08	
flashfire/ explosion in cabin	1.04E-08		1.04E-08	
no injury to persons in cabin	1.04E-05		1.04E-05	
no injury to persons in cabin	1.04E-05		1.04E-05	
Summary- Total	2.25E-05	6.74E-07	2.08E-05	1.01E-06
diffuse fire at source	1.88E-08	3.37E-09	1.04E-08	5.05E-09
flashfire/ explosion in cabin	1.87E-08	3.33E-09	1.04E-08	5.00E-09
no injury to persons in cabin	2.24E-05	6.67E-07	2.07E-05	1.00E-06

FIGURE A16.1

EVENT TREE FOR INCIDENTS 6,8, 12: SMALL CAR, 1mm LEAK



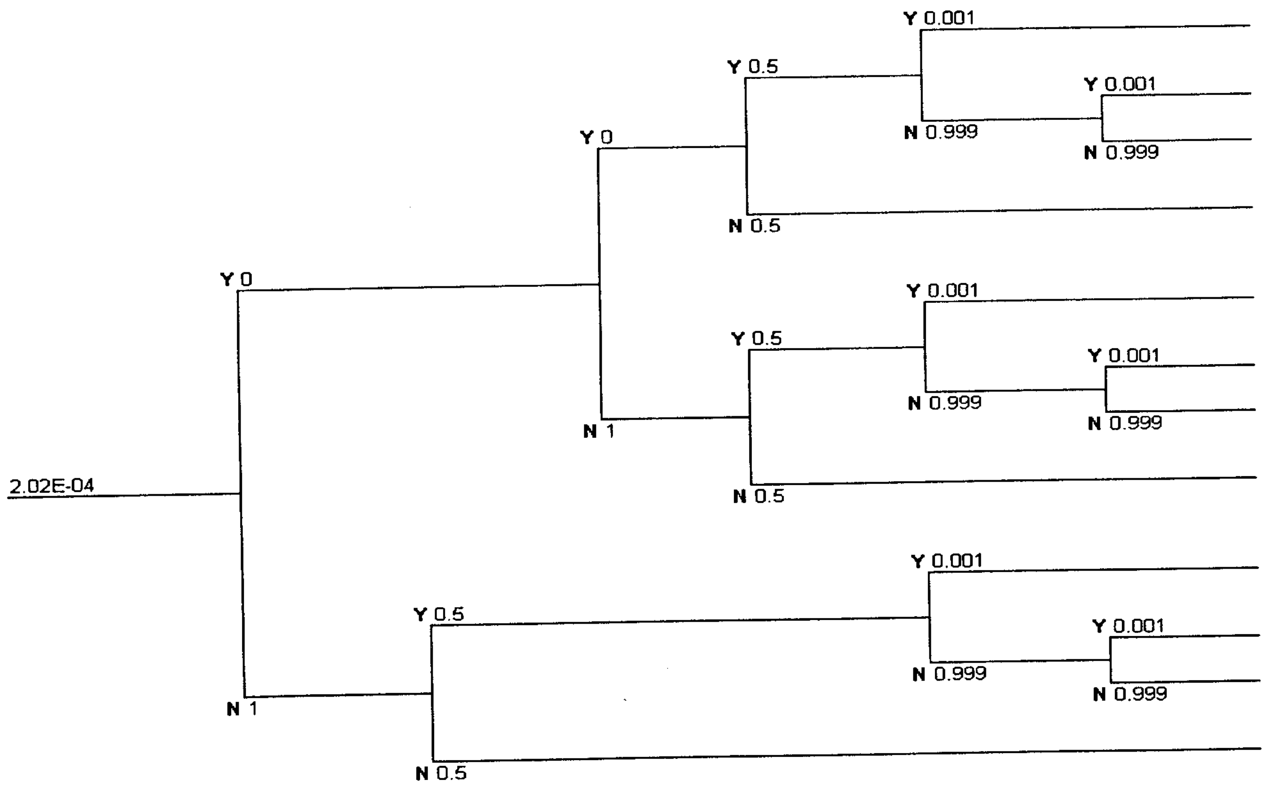
Outcome		Event 8 (M&L)	Event 8 (medium)	Event 8 (large)
diffuse fire at source	0.00E+00			
flashfire/ explosion in cabin	0.00E+00			
no injury to persons in cabin	0.00E+00			
no injury to persons in cabin	0.00E+00			
diffuse fire at source	1.12E-07	1.12E-07	2.25E-08	8.98E-08
flashfire/ explosion in cabin	1.11E-07	1.11E-07	2.22E-08	8.89E-08
no injury to persons in cabin	1.10E-05	1.10E-05	2.20E-06	8.80E-06
no injury to persons in cabin	1.12E-05	1.12E-05	2.25E-06	8.98E-06
diffuse fire at source	0.00E+00			
flashfire/ explosion in cabin	0.00E+00			
no injury to persons in cabin	0.00E+00			
no injury to persons in cabin	0.00E+00			
Summary- Total	2.25E-05	2.25E-05	4.49E-06	1.80E-05
diffuse fire at source	1.12E-07	1.12E-07	2.25E-08	8.98E-08
flashfire/ explosion in cabin	1.11E-07	1.11E-07	2.22E-08	8.89E-08
no injury to persons in cabin	2.22E-05	2.22E-05	4.45E-06	1.78E-05

