ATSB
Australian Transport Safety Bureau

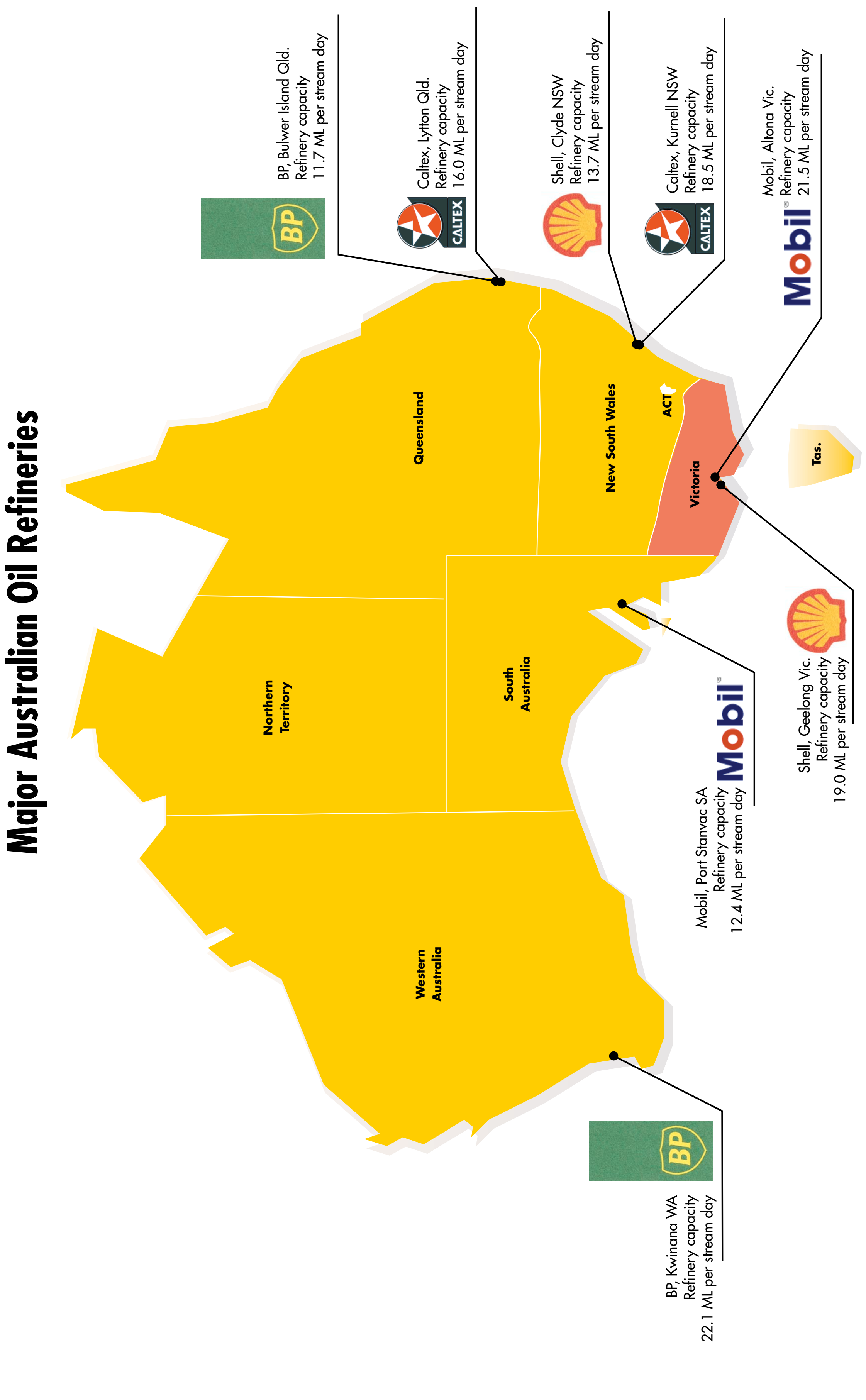
AUSTRALIAN TRANSPORT SAFETY BUREAU

AIR SAFETY INVESTIGATION

Systemic Investigation into Fuel Contamination

COMMONWEALTH DEPARTMENT OF TRANSPORT AND REGIONAL SERVICES

FIGURE 1. Major Australian oil refineries



Stream day - refers to a day that the refinery is operating at maximum capacity

Refinery capacity - refers to the design crude oil refining capacity. In reality, annual maximum operating capacity is approximately 85–88% of design capacity

Department of Transport and Regional Services

Australian Transport Safety Bureau

INVESTIGATION REPORT

Systemic Investigation into Fuel Contamination

Released under the provisions of Section 19CU of Part 2A of the *Air Navigation Act 1920*.

When the Australian Transport Safety Bureau (ATSB) makes recommendations as a result of its investigations or research, safety (in accordance with its charter) is its primary consideration. However, the Bureau fully recognises that the implementation of recommendations arising from its investigations will in some cases incur a cost to the industry that must also be considered.

Readers should note that the information in ATSB reports is provided to promote safety: in no case is it intended to imply blame or liability.

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This report was produced by the Australian Transport Safety Bureau (ATSB), PO Box 967, Civic Square ACT 2608.

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EXECUTIVE SUMMARY

Following the grounding of large numbers of piston-engine aircraft across eastern Australia in early January 2000 as a consequence of using contaminated aviation gasoline (Avgas), the Australian Transport Safety Bureau initiated a major safety deficiency investigation into the circumstances of the contamination. Guidance for the investigation was subsequently provided in the form of Terms of Reference, which stated that the investigation was being widened to examine the following:

1. the existing standards for aviation gasoline;
2. the details of risk analyses undertaken prior to and during the production of aviation gasoline at Mobil's Altona refinery;
3. the adequacy of the production control, distribution control, and recording processes used by Mobil and other refiners;
4. the current arrangements for the oversight of aviation gasoline quality, including the procedures followed by Mobil and other refiners to disclose information with potential aviation safety implications; and
5. any other matter of material relevance to the above.

The ATSB investigation team identified a number of factors related to the manufacture, standards and oversight of Avgas that contributed to the contamination, which are outlined below. The relevance of these factors was also considered in relation to the manufacture of other aviation fuels.

The fitness for purpose of aviation fuels is safety critical, however the systems of manufacture, distribution, supply and use in aircraft were not supported by all the defences that are normally incorporated into other safety critical aviation systems. Despite the safety risk, there were no significant redundant systems to enhance the defences for aviation fuel quality.

The deficiencies that have been identified in relation to the supply of Avgas that was not fit for purpose also have the potential to affect the fitness for purpose of other aviation fuels, like Jet A-1. Aircraft that use Avgas are normally small compared with civilian airliners which normally use aviation turbine fuel such as Jet A-1. If a similar contamination of Jet A-1 had led to similar deficiencies in engine reliability, then the potential for a major accident with large loss of life would have been significant.

A temporary variation in the production process in Mobil's Altona refinery in late 1999 led to an increased dosage of an anti-corrosion chemical being injected into the Avgas process stream, which led to a contamination of Avgas. The anti-corrosion chemical, Neutramine D, contained an active ingredient called ethylene diamine. Ethylene diamine was not completely extracted during Avgas manufacture. Excess ethylene diamine from the injected Neutramine D was expected to be extracted from the process stream in water taken from the deisobutaniser tower during manufacture, however the extraction mechanism was not fully effective. The concentration of ethylene diamine in the final product was small and none of the many quality assurance and specification tests used during manufacture and distribution identified the presence of the ethylene diamine in the final product.

The refiner's knowledge of the process within the alkylation unit was not complete. The manufacturing process for Avgas is very complex, and there are many variables and factors that can affect the process. A lot of information was available to the operating team at the refinery, however not all the activities were fully recorded and available for future reference.

Mobil did not define or clearly document procedures for managing process deviations outside some of the limits for normal operations within the alkylation unit. The refiner aimed to operate the plant within predefined parameters, to effectively control the process and maximise its efficiency. The parameter deviations at which the alkylation unit would be considered to be outside normal operations were not clearly defined in all cases, nor were the initial considerations or actions to be taken in such circumstances clearly laid out.

The processes for monitoring the reliability of plant equipment did not provide the best possible indication of reliability. A number of systems were used for predicting and managing the reliability of various components in the alkylation unit. Some of these systems could have been used more effectively to predict reliability. Systems to assess the adequacy of the reliability prediction systems were also not completely effective.

Management of change at the refinery did not consider the effectiveness of the extraction mechanism for ethylene diamine from the Avgas process stream. Changes within the refinery that might have indicated a variation in the properties of the process stream, and therefore might have influenced the efficiency of the extraction mechanism for ethylene diamine included:

- a decrease in the efficiency of the caustic wash system due to problems with caustic circulation pumps and a system leak; and
- concentrations of sulfates and pH in water from the deisobutaniser tower overheads that were outside their normal ranges, indicating increased acid and alkyl sulfate carryover from the alkylation reactor.

These changes were not considered in the context of their potential to affect the ability of the system to ensure that any ethylene diamine that was injected into the process stream would be effectively extracted.

Mobil did not have an effective process in place to identify the adverse consequences of the cumulative effects of multiple planned and unplanned process changes on the degree of control in the alkylation unit. A number of planned and unplanned changes were taking place in the alkylation unit at the time of the contamination event. Any one of the changes could be effectively managed, however the effect of one change on another change would decrease the ability to manage the potential cumulative effect of all the changes, so that the degree of knowledge, and ability to control the unit to the same level of accuracy would be degraded.

The refiner's procedures were not effective in ensuring that decisions were fully implemented, or that progress with recommendations was regularly reported and reviewed. Following a previous contamination event, a number of recommendations and improvement actions were identified. They were not all acted on and followed through to completion.

The refiner's risk management process considered an overly narrow predefined set of undesirable outcomes. The process did not allow Mobil to identify all the undesirable outcomes (such as hazards to aviation safety) that could prevent them from producing products that were fit for purpose and from achieving their broader organisational objectives.

The refiner had not satisfied itself that all compounds that could be in the process stream during manufacture, (with particular attention to process chemicals that were introduced during the manufacturing process), would not adversely affect the systems in which the final product was intended to be used. The manufacturing process was designed to ensure that all chemicals that were in the process stream that were not desired in the end product would be extracted from the process stream during manufacture. Despite this, process deviations may have reduced the effectiveness of these extraction mechanisms. The refiner did not have procedures in place to rigorously consider the likely consequences of product contamination by any of the chemicals that were introduced into the process stream during manufacture, nor of any of the likely products of reaction of those chemicals.

The refiner did not conduct any specific practical validation of its assumption that ethylene diamine would be extracted during manufacture following the introduction of Neutramine D injection in 1991. Neutramine D was first used in the alkylation unit before the introduction of a formal *Management of Change* process at the refinery. At the time of the introduction, a number of concerns were addressed, however no practical validation was undertaken to assess the effectiveness of the extraction mechanism to ensure that ethylene diamine was removed from the process stream.

The use of Neutramine D to help manage corrosion in the deisobutaniser tower had been contracted out. The process of contracting out the corrosion control at the Altona refinery alkylation unit was not managed to ensure that the fulfillment of the contractor's objectives would not adversely affect Mobil's broader objectives. The corrosion control contractor was required to control the rate of Neutramine D injection as a result of pH indications taken from water samples from the deisobutaniser distillation tower overheads. This requirement did not address the potential for the objectives of the corrosion control contractor (to meet these requirements) to affect the refiner's broader product quality objective of ensuring that the product was fit for purpose.

The refiner's manufacturing process was accredited to ISO 9002, and has been subsequently reaccredited. The refiner's use of its accredited quality assurance system was not effective in ensuring that Avgas was supplied that was fit for purpose.

Following up a recommendation arising from a previous contamination event could have allowed Mobil the opportunity to identify ethylene diamine contamination. The refinery had experienced a previous contamination event from microbiological contamination. Dead bacteria had been transferred along the delivery path and clogged filters. It was thought that the bacteria had been killed by the unusually alkaline water in the bottom of the Avgas storage tank. While the reason for the alkalinity of that water was never ascertained, ethylene diamine dissolved in water will markedly increase its alkalinity.

A clear understanding did not exist among the manufacturers, regulators and users of aviation fuel that compliance with a fuel standard, by itself, would not provide assurance that fuel would be fit for purpose. When the quality of the supplied Avgas was first suspected, it was immediately re-tested to ensure that it met its specification. Avgas is normally sold on the condition that it meets its specification. The fuel that contaminated the aircraft met its specification as defined by the tests that were used to ensure that the Avgas does meet its specification. Fuel is normally fully tested only once during manufacture and distribution to ensure that it meets its specification. A number of other issues have to be addressed beyond the specification to ensure that Avgas is, and remains, fit for purpose.

Despite aviation fuels being a global commodity, no single global standard existed or was used for each main grade of aviation fuel. Manufacturers of Avgas normally use their own specification for their product that meets or slightly exceeds the major international standards. Each manufacturer's specification is normally slightly different, so the actual standard for this global commodity is not consistent.

It was impossible to comply with the literal interpretation of the major international standards for aviation gasoline because they did not specify maximum permissible concentrations of undesired compounds, either singly or collectively. The major international standards for Avgas implied a zero permissible concentration of undesired compounds in the product. It is not possible to measure zero concentrations, only to measure to the lowest measurable limit (and this is normally impractical and expensive in a production environment). It was therefore not possible to comply exactly with the specifications. If the specifications allowed a permissible small concentration of classes of undesired compounds, then this would have allowed the specification to be met exactly. However, this would have required an understanding of the potential impact of such compounds both by themselves and in combination with other compounds that are, or could be, in the fuel.

Accepted definitions did not exist for all the physical and chemical properties of aviation fuels that were required to ensure that aviation fuels were fit for purpose. A number of properties of Avgas are essential for fitness for purpose which are not defined in the international standards. These properties are known by people and organisations who are responsible for ensuring that they exist, however there are no defined levels for these properties for Avgas. This meant that Avgas could have been supplied that met the international standards and yet the undefined essential physical and chemical properties may have been addressed to a varying extent, or not at all.

Despite the criticality to safety of aviation fuel quality, no regulatory requirements for fuel quality testing existed beyond the requirement to visually assess a sample of fuel drained from an aircraft before the first flight of a day, or after refuelling. Australian law that applied to the operation of civil aircraft did not require any testing of fuel quality, beyond the need for a sample to be drained from the bottom of aircraft fuel tanks before the first flight of a day, and after refuelling. The sample was to be examined to confirm the correct clarity, colour and odour, and tested for water, either with water detecting equipment, or visually. These tests would not have identified the presence of ethylene diamine in a sample of the contaminated fuel.

There was a diffusion of responsibility among the various regulatory bodies that had the potential to oversee aviation fuel manufacture, quality assurance, supply and use. Aviation fuel was manufactured at a workplace which was regulated by relevant occupational health and safety organisations. It was sold in commercial transactions that were covered by the obligations of state and federal trade practices legislation. It was used in aircraft that were regulated by the civil aviation regulator. It was possible for each of these responsibilities to have an influence on aviation fuel during its life from manufacture to consumption, but there was no clear delineation of the roles and responsibilities of the respective regulatory organisations in relation to the quality of aviation fuel.

There was no indication to show that the then Civil Aviation Authority considered the effect on safety when it made a safety related decision to discontinue any oversight of aviation fuel quality. When the Civil Aviation Authority discontinued its oversight of aviation fuel manufacture and distribution in 1991, its reasoning was primarily that the expertise in these areas rested with the manufacturing organisations, and they were therefore considered to be the best people to ensure that the quality of fuel was maintained. A lack of expertise within the Authority was not a relevant justification for a change to regulatory oversight which could affect a safety critical aspect of aviation.

No mechanism existed to ensure that the Civil Aviation Safety Authority was made aware in a timely manner of information relating to the management of situations related to fuel quality that could affect the safety of flight. Following the discontinuation of any form of regulatory oversight by the then Civil Aviation Authority, no formal lines of communication existed between the Authority and manufacturers or distributors of aviation fuel, and hence the initial notification of a fuel quality problem was likely to occur through informal channels, and the timeliness of formal notification was at the behest of the manufacturer or distributor.

The Australian Transport Safety Bureau identified a number of deficiencies in the development of manufacturing processes and the management of those processes within the refinery, the relevance of standards that were used in the manufacture of Avgas, and the oversight of aviation fuels.

These safety deficiencies formed the basis for the development of safety recommendations issued by the Bureau. The recommendations are designed to reinforce the defences that are, or could be, put in place to reduce the probability that the safety of civil aviation could be compromised in the future.

The recommendations fall into three main groupings:

- The first group relate primarily to the management of the processes for the manufacture of Avgas. They are addressed to the refiner, and may be considered as relevant to other manufacturers of aviation fuels, as well as managers of complex, safety critical systems.
- The second group relate to the development and use of international standards for Avgas, including their use in ensuring the fitness for purpose of Avgas used in aircraft.
- The third group relate to the use of regulatory oversight as an effective defence in ensuring that fuel quality as a safety critical aviation system is, and remains, consistently fit for purpose, and the need to eliminate any diffusion of responsibility among regulators who have the potential to regulate aviation fuel quality.

The full text of the recommendations can be found in section 5 of the report.