Note:
- Manipulating event tree to provide value ONLY for Event 8
- As split between cars is 50% small, 10% medium and 40% large, had to adjust when only medium and large vehicles present.

FIGURE A16.2

EVENT TREE FOR INCIDENT 8: MEDIUM AND LARGE CARS, 1mm LEAK

Initiating Frequency (per car per year)	Prob. Vehicle is Moving	Prob. Car is parked in Enclosure	Prob. AC is on	Prob. Vents are Closed	Prob. Ignition (immediate)	Prob. Ignition (delayed)
	0	0.5	0	0.5	0.001	0.001

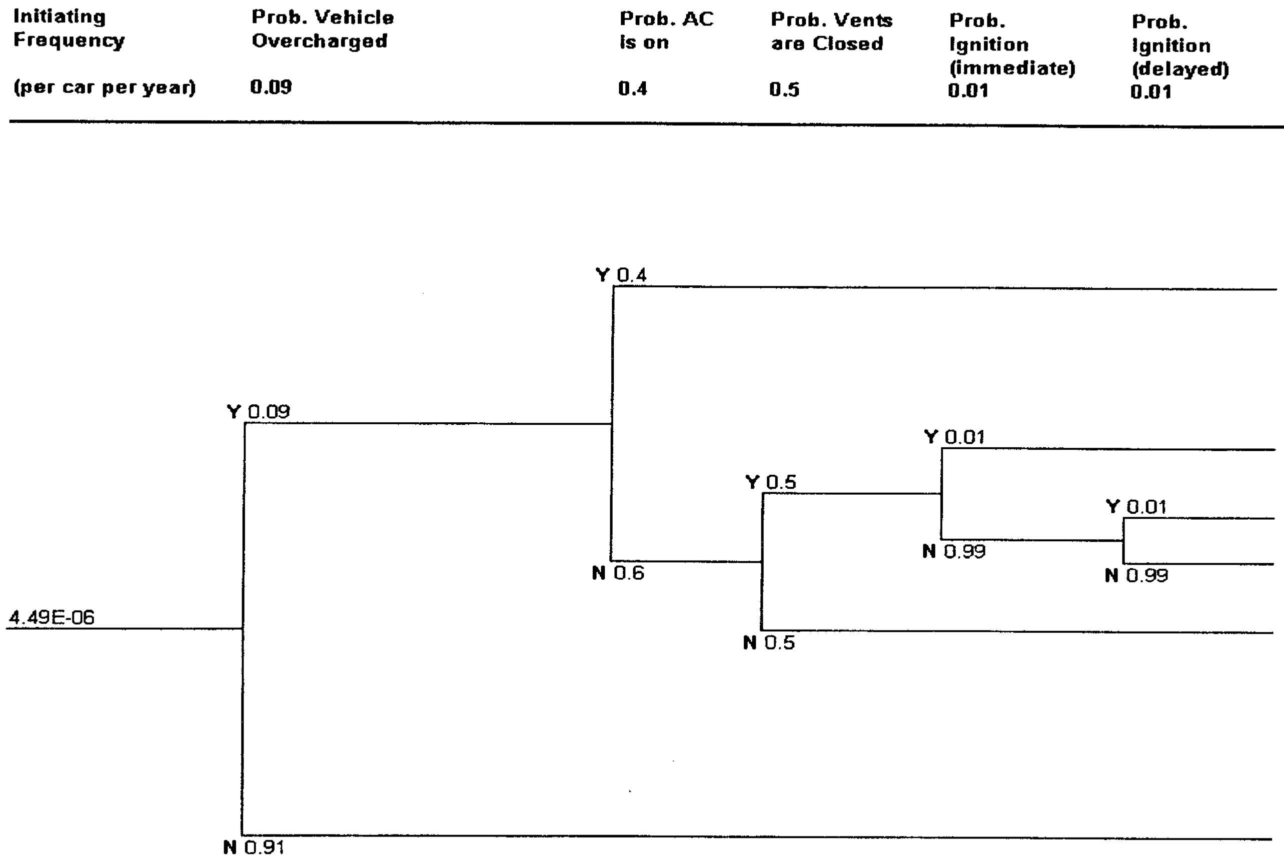


Outcome		Event 12
diffuse fire at source	0.00E+00	
flashfire/ explosion in cabin	0.00E+00	
no injury to persons in cabin	0.00E+00	
no injury to persons in cabin	0.00E+00	
diffuse fire at source	0.00E+00	
flashfire/ explosion in cabin	0.00E+00	
no injury to persons in cabin	0.00E+00	
no injury to persons in cabin	0.00E+00	
diffuse fire at source	1.01E-07	1.01E-07
flashfire/ explosion in cabin	1.01E-07	1.01E-07
no injury to persons in cabin	1.01E-04	1.01E-04
no injury to persons in cabin	1.01E-04	1.01E-04
Summary- Total	2.02E-04	2.02E-04
diffuse fire at source	1.01E-07	1.01E-07
flashfire/ explosion in cabin	1.01E-07	1.01E-07
no injury to persons in cabin	2.02E-04	2.02E-04

Note:
- Manipulate event tree to provide values ONLY for incident 12.