PREFACE

The Australian Transport Safety Bureau (ATSB) is a multimodal Bureau within the federal Department of Transport and Regional Services that is treated as a Division for administrative purposes. The ATSB is entirely separate from transport regulators, and ATSB investigations are independent of regulatory or other external influence.

In terms of aviation, the ATSB is responsible for investigating accidents, serious incidents, incidents and safety deficiencies involving civil aircraft operations in Australia, as well as participating in overseas investigations of accidents and serious incidents involving Australian registered aircraft. The ATSB also conducts investigations and studies of the aviation system to identify underlying factors and trends that have the potential to adversely affect safety. A primary concern is the safety of commercial air transport, with particular regard to fare-paying passenger operations.

The ATSB performs its aviation functions in accordance with the provisions of the *Air Navigation Act 1920*, Part 2A. Section 19CA of the Act states that the object of an investigation is to determine the circumstances surrounding any accident, serious incident, incident or safety deficiency to prevent the occurrence of other similar events. The results of these determinations form the basis for safety recommendations and advisory notices, statistical analyses, research, safety studies and ultimately accident prevention programs. As with equivalent overseas organisations, the ATSB has no power to implement its recommendations.

It is not the object of an investigation to determine blame or liability. However, it should be recognised that an investigation report must include factual material of sufficient weight to support the analysis and conclusions reached. That material will at times contain information reflecting on the performance of individuals and organisations, and how their actions may have contributed to the outcomes of the matter under investigation. At all times the ATSB endeavours to balance the use of material that could imply adverse comment, with the need to properly explain what happened, and why, in a fair and unbiased manner.

ACKNOWLEDGMENTS

The independent investigation team was provided with general and technical assistance by a number of refining companies, standards organisations, regulatory authorities, government departments and a wide range of individuals from around the world. These organisations included:

Air Accidents Investigation Branch (UK)
Air BP
Air New Zealand
American Society for Testing and Materials
Ansett Airlines
Australian Competition and Consumer Commission
Australian Geological Survey Organisation
Australian Government Analytical Laboratory
Australian Institute of Petroleum
Bureau of Meteorology
Caltex
Civil Aviation Authority (NZ)
Civil Aviation Authority (UK)
Civil Aviation Safety Authority
Consumer and Business Affairs Victoria (formerly Office of Fair Trading Victoria)
Defence Evaluation Research Agency (UK)
Defence Science and Technology Organisation
Department of the Treasury
Eurotunnel (UK)
Federal Aviation Administration (US)
Health and Safety Executive (UK)
Joint Fuels and Lubricants Agency
Mobil
National Transportation Safety Board (US)
Probe Analytical
Qantas Airways
Shell Aviation
Transportation Safety Board (Canada)
Workcover Victoria

The ATSB also received a substantial amount of information and generous assistance from many Australian general aviation maintenance and flying organisations.

The team gathered information in the form of extensive interviews, reports, documented procedures and records, and from visits to relevant sites. The open participation and cooperation in the investigation process of all parties is acknowledged. The ATSB would like to thank all those experts for their unfailing courtesy in responding to questions, and for the patience with which they have almost always preceded their answers with, 'Well, it's not that simple…'

GLOSSARY

Abnormal	Operations are considered to be abnormal when the plant is operating with one or more of the operating parameters outside the normal limits.
Alarm limits	Alarm limits are parameter values at which an audible alarm would sound in the control room of a refinery, and a visual message would be displayed on a refinery control screen.
Alkanes	Alkanes are hydrocarbons whose molecular structure contains only single bonds between any two carbon atoms in a molecule. Alkanes are the chief components of petroleum fuels such as Avgas. The name for an alkane chemical ends with the suffix -ane (for example, butane).
Alkenes	Alkenes are hydrocarbons in which the molecular structure contains at least one double bond between two adjacent carbon atoms in a molecule. Alkenes are important intermediaries in the refining of petroleum fuels such as Avgas. The name for an alkene chemical ends with the suffix -ene, (for example, butene or butylene).
Alkyl-	Alkyl- is a generic description of a part of a compound that is derived by removing a hydrogen atom from an alkane molecule.
Alkylation	Alkylation describes a reaction combining an alkane with an alkene. In this report, it refers to the reaction of isobutane with butylene in the presence of an acid catalyst.
Amine	Amines are a class of organic compounds derived from replacing one or more hydrogen atoms in an ammonia molecule with alkyl groups.
Aqueous	Aqueous refers to being in water.
Avgas	Avgas is an abbreviation for aviation gasoline, which is the common fuel for piston-engine aircraft. Two grades of Avgas are manufactured in Australia, Avgas 100/130 and Avgas 100LL. Avgas 100LL has a lower maximum lead concentration than Avgas 100/130 and a different identification colour.
Blendstock	Blendstock is a product manufactured in a refinery that is used to blend with other blendstocks to make a saleable product such as gasoline.
Catalyst	A catalyst is a chemical that is necessary for a chemical reaction to be initiated. The catalyst is the same at the start and the end of the reaction.
Chelate	A chelate is a chemical compound in which a metallic ion is bonded to more chemical groups than its chemical characteristics would normally indicate.
Complexing	Complexing agents are chemicals that combine with metallic ions to form complex ions. A chelate is one example of a complex ion.
Contaminant	A contaminant is a substance that is not intended to be in a manufactured product.
Defence	In the context of this report, anything that could reduce the probability of an outcome may be considered as a defence. It is valid to consider an active defence, such as an alarm to alert operating staff to an abnormal situation, or to consider an organisational defence, such as a procedure

	to return information describing the performance of an activity to a decision maker.
Dewatering	Dewatering is the process of draining liquid from the lowest point of a vessel of gasoline-type product to remove any water that may have separated and settled there.
Dry	In this report, dry Avgas is Avgas that has been sampled, the sample tested with water-detecting paste and found to contain no indication of water.
Effluent	In this report, effluent refers to the liquid that flows out of the reactor vessel after the reaction has been completed. It does not refer to a waste product.
Entrained	Entrained refers to solid particles or fluids that are carried along in the flow of another fluid.
Ethylene diamine	Ethylene diamine is a compound that will neutralise acids. It is also a strong chelating or complexing agent.
Feedstock	Feedstock is the supply of chemical that is reacted to form the end product.
Fit for purpose	In this report a product is fit for purpose if it is capable of performing the function for which it is intended.
Fraction	In this report, a fraction is one product with a particular boiling point range that is separated from another by distillation.
Hazard	A hazard is a source of potential harm to an organisation's objectives.
Hydrocarbon	A hydrocarbon is one of a group of organic chemicals with molecules that consist of only hydrogen and carbon.
Immiscible	Two liquids that will not dissolve in each other are said to be immiscible (for example, oil and water).
Impeller	An impeller is the part of a pump that is rotated inside the pump case to force fluid through the pump.
Ion	An ion is an atom or a group of atoms that has either gained or lost one or more electrons (for example H^+ or SO_4^{2-}).
Intimate	In this report, an intimate mixture is one in which the components have mixed to a molecular level.
Isomer	An isomer is a molecule that has the same number and kind of atoms, but has a different arrangement of those atoms, giving a different molecular shape. An isomer will normally have different chemical and physical properties. An isomer of a compound can be named by adding the prefix iso- (for example, an isomer of butane is called isobutane in the petroleum industry).
Moment	In this report, a moment is a force that will try to cause something to rotate.
Neutramine D	Neutramine D is a proprietary product that contains ethylene diamine.
Olefin	Olefin is another name for the group of hydrocarbons known as alkenes.

Organic	An organic compound is a compound that contains carbon atoms except carbon monoxide, carbon dioxide, carbonates and cyanides. Petroleum products are largely made up of organic compounds
Objectives	An organisation exists to achieve a set of objectives. These organisational objectives are susceptible to factors, circumstances or influences that will make it harder for the organisation to achieve its objectives.
Overheads	Overheads are the ancillary equipment and pipework that are found at the top of a distillation tower.
Partition ratio	The partition ratio is the ratio of concentrations of a solute in two solvents which are mixed together. (For example, if oil and water are in the same bottle with some sugar, the partition ratio for the sugar is the ratio of the concentration of dissolved sugar in the oil and the concentration of dissolved sugar in the water).
Process stream	In this report, process stream refers to to the flow of fluid through sections of a refinery that will be processed to manufacture Avgas.
pH	Aqueous solutions may be acid, neutral or alkaline. The degree of acidity or alkalinity may vary over a range. A pH value, from one (strongly acidic) to seven (neutral) to fourteen (strongly alkaline), indicates this range. The pH number indicates the concentration of hydrogen ions (H^+) in the liquid. The concentration of H^+ ions increases with greater acidity.
Reactant	A reactant is a chemical that undergoes a chemical reaction.
Redundancy	In this report, redundancy refers to a design principle in which an alternative is in place to replace anything which fails in a complex system (for example, having two pumps side by side, so that one can replace another if it fails is a redundant system).
Reflux	Reflux is a process of recirculating material from a distillation tower to recover a greater proportion of product.
Risk	A risk is the chance of something happening that will have an adverse impact on the objectives of an organisation.
Solute	A solute is a substance that is dissolved in a solvent to form a solution. The solute may be a solid, liquid or gas.
Solution	A solution is formed when one substance, called the solute, is dissolved in another substance, called the solvent. (For example, salt is a solute that can be dissolved in water, a solvent, to form a solution of salt water).
Solvent	A solvent is a substance that can dissolve a solute. In the context of this report, a solvent may be a petroleum product or water.

1. INTRODUCTION

1.1 Sequence of events

On 16 December 1999, the proprietor of a Bankstown aircraft fuel system overhaul company told Mobil's Logistics Aviation Inspector that he had found a black substance in a number of fuel boost pumps. The pumps had clogged and failed.

The following day, Mobil's agent at Moorabbin told the Logistics Aviation Inspector that operators had reported a number of problems related to black deposits in fuel systems of piston-engine aircraft. One of the affected aircraft had used only Mobil aviation gasoline (Avgas) since a previous filter inspection. The Logistics Aviation Inspector obtained filter screens from that aircraft and arranged for them to be tested at Mobil's laboratory at the Yarraville distribution terminal. Chemists at the laboratory washed the filters with water with a pH of 7, and the resulting solution was found to be purple, with an alkaline pH of 10. The Logistics Aviation Inspector contacted a senior company chemist at Mobil's technical centre at Paulsboro, New Jersey, USA, and told him of the findings. The possibility was raised that the purple colour could be indicative of a copper-amine complex.

On 20 December 1999, the Logistics Aviation Inspector sent an email to several Mobil personnel detailing the information that was known at the time, and suggesting further actions including a visit to Moorabbin the next day.

On 21 December 1999, a pilot in a Cessna 150M aircraft commenced a flight from Moorabbin airport in Victoria. Shortly after take-off, the engine lost power and the pilot conducted a successful forced landing onto a grassed area beyond the runway. As the aircraft touched down, the power resumed. The pilot closed the throttle and stopped the aircraft.

The aircraft was examined by a maintenance organisation, and a sticky black substance was revealed in the carburettor. The chief flying instructor from the school at which the aircraft was based contacted other operators, who told him of several unexplained losses of power within a short period of time involving aircraft based at Moorabbin. Mobil's Logistics Aviation Inspector was able to inspect the aircraft, and the problem was identified as a sticking carburettor needle. At 1800, following a discussion with the Altona refinery manager, the inspector decided to quarantine further distribution of Avgas from the Altona refinery and Yarraville distribution depot (see Fig. 13). At 1830, the Moorabbin airport Avgas refuelling facility was quarantined. The inspector arranged for a response team to meet the next day.

The Mobil response team met on 22 December 1999, and then told the Moorabbin office of the Civil Aviation Safety Authority (CASA) of the situation. At 1235 on the same day, the response team also quarantined the Essendon airport Avgas refuelling facility. Both Moorabbin and Essendon agencies had delivered fuel to other locations and these locations were also quarantined.

On the evening of 22 December 1999 CASA issued Notice to Airmen C0161/99, alerting operators to a potential contamination of aviation gasoline, and recommending they contact fuel vendors and maintenance organisations before flying their aircraft.

On 23 December 1999, Mobil's initial response team learnt that a corrosion-control neutralising amine used in the refinery had been injected at a relatively high rate during November and December. The Mobil Oil Australia board assumed control of the response at this time and formed a number of different response teams. The board also quarantined all

Mobil Avgas that had been manufactured at Altona and met with CASA and Air BP personnel. (Air BP had sold some Avgas that had been manufactured at the Altona refinery.)

CASA issued its first Airworthiness Directive related to contaminated Avgas on 24 December 1999.

Most of the deposits of the sticky black substance were found in the carburettor needle seats of smaller aircraft, high pressure electrically driven fuel pumps in larger aircraft, and in brass fuel filters found in some aircraft types.

The black substance found in the aircraft fuel system was identified as a complex of copper and a chemical called ethylene diamine. Neutramine D, a product containing ethylene diamine had been used to assist in the control of corrosion within a part of Mobil's Altona refinery used in the manufacture of Avgas. Ethylene diamine was present in very low concentrations within the contaminated Avgas (see appendix C); however, it reacted with metallic copper in pure or alloyed form in the fuel systems of aircraft to form a black substance, referred to as 'gunk'. The 'gunk' affected the operation of aircraft fuel systems in such a way that the aircraft were no longer airworthy. A specific sophisticated test had to be developed to detect ethylene diamine at the concentrations that were present in the contaminated Avgas.

CASA initially required inspections of certain components and a flushing of contaminated aircraft fuel systems with uncontaminated Avgas. It soon became apparent that the flushing did not effectively stop the formation of, or remove, the 'gunk' in aircraft fuel systems. All aircraft that could have been exposed to the contaminated fuel were then grounded on 10 January 2000 by airworthiness directive AD/GEN/78. The grounding remained in force until aircraft were either proven not to have been fuelled with contaminated Avgas, or until an effective cleaning procedure and test had been developed and used to ensure that aircraft were no longer affected by chemicals that could react to form the 'gunk'. Thousands of aircraft were grounded across eastern Australia.

Having already investigated several occurrences in which fuel contamination was found to have led to power failures in aircraft, the ATSB assessed that an aviation safety deficiency existed. An investigation commenced on 6 January 2000 into systemic issues associated with the manufacture of Avgas, which was later provided with guidance in the form of the terms of reference that were published on 12 January 2000, and can be found in Appendix A.

Arising from the terms of reference, the investigation included an examination of four key issues:

- the process by which Avgas was manufactured at the Altona refinery, the way that the manufacturing process was managed, and the way that any temporary or permanent changes to the process were managed. The investigation also examined methods for identifying hazards to the process, and for managing risks;
- the relevance and limitations of standards that were used in defining aviation fuels to organisations that were connected with the manufacture, handling and use of the fuels;
- the systems of oversight for the manufacture and distribution of aviation fuels; and,
- the potential consequences of the use of contaminated fuel in aircraft.

A detailed or comprehensive audit of the refinery processes was neither required nor conducted.

The Bureau identified a number of deficiencies in the development and management of processes within the refinery; the relevance of standards that are used in the manufacture of Avgas; and the oversight of the manufacture of aviation fuel.

These safety deficiencies formed the basis for the development of safety recommendations issued by the Bureau. The recommendations are designed to reinforce the defences that are, or could be put in place to reduce the probability that the safety of civil aviation could be compromised.

Ethylene diamine had been injected into the process stream during manufacture to neutralise any acids. Any excess ethylene diamine was assumed to be extracted in later stages of the manufacturing process. After a number of changes in the manufacturing process it had been considered necessary to increase the rate of Neutramine D injection into the process stream for a period of weeks (see Fig. 8). Some of the fuel that was manufactured during this time was later found to have contained ethylene diamine. During that period the ethylene diamine extraction mechanism in the manufacturing process had not been effective, nor had testing for its presence been sufficiently sensitive.

1.2 The role of fuel quality in aviation

The quantity of Avgas manufactured in Australia is small when compared with the quantities of all other aviation fuels. Despite the dramatic effect on the Australian piston-engine aircraft industry, the Avgas contamination event should be considered an invaluable learning experience for the aviation and refining industry as a whole. The lessons that can be derived from the event are particularly significant because they can be compared with the consequences of a similar contamination of aviation turbine fuel.

No serious aviation accident occurred and there were no injuries to persons as a result of the ethylene diamine contamination event in 1999. This investigation was not an accident investigation, and although aviation incidents did occur, they are referred to in this report only to the extent necessary to illustrate the systemic deficiencies. Safety deficiencies that failed to prevent those incidents and that could have led to serious accidents are addressed.

Aviation fuel is an essential component for most powered aircraft in flight. Although an aircraft component is normally considered to be a discrete unit in an aircraft's assembly, fuel is just as necessary in a powered aircraft as any other unit. Fuel has to perform the function for which it is designed without any undesired side-effects on other aircraft systems. It is therefore reasonable to consider fuel as a component.

All aircraft components are required to be airworthy for reliable flight. Aviation fuel as an aircraft component is replaced in an aircraft more frequently than any other component. Aircraft fuel is therefore required to be no less airworthy than any other component of an aircraft in flight.