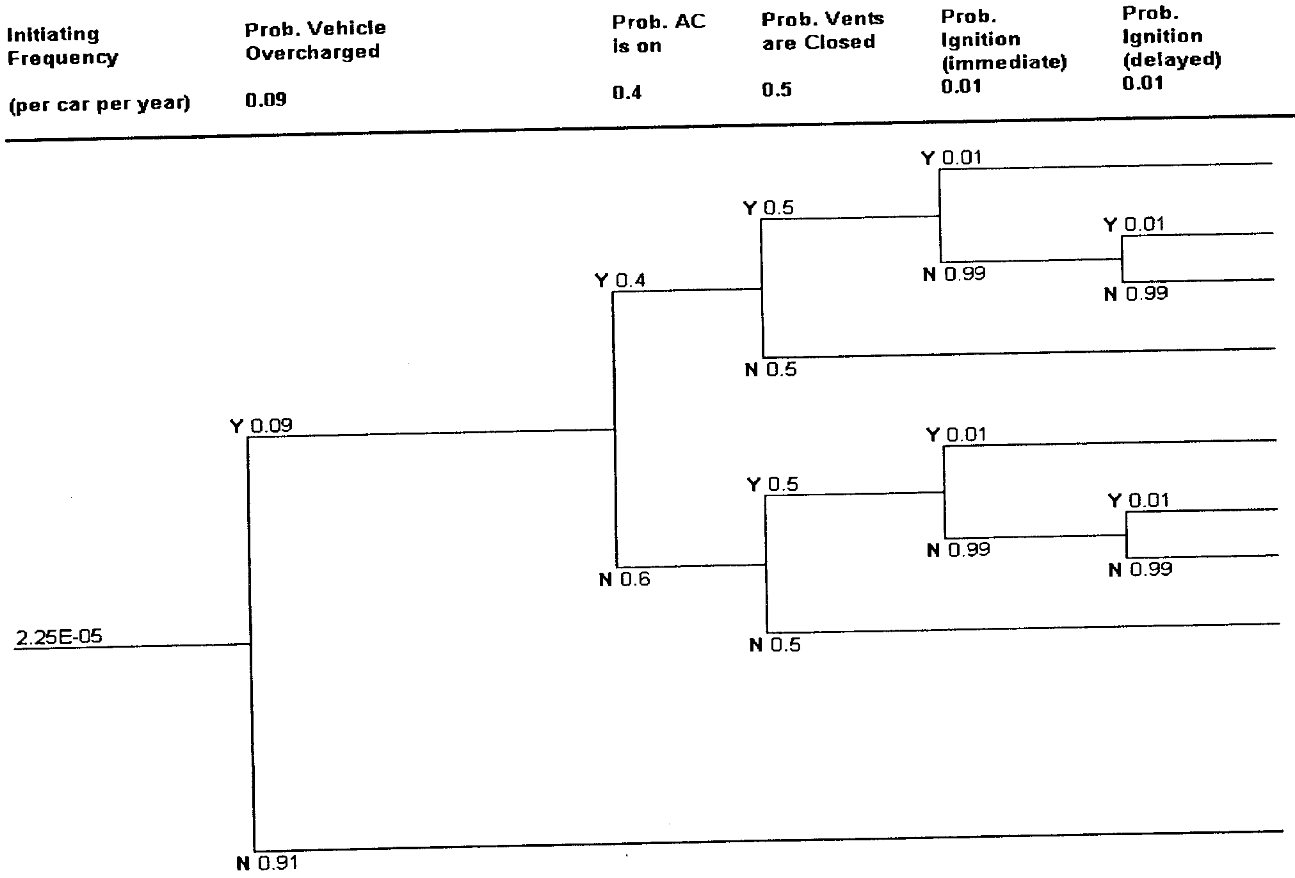
FIGURE A16.3

EVENT TREE FOR INCIDENT 12: SMALL CAR, 0.1mm LEAK



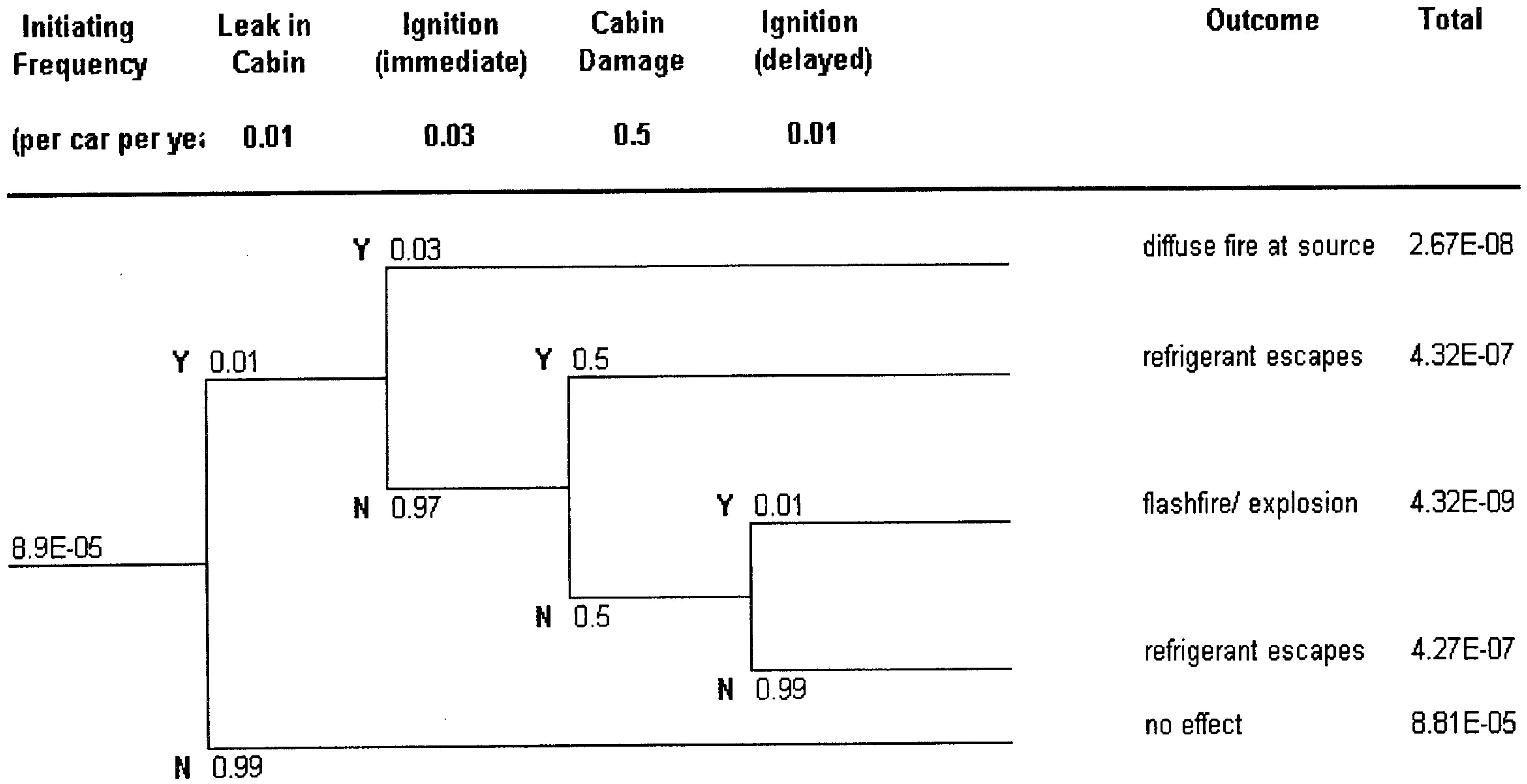
Outcome		Event 18
no injury to persons in cabin	1.62E-07	1.62E-07
diffuse fire at source	1.21E-09	1.21E-09
flashfire/ explosion in cabin	1.20E-09	1.20E-09
no injury to persons in cabin	1.19E-07	1.19E-07
no injury to persons in cabin	1.21E-07	1.21E-07
Car is not overcharged and falls under previous event tree developed for Event B (medium car - 1mm leak)	4.09E-06	4.09E-06
Summary- Total	4.49E-06	4.49E-06
diffuse fire at source	1.21E-09	1.21E-09
flashfire/ explosion in cabin	1.20E-09	1.20E-09
no injury to persons in cabin	4.02E-07	4.02E-07
To event tree B	4.09E-06	4.09E-06