The manufacture of aviation fuels is a complex process and, in order to ensure the maximum reliability of the manufacturing process, it is necessary to have both correct knowledge and control of the manufacturing process. If any process is complex, it is also necessary to control the procedures that are used to control that process, so that the control activities are consistent and correct. It is also necessary to ensure that the procedures that are used are clear, relevant, workable and resistant to human error. Such defences as exist to maintain the quality of Avgas in Australia are the same for all types of aviation fuel.

The systems used in civil aviation in Australia are designed to be as reliable as possible. This is partly achieved by building redundancy into safety-critical systems where this is considered appropriate. The principle may be seen in the duplication of power, control and instrumentation systems in aircraft. The procedures that are used in the control of an aircraft in flight are also designed to be resistant to human error when properly applied. These principles may be applied to all safety critical systems in aviation.

Larger aircraft have multiple engines so that if one engine system fails, built-in redundancy allows the aircraft to continue flying using its remaining engine(s). The supply of fuel to an aircraft does not normally have built-in redundancy systems, in that one fuel supply is normally used to fill all the aircraft fuel tanks that supply all the aircraft engines. The supply of unairworthy fuel has the potential to cause multiple aircraft power systems to fail at the same time, thereby negating the redundancy in multiple power systems. In the absence of redundant systems, enhanced checking and quality systems may reduce the probability of such a single system failing and leading to a safety occurrence.

Similar fuel quality problems can also occur in large transport aircraft.

In May 1974, a Boeing 747 aircraft was operating a passenger-carrying service from Frankfurt to London. Shortly before the crew began to descend the aircraft into London, they were required to shut down both the number 1 and number 2 engines following a rise in exhaust gas temperature. The crew subsequently landed the aircraft at London.

Maintenance personnel then ran the remaining engines on the ground; however, they had to shut down the number 3 engine following a rise in exhaust gas temperature, and the auxiliary power unit shut itself down due to fuel starvation. It was considered that if the aircraft had needed to fly much further, these shutdowns would have occurred in flight.

The power systems were examined, and the problems were attributed to blockages and corrosion due to fuel that had been contaminated with common salt. The fuel had passed specification testing. The Boeing 747 aircraft type is commonly used for long overwater flights; however, in this case, a suitable aerodrome was nearby when the engine problems occurred.

In the days following this incident, a number of other aircraft experienced engine problems as a consequence of using salt-contaminated fuel. One of these additional incidents also involved the shut down of two engines in flight on another Boeing 747 aircraft.

Some large aircraft with two engines that operate for long distances over water have additional procedural systems in place to increase the reliability of operations and to reduce the risk of the aircraft experiencing an engine failure, or not being able to reach a suitable landing site in the event of an engine failure. These procedures do not include any enhanced procedural considerations to ensure the quality of fuel supplied to the aircraft. Civil aviation is a highly complex system that requires a high degree of reliability. This need is recognised and supported by the provision of an enhanced regulatory service. This enhanced regulatory oversight did not address fuel quality, a safety critical aspect of aviation.

The Australian Transport Safety Bureau investigates safety deficiencies to enhance the safety of civil aviation. The supply of fuel that was not airworthy, but that was considered to be airworthy at the time of supply, was a systemic safety deficiency. The Bureau investigated the sequence of events and the systemic factors that led to the production and distribution of contaminated fuel.

In order to examine the system that supplies airworthy fuel to aircraft, it was necessary to examine the process of fuel manufacture, and the methods used to ensure that fuel becomes, and remains airworthy. This report discusses the manufacturing of Avgas in general. It examines the history of manufacture in the period leading up to the contamination event, and the processes that were used to control the manufacture of Avgas during that period.

1.3 Report structure

Because the report covers a wide range of issues, it is likely that not all of the report will be of interest to every reader. In some cases, information relating to a particular aspect is not addressed directly to the organisation responsible for that aspect. As an example, the description of the processes in the alkylation unit is not intended to be of great relevance to those who operate the unit, as their knowledge of the process is already much more detailed. Similarly, the section relating to fuel standards is not only addressed to those who maintain the standards, and sections that relate to the management of organisational processes may be equally relevant to a number of different organisations.

The following summary is intended to assist those who wish to read parts of the report that relate to a particular aspect of the investigation.

The report is subdivided into a number of sections.

Section 2	Comprises factual information.
Section 2.1	Describes the major oil refining capacity in Australia and the processes of alkylation that are available for use in the manufacture of Avgas.
Section 2.1.1	Is a summary of events at the refinery that were relevant to the investigation.
Section 2.1.2	Describes the systems and organisational structures that were in place to manage the process of manufacture of Avgas in late 1999.
Section 2.1.3	Describes the tools, and the management of the tools used to control corrosion in parts of the refinery that were used to manufacture Avgas.
Section 2.1.4	Describes the history of corrosion control in the alkylation unit and its relevance to the investigation.
Section 2.1.5	Describes the way the refinery company identified situations when parts of the refinery were not operating normally, and the way in which a response to such an abnormal situation was managed.
Section 2.1.6	Describes the way that maintenance was managed at the refinery.
Section 2.1.7	Describes the quality assurance systems that were in place at the refinery, and addresses the potential for an effective quality assurance process to increase the probability of supplying a product that is fit for purpose.
Section 2.1.8	Describes the process by which risk was managed at the refinery.
Section 2.1.9	Addresses the investigation of a previous incident within the refinery, and the potential for improved management processes to have been identified from that investigation.
Section 2.2	Describes the standards that are used to describe Avgas and their relevance to all stakeholders in ensuring that Avgas is, and remains, fit for purpose.
Section 2.3	Describes the regulatory oversight that existed over the manufacture and supply of Avgas.
Section 3	Comprises analysis that pertains directly to the factual information.
	The introduction to section 3 addresses the potential for aviation fuel that is not fit for purpose to affect aviation safety.

Section 3.1	Addresses the need to maintain an appropriate level of knowledge of what is going on in a process, and the systems available to maintain that level of knowledge. It also addresses the potential for planned and unplanned changes to affect that level of knowledge, and the methods for managing that knowledge, so that an appropriate degree of control over the process may be maintained.
Section 3.2	Addresses the relevance of standards that existed to all the stakeholders in maintaining the fitness for purpose of aviation fuel.
Section 3.3	Addresses the potential for regulatory oversight to provide an effective defence in ensuring the safety of flight, and how this potential had been used to reduce the risk to safety of flight from fuel that was not fit for its purpose.
Section 4	Comprises conclusions from the investigation.
Section 5	Comprises recommendations from the investigation.
Section 6	Details safety actions that have been undertaken in the light of the fuel contamination event.
Appendix A	Is the terms of reference under which the investigation was conducted, and how those terms of reference were addressed.
Appendix B	Is a chemical analysis of a typical sample of Avgas taken from the Altona Refinery.
Appendix C	Is a precis of some conclusions drawn from laboratory analyses of the properties of ethylene diamine in Avgas.
Appendix D	Provides a short description of naming conventions for organic chemicals.
Appendix E	Is a graph of Neutramine D injection rates over an extended period of time at the Altona refinery.
Appendix F	Is an explanation of the nature and relevance of octane ratings in Avgas.
Appendix G	Describes the process of manufacture of Avgas at the refinery at Altona, from the primary feedstock of crude oil to the supply of the end product to the distribution depot, including a description of the testing to ensure that the end product met a specification for Avgas.
Appendix H	Comprises a chronological listing of relevant events leading up to the contamination episode at the Altona refinery.

2. FACTUAL INFORMATION

2.1 Manufacture of aviation fuel in Australia

At the time of the contamination, there were eight major crude oil refineries in Australia. The refineries were:

Company	*Refinery*	*State*	*Year started**	*Alkylation process*	*Avgas manufacture*	*Jet A-1 manufacture*
BP	Kwinana	WA	1955	HF	Yes	Yes
BP	Bulwer Is.	Qld	1965	HF	No	Yes
Caltex	Lytton	Qld	1965	HF	No	Yes
Caltex	Kurnell	NSW	1956	H_2SO_4	No	Yes
Shell	Geelong	Vic.	1954	HF	Yes	Yes
Shell	Clyde	NSW	1928	HF	No	Yes
Mobil	Altona	Vic.	1949	H_2SO_4	Yes	Yes
Mobil	Port Stanvac	SA	1963	None	No	Yes

* This is the year that the original plant began operating HF – hydrogen fluoride, H_2SO_4 – sulfuric acid

The locations of these refineries can be seen in the diagram on the inside front cover of this report.

Refineries separated crude oil into different fractions by distillation. A process called catalytic cracking was used to break up larger molecules in fractions with higher boiling points into smaller molecules. This process made products of a higher value that could be used to blend and manufacture other products. Some of the products of catalytic cracking were used in an alkylation process, which chemically combined the smaller molecules into larger ones that could be blended with other products to make fuel products. One of the products from this process was used to make Avgas.