FIGURE A16.4
EVENT TREE FOR INCIDENT 18: OVERCHARGING, MEDIUM CAR



Outcome		Event 19
diffuse fire at source	4.04E-09	4.04E-09
flashfire/ explosion in cabin	4.00E-09	4.00E-09
no injury to persons in cabin	3.96E-07	3.96E-07
no injury to persons in cabin	4.04E-07	4.04E-07
diffuse fire at source	6.06E-09	6.06E-09
flashfire/ explosion in cabin	6.00E-09	6.00E-09
no injury to persons in cabin	5.94E-07	5.94E-07
no injury to persons in cabin	6.06E-07	6.06E-07
Car is not overcharged and falls under previous event tree developed for Event 6,8,12 (small car - 1mm leak)	2.04E-05	2.04E-05
Summary- Total	2.25E-05	2.25E-05
diffuse fire at source	6.06E-09	6.06E-09
flashfire/ explosion in cabin	6.00E-09	6.00E-09
no injury to persons in cabin	1.60E-06	1.60E-06
To event trees	2.04E-05	2.04E-05

FIGURE A16.5
EVENT TREE FOR INCIDENT 19: OVERCHARGING, SMALL CAR



Summary - Total:	8.90E-05
diffuse fire at source	2.67E-08
refrigerant escapes	8.90E-05
flashfire/ explosion	4.32E-09

FIGURE A16.6
EVENT TREE FOR INCIDENTS 20: COLLISION

A16.3.3 Sensitivity Case 1

As given in **Table A16.2**, Sensitivity Case 1 involved changing the probability of a stationary vehicle being parked outside or inside. This change affected only the results for Incident 12, as it was the only incident carried forward to this part of the analysis where the car is stationary. The resulting event frequencies are shown in **Table A16.4**.

TABLE A16.4
SENSITIVITY CASE 1 RESULTS

Event No.	Event Description	Outcome (/ car-year)								
		Diffuse Fire			Flashfire/ Explosion			No Effect/ Safe Dispersion		
		S	M	L	S	M	L	S	M	L
6	Small car, moving, vents closed, AC on, 1mm leak	3.4E-09	-	-	3.3E-09	-	-	6.7E-07	-	-
8	All cars, moving, vents closed, AC off, 1mm leak	5.1E-09	2.3E-08	9.0E-08	5.0E-09	2.2E-08	9.0E-08	1.0E-06	4.5E-06	1.8E-05
12	Small car, stationary, inside, 0.1 and 1mm leak	6.7E-08	-	-	6.7E-08	-	-	2.2E-04	-	-
18	Medium car, overcharged, AC off, 1mm leak	-	1.2E-09	-	-	1.2E-09	-	-	4.0E-07	-
19	Small car, overcharged, AC off, 1mm leak	6.1E-09	-	-	6.0E-09	-	-	1.6E-06	-	-
Sub-Total		8.1E-08	2.4E-08	9.0E-08	8.1E-08	2.3E-08	9.0E-08	2.3E-04	4.8E-06	1.8E-05
20	Collision	2.7E-08			4.3E-09			8.9E-05		
Total		2.2E-07			2.0E-07			3.4E-04		

A16.3.4 Sensitivity Case 2

The probability of whether the car would be moving or stationary was changed for this sensitivity case. This change affected Incidents 6, 8 and 12 only. The resulting event frequencies are shown in **Table A16.5**.

TABLE A16.5
SENSITIVITY CASE 2 RESULTS

Event No.	Event Description	Outcome (/car-year)								
		Diffuse Fire			Flashfire/ Explosion			No Effect/ Safe Dispersion		
		S	M	L	S	M	L	S	M	L
6	Small car, moving, vents closed, AC on, 1mm leak	1.1E-08	-	-	1.1E-08	-	-	2.2E-06	-	-
8	All cars, moving, vents closed, AC off, 1mm leak	1.7E-08	2.3E-08	9.0E-08	1.7E-08	2.2E-08	9.0E-08	3.3E-06	4.5E-06	1.8E-05
12	Small car, stationary, inside, 0.1 and 1mm leak	1.1E-07	-	-	1.1E-07	-	-	2.2E-04	-	-
18	Medium car, overcharged, AC off, 1mm leak	-	1.2E-09	-	-	1.2E-09	-	-	4.0E-07	-
19	Small car, overcharged, AC off, 1mm leak	6.1E-09	-	-	6.0E-09	-	-	1.6E-06	-	-
Sub-Total		1.4E-07	2.4E-08	9.0E-08	1.4E-07	2.3E-08	9.0E-08	2.3E-04	4.9E-06	1.8E-05
20	Collision	2.7E-08			4.3E-09			8.9E-05		
Total		2.8E-07			2.6E-07			3.4E-04		

A16.3.5 Sensitivity Case 3

The probability that the air-conditioning system would be on was varied for this sensitivity case. The resulting outcomes are presented in **Table A16.7**. Changes occurred for Incidents 6, 8, 18 and 19.