Two alkylation processes were used in Australian refineries: the sulfuric acid process, and the hydrogen fluoride process.

The sulfuric acid process was patented in 1936. The desired operating range of the temperature in the reaction vessel is between 2 degrees C and 16 degrees C. The alkylation reaction happens at the greatest efficiency within this temperature range; however, the reaction generates heat so it is necessary to refrigerate the process. The reactors, vessels and associated piping are normally made of carbon steel, which is resistant to sulfuric acid at the concentration used, but some of the other products of reaction have the potential to cause corrosion if they are not controlled. The chemicals in this reaction have different densities, and the sulfuric acid is sufficiently viscous that an intense stirring mechanism is required to ensure sufficient mixing so that the reaction occurs as required.

The hydrogen fluoride process was patented in 1938, and is now more common in Australia. The reaction does not produce an end product that is capable of such a high octane rating as that from the sulfuric acid process, but aircraft that require such a high octane rating (such as the Lockheed Super Constellation) are now rare. In the hydrogen fluoride process, the reaction can occur at 25 degrees C to 45 degrees C, and this temperature can be maintained using cooling water instead of refrigeration. The hydrogen fluoride catalyst, if it remains dry, is a stable compound with a boiling temperature that allows it to be distilled out of the product of the reaction for further recycling. Hydrogen fluoride is therefore more completely recovered after the reaction, reducing the need for additional fresh catalyst. There is a greater requirement, however, for the reaction feedstock to be thoroughly dried before the reaction, as wet hydrogen fluoride is highly corrosive. Hydrogen fluoride is less viscous than sulfuric acid, and the reaction occurs more rapidly, so there is less need for stirring the chemicals in a reaction vessel. Concerns have arisen relating to the environmental implications surrounding the use of large quantities of hydrogen fluoride, which have led more recently to greater use of the sulfuric acid process in new plants.

Of the seven Australian refineries that had alkylation processes, three manufactured aviation gasoline. The BP refinery at Kwinana, Western Australia, manufactured Avgas 100/130 using hydrogen fluoride as a catalyst. The Shell refinery at Geelong, Victoria, manufactured Avgas 100LL using hydrogen fluoride as a catalyst, and the Mobil refinery at Altona, Victoria, manufactured Avgas 100/130 using sulfuric acid as a catalyst.

Of the total refined products manufactured from crude oil in Australia in 1998, 12 per cent was fuel for turbine-powered aircraft, and 0.4 per cent was Avgas.

The alkylation unit at the Altona refinery contained a series of treatment sections that processed and purified the process stream. After entering the alkylation unit, olefin feed was reacted with isobutane in the presence of a concentrated sulfuric acid catalyst. This reaction was used to produce the desired product, iso-octane, the major component of Avgas. The reactor effluent, or main process stream, then entered the caustic (alkaline) wash system where acidic compounds were neutralised. This effluent was subsequently washed with water to remove water-soluble compounds. An anti-corrosion chemical, Neutramine D, was then injected into the process stream to neutralise remaining acid compounds. The effluent was then separated in a series of three distillation towers. These towers were named the deisobutaniser, the debutaniser and the rerun towers. The product was then piped to another refinery unit where additives were blended in to make Avgas.

A more detailed explanation of the method by which crude oil was processed to manufacture Avgas can be found in appendix G, and knowledge of this appendix will be of benefit in understanding the following sections.

The individual oil companies bought and sold Avgas of the different grades between themselves, and imported and exported Avgas from and to other countries.

The diagrams on the following pages show the main processes used at the refinery to manufacture Avgas.

2.1.1 Manufacturing process variations

A detailed description of the sequence of events that were relevant to the investigation are described chronologically in appendix H. This section is a summary of that description. Further information regarding process variation in the refinery is presented graphically on Figs. 8 and 9.

The nature and complexity of refinery operations meant that it was normal for continual maintenance, inspection and adjustment work to occur. Operators were working throughout the refinery all the time, and this was normal.

The alkylation caustic wash system circulation pumps numbered G-A3-33 and G-A3-34 were piped in parallel so that either one could be used to circulate caustic (see Fig. 6). They were not instrumented to display on or off condition, or any fault on the computerised

FIGURE 2. Crude oil refining at Mobil's Altona refinery

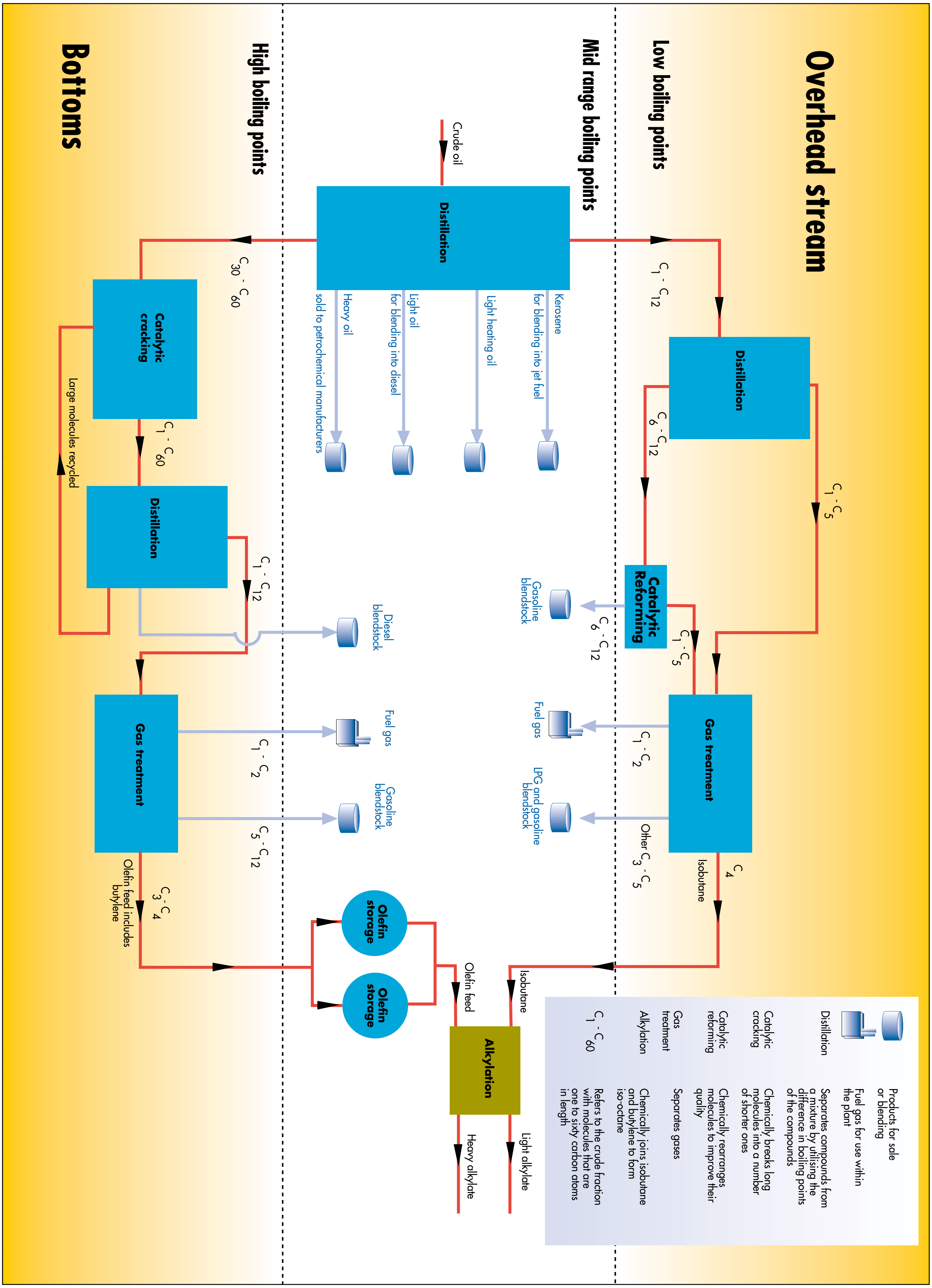
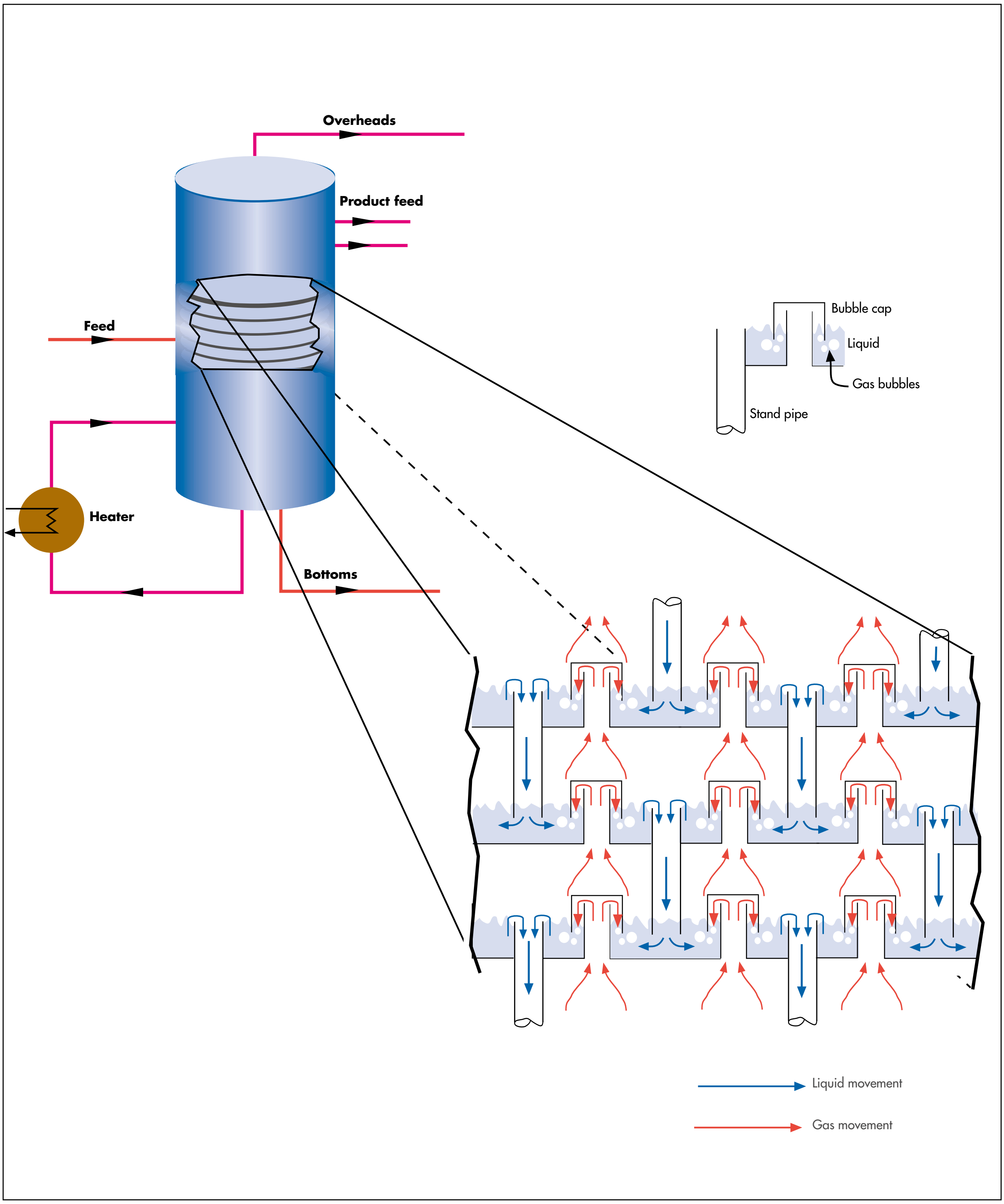