TABLE A16.7
SENSITIVITY CASE 3 RESULTS

Event No.	Event Description	Outcome (/car-year)								
		Diffuse Fire			**Flashfire/ Explosion**			**No Effect/ Safe Dispersion**		
		S	**M**	**L**	**S**	**M**	**L**	**S**	**M**	**L**
6	Small car, moving, vents closed, AC on, 1mm leak	5.1E-09	-	-	5.0E-09	-	-	1.0E-06	-	-
8	All cars, moving, vents closed, AC off, 1mm leak	3.4E-09	2.3E-08	9.0E-08	3.3E-09	2.2E-08	9.0E-08	6.7E-07	4.5E-06	1.8E-05
12	Small car, stationary, inside, 0.1 and 1mm leak	1.1E-07	-	-	1.1E-07	-	-	2.2E-04	-	-
18	Medium car, overcharged, AC off, 1mm leak	-	8.1E-10	-	-	8.0E-10	-	-	4.0E-07	-
19	Small car, overcharged, AC off, 1mm leak	4.0E-09	-	-	4.0E –09	-	-	1.4E-06	-	-
Sub-Total		1.2E-07	2.3E-08	9.0E-08	1.2E-07	2.3E-08	9.0E-08	2.3E-04	4.9E-06	1.8E-05
20	Collision	2.7E-08			4.3E-09			8.9E-05		
Total		2.6E-07			2.4E-07			3.4E-04		

A16.3.6 Sensitivity Case 4

As given in **Table A16.2**, Sensitivity Case 4 involved changing the probability of ignition for a stationary vehicle to that equal to the ignitoon prbaility when a vehicle is in operation (all electrical systems active). The resulting outcomes are presented in **Table A16.8**. Changes occurred for Events 6,8,18.

TABLE A16.8
SENSITIVITY CASE 4 RESULTS

Event No.	Event Description	Outcome (/ car-year)								
		Diffuse Fire			Flashfire/ Explosion			No Effect/ Safe Dispersion		
		S	M	L	S	M	L	S	M	L
6	Small car, moving, vents closed, AC on, 1mm leak	3.4E-09	-	-	3.3E-09	-	-	6.7E-07	-	-
8	All cars, moving, vents closed, AC off, 1mm leak	5.1E-09	2.3E-08	9.0E-08	5.0E-09	2.2E-08	9.0E-08	1.0E-06	4.5E-06	1.8E-05
12	Small car, stationary, inside, 0.1 and 1mm leak	1.1E-06	-	-	1.10E-6	-	-	2.2E-04	-	-
18	Medium car, overcharged, AC off, 1mm leak	-	1.2E-09	-	-	1.2E-09	-	-	4.0E-07	-
19	Small car, overcharged, AC off, 1mm leak	6.1E-09	-	-	6.0E-09	-	-	1.6E-06	-	-
Sub-Total		1.1E-06	2.4E-08	9.0E-08	1.1E-06	2.3E-08	9.0E-08	2.3E-04	4.8E-06	1.8E-05
20	Collision	2.7E-08			4.3E-09			8.9E-05		
Total		1.2E-06			1.2E-06			3.4E-04		