FIGURE 3. Principles of distillation

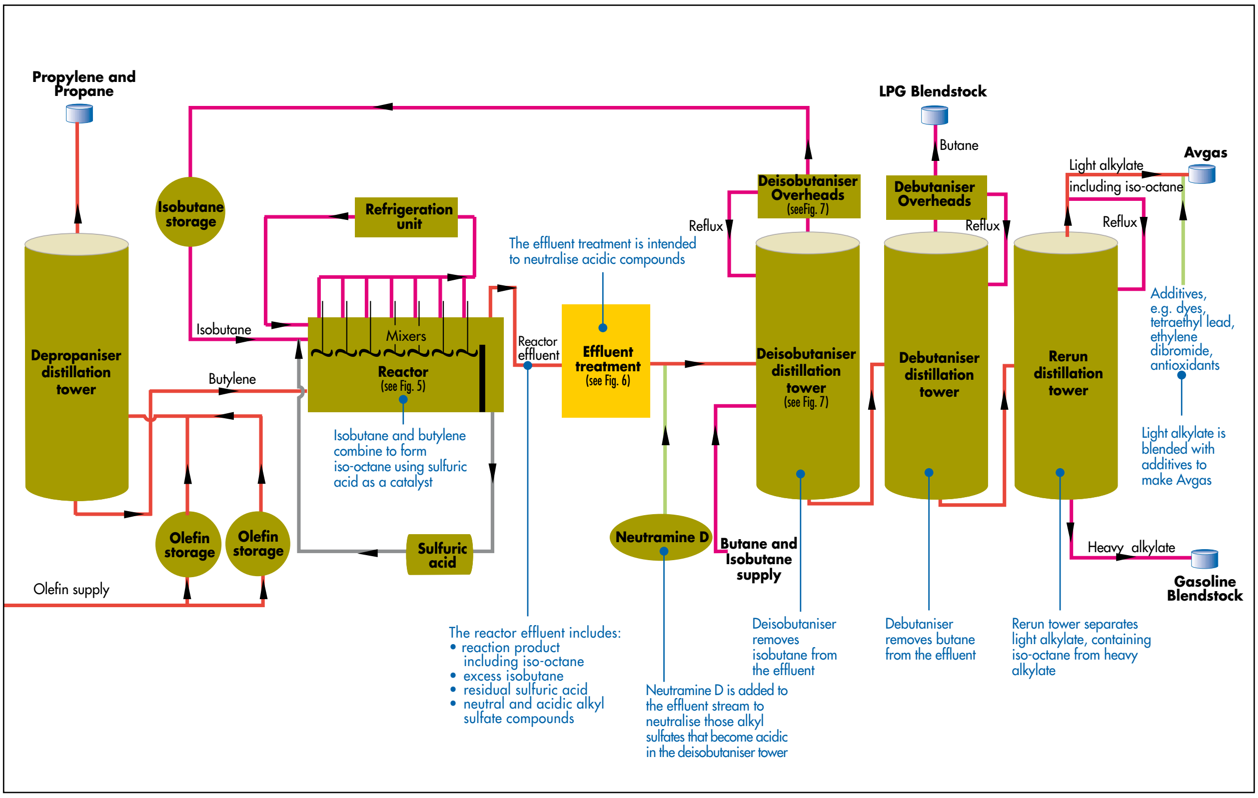


Distillation towers utilise the difference in boiling points of components within a mixture in order to separate them.

Typically, a distillation tower is heated by heating liquid components that have been removed from the bottom of the tower and returning them back near the base of the tower. Temperatures at the top of distillation towers are cooler than at the bottom. Towers are stacked with interconnecting horizontal trays. Liquids are able to move down between trays, while gases are able to move upwards. Compounds with lower boiling points come off at the top of the tower as a gas while compounds with higher boiling points come off at the bottom of the tower as a liquid known as bottoms.

Boiling temperatures of compounds are affected by pressure. Generally, a decrease in pressure decreases the temperature at which a compound boils, or changes to a gaseous state. Large hydrocarbon compounds tend to boil at temperatures that also cause them to break down. To prevent this, vacuum distillation is used to maintain the integrity of compounds by reducing the temperature at which the compound boils. Design engineers specify the optimum operating temperatures and pressure for each distillation tower in order to take advantage of varying differences in boiling point between different compounds at varying pressures.

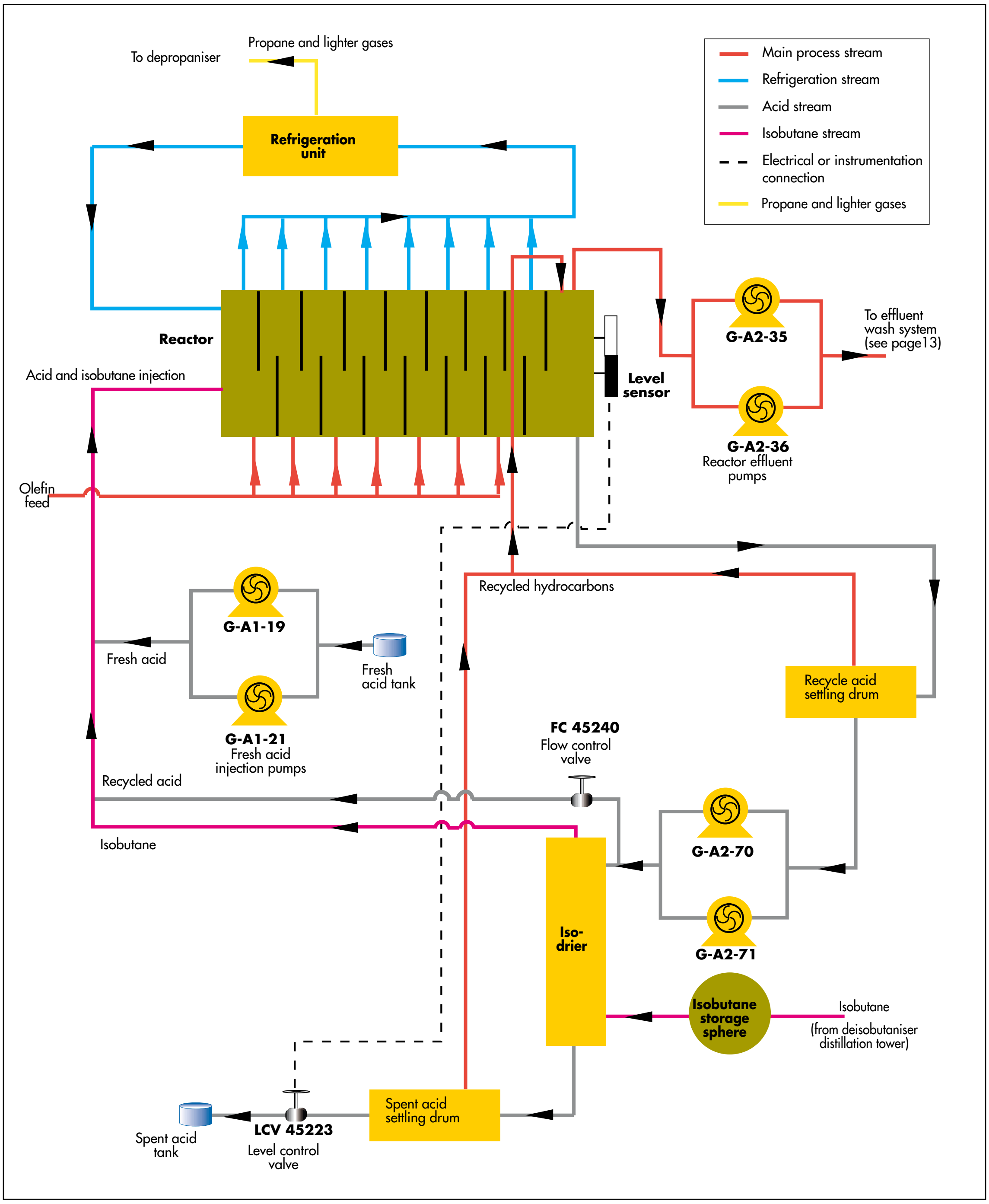
FIGURE 4. Alkylation unit



Distributed Control System (DCS) display board in the control room. (This system is described in section 2.1.2.2). Pump G-A3-63 was intended to be used for caustic charge to the depropaniser feed treatment, however pipework existed to permit the use of pump G-A3-63 for circulation in the effluent caustic wash system. If pump G-A3-63 was used to circulate caustic in the effluent treatment section, then some of the pipework that would normally be used for injecting fresh caustic would not be available for that function. Therefore, it would have been necessary to use a temporary alternate line for the injection of fresh caustic while pump G-A3-63 was being used to circulate caustic. Pump G-A3-63 was a deep well pump, a different type that had a lower capacity than either of the two pumps that were normally available for caustic circulation. Under normal operations, only one pump was running at any given time for caustic wash circulation. In order to transfer operations to a different pump, an operator was required to manually re-route the flow to the required pump on site. The only remote indication of a pump's failure to perform was a low-flow or a no-flow indication measured from a point downstream from the pump and displayed in the control room. The pumps did not have any defined overhaul frequency or retirement time. Pumps were assessed for condition, and maintenance was then planned on the basis of that assessment.

Early in August 1999, circulation pump G-A3-33 was noted to have a high level of vibration during regular testing. The pump was monitored more frequently, in accordance with company procedures. In the second half of September 1999, pump G-A3-34 was noted to have a low-flow condition. The following day, it was taken off line for inspection, and the impeller was found to be damaged. The pump was removed for overhaul. The alkylation unit continued to operate using pump G-A3-33 for caustic circulation. This pump received increased maintenance, including regular transfusions of oil; however, on November 2, the pump exceeded limits and was also taken off line. In order to keep the alkylation unit operating, pump G-A3-63 was brought onto line for caustic circulation.

FIGURE 5. Alkylation reactor



Acidity and other indications of corrosion, including sulfate concentrations (see Fig. 8), in the deisobutaniser distillation tower started to increase, and as the pH of water sampled from the deisobutaniser distillation tower overheads dropped (see Fig. 7), the flow of Neutramine D was increased to compensate.

No evidence was identified to indicate that pump repair and overhaul practices had been deficient.

On 5 November 1999, pump G-A3-34 was returned to service after overhaul. The pH levels were still outside the limits for normal operation. A test scheduled for 8 November 1999 of the environment within the deisobutaniser tower was not conducted. Operations continued with the higher level of Neutramine D injection until 10 November when a routine water test indicated an abnormally low pH. The Neutramine D injection pump was found to have

FIGURE 6. Effluent treatment

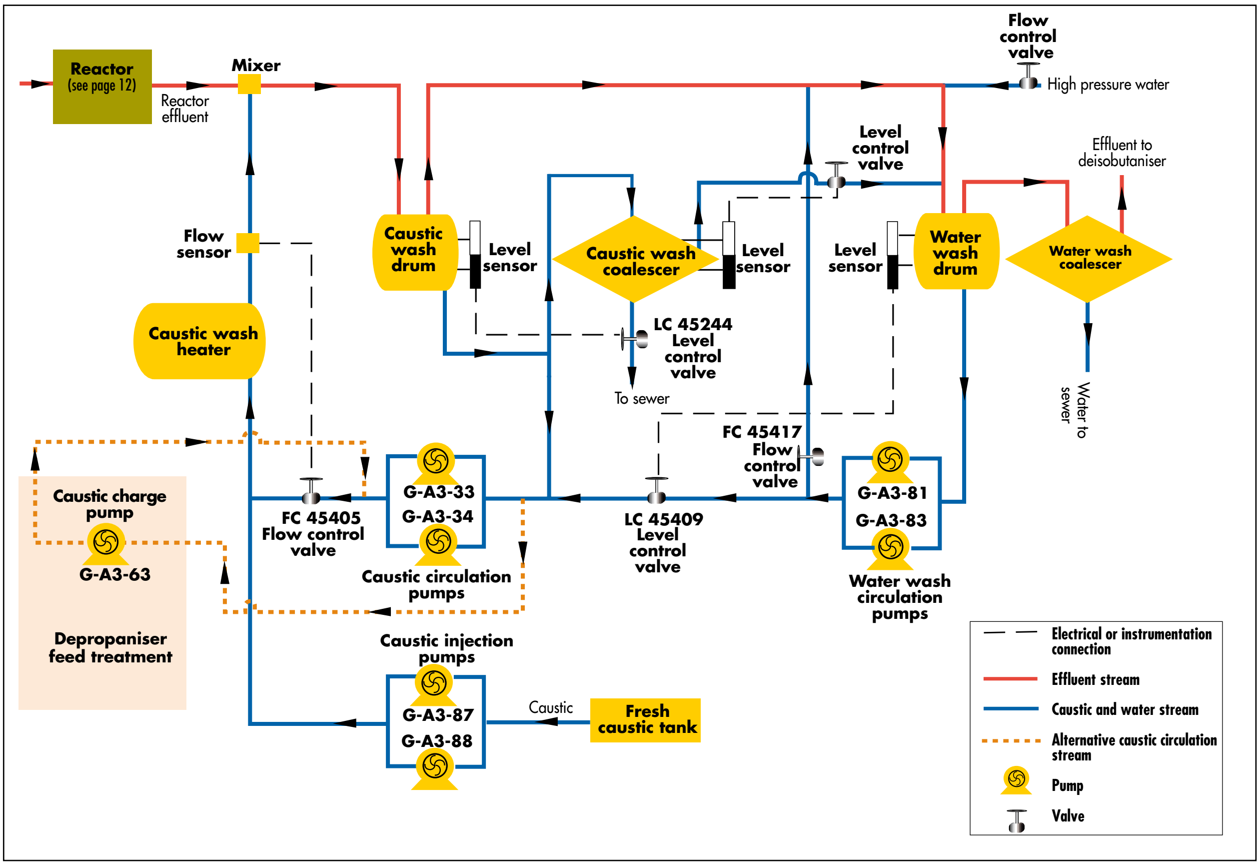