A16.3.7 Summary of Results

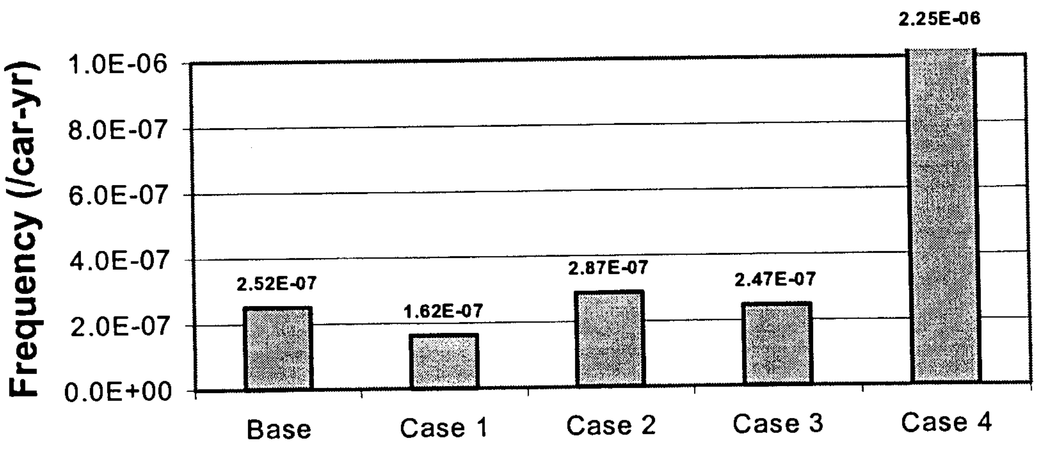
A16.3.7.1 Non-Collision Events

A summary of the results for non-collision events is given in **Table A16.9**. **Figure A16.7** shows the results for small cars in graphical form.

TABLE A16.9
SUMMARY OF NON-COLLISION RESULTS CAUSING INJURY

Case	Car Type	Value (/ car-year)	% Contribution	
			Flashfire/ Explosion	Diffuse Fire
Base	Small	2.5E-07	50	50
	Medium	4.7E-08	50	50
	Large	1.8E-07	50	50
Sensitivity Case 1	Small	1.6E-07	50	50
	Medium	4.7E-08	50	50
	Large	1.8E-07	50	50
Sensitivity Case 2	Small	2.9E-07	50	50
	Medium	4.7E-08	50	50
	Large	1.8E-07	50	50
Sensitivity Case 3	Small	2.5E-07	50	50
	Medium	4.6E-08	50	50
	Large	1.8E-07	50	50
Sensitivity Case 3	Small	2.25E-06	50	50
	Medium	4.7E-08	50	50
	Large	1.8E-07	50	50

FIGURE A16.7
SMALL CAR - NON-COLLISION EVENTS



It can be observed from the values in **Table A16.8** and **Figure A16.7** that the small car events are most affected by the sensitivity analysis. The range of values for a small car is 1.6E-07 to 2.9E-07 /car-yr with the base case of 2.5E-07 /car-yr.

A16.3.7.2 Collision Events

Table A16.10 shows the frequency of collision events calculated for each case.

TABLE A16.10
SUMMARY OF COLLISION RESULTS CAUSING INJURY

Case	Value (/ car-year)	% Contribution	
		Diffuse Fire	Flashfire/ Explosion
Base	3.1E-08	86	14
Sensitivity Case 1	3.1E-08	86	14
Sensitivity Case 2	3.1E-08	86	14
Sensitivity Case 3	3.1E-08	86	14
Sensitivity Case 4	3.1E-08	86	14

APPENDIX 17

COMPANY BACKGROUND AND PERSONNEL INVOLVED IN STUDY

TABLE OF CONTENTS

A17.1. COMPANY BACKGROUND

Granherne Pty Ltd is a wholly owned subsidiary of the Halliburton Company, an international engineering company offering a range of professional services to the world's oil and gas production, processing, refining, chemical process industries and mining and minerals processing industries. Granherne has successfully developed a world-wide consultancy capability in the specialist areas of front end engineering, process engineering, safety technology, reliability engineering, risk management and environmental protection.

Granherne Management and Employees have a commitment to quality and an effective Quality Management System has been established to satisfy this pledge. The company has achieved accreditation to ISO 9001 as approved by Lloyds Register Quality Assurance Limited.

Granherne employs over 600 people world-wide, in our offices in the UK, USA, Middle East, South East Asia and Australia. In Australia, Granherne employs around 70 professional engineers and scientists, of whom approximately 50 work in field development engineering and 20 are specialists in the fields of safety, risk, environment and reliability engineering. This resource is divided between our Perth, Sydney and Melbourne offices.

A17.2. PROJECT MANAGEMENT

A17.2.1 Project Team

The following Granherne personnel were involved in the study:

Dr Raghu Raman	Head Consultant (Project Manager)
Mr Ray Wells	Head Consultant (Technical Checker)
Mr Steve Sylvester	Senior Consultant
Mr Stuart Chia	Principal Safety/ Environmental Engineer (Team Leader)
Mr John Bertram	Senior Safety Engineer
Mr John Brini	Senior Safety Engineer (Quality Assurance reviewer)
Ms Belinda Gourlay	Safety Engineer

All the above personnel are either members of professional institutions or qualified to be members of the Institution of Engineers, Australia.

A17.2.2 Brief Summary of Experience

A brief summary of experience for each consultant is given below.

Dr Raghu Raman

Dr Raman is a Head Consultant, based in Granherne's Sydney office, and has over 30 years engineering experience and over 14 years experience in risk and safety studies. He is one of Australia's recognised leaders in risk and safety engineering and has led and conducted over 500 safety studies for industry and government. Dr. Raman has extensive experience in the assessment of risks and the development of Safety Management Systems (SMS) using the Safety Case approach. He has performed Safety Case assessments and risk assessment studies for a number of offshore oil and gas platforms.

Dr Raman has a PhD in chemical engineering and is a Fellow of the Institution of Chemical Engineers.

In this study, Dr. Raman was the Project Manager.

Ray Wells

Currently Head Consultant within the Granherne Melbourne office, Ray has 23 years' post-graduate experience, of which 19 years have been in safety risk and reliability engineering, safety and reliability analysis, and safety management. He holds a degree in physics and is a Registered Safety Professional with the Institution of Chemical Engineers.

Mr. Wells' role in the Safety Study was to undertake the technical audit of the Safety Study calculations.

Steven Sylvester

Mr. Sylvester is a Senior Consultant at Granherne and has over 25 years of wide ranging experience, covering marine engineering, heavy engineering production and maintenance, and chemical process industry. Over 11 years specifically related to risk and reliability engineering and technical safety in the chemical, mineral processing, mining and oil and gas industries. He holds a bachelor's degree in Mechanical Engineering.

Mr. Sylvester was previously Risk Engineering Technical Manager, BHP Engineering Pty Ltd, responsible for managing and conducting risk engineering projects both in-house and for external clients. Studies conducted cover a wide range of industries: chemical process, oil and gas, mineral processing, mining (open cut and underground, both coal and metalliferous), and manufacturing. The projects include hazard identification, quantitative risk analysis (QRA), hazard and operability studies (HAZOPs), technical safety audits, reliability and maintenance planning, and HAZOP training courses. In this Safety Study, Mr. Sylvester was the FMEA leader and provided mechanical engineering support.

Stuart Chia

Mr. Chia is a chemical and environmental engineer with over 7 years' experience in the process safety and environmental field. Studies have been conducted for clients in the offshore and downstream oil and gas, chemical process industries, mineral processing, waste management, hazardous materials transportation and storage terminals. Mr Chia holds a bachelor's degree in Chemistry and Chemical Engineering, and a Masters degree in Environmental Engineering. He is a graduate member of the Institution of Engineers Australia, and the Institution of Chemical Engineers.

Experience in process safety engineering has included studies involving Hazard Identification, Hazard Analysis (HAZAN), Scenario Based Hazard Identification, Quantitative Risk Analysis (QRA), Emergency Response Plans, Fire Safety Studies, Hazard Audits and offshore Safety Case (SC) preparation.

Mr. Chia has been involved in major studies for oil and gas clients such as Shell International, Caltex Australia and Boral Energy. In this study, he was the team leader of the Safety Study and was involved extensively in the experimental trials, workshop surveys, coordination with research and government organisations and consequence assessment as well as the risk assessment.

John Bertram

Mr. John Bertram has over 18 years of experience in the fields of power plant engineering, risk and reliability engineering. Has a wide background in consulting, maintenance management and maintenance planning. Experienced in the supervision of engineering maintenance teams, hazard analysis of industrial facilities; system analysis and reliability assessment. Over 8 years experience in the field of risk and reliability engineering. He holds a bachelor's degree in Electrical Engineering.

Currently Senior Safety Engineer, Granherne Pty Ltd, located in the Sydney Office, Australia, and responsible for providing safety and risk engineering consulting services. Mr. Bertram was involved in the assessment of automobile electrical systems.

John Brini

Mr. John Brini has over 12 years of experience in Over 6 years experience in production and process safety consulting. Mr. Brini has been involved with commissioning and monitoring performance of production, conceptual process design and reviewing process design for on-shore and off-shore oil and gas facilities. One year experience in design of processing facilities in the energy industry. Mr Brini is a graduate in chemical engineering and is a graduate member of the Institution of Chemical Engineers.

In this study, Mr. Brini was the lead quality assurance reviewer of all documents produced in the Safety Report.

Belinda Gourlay

Miss Belinda Gourlay is a graduate chemical engineer, and is currently a Safety Engineer at Granherne. In the last eighteen months has been a team member on a number of safety studies, including the Formal Safety Assessment of the BHP Hot Briquetted Iron facility, LPG dispersion studies for Shell Lara Terminal, and hazard analysis of two agricultural chemicals formulation plants.

She was also a team member involved in Building Respiration Tracer Gas Studies for the WA Water Corporation.

In this study, Miss Gourlay has been a team member, performing experimental work, consequence analysis modelling and risk assessment.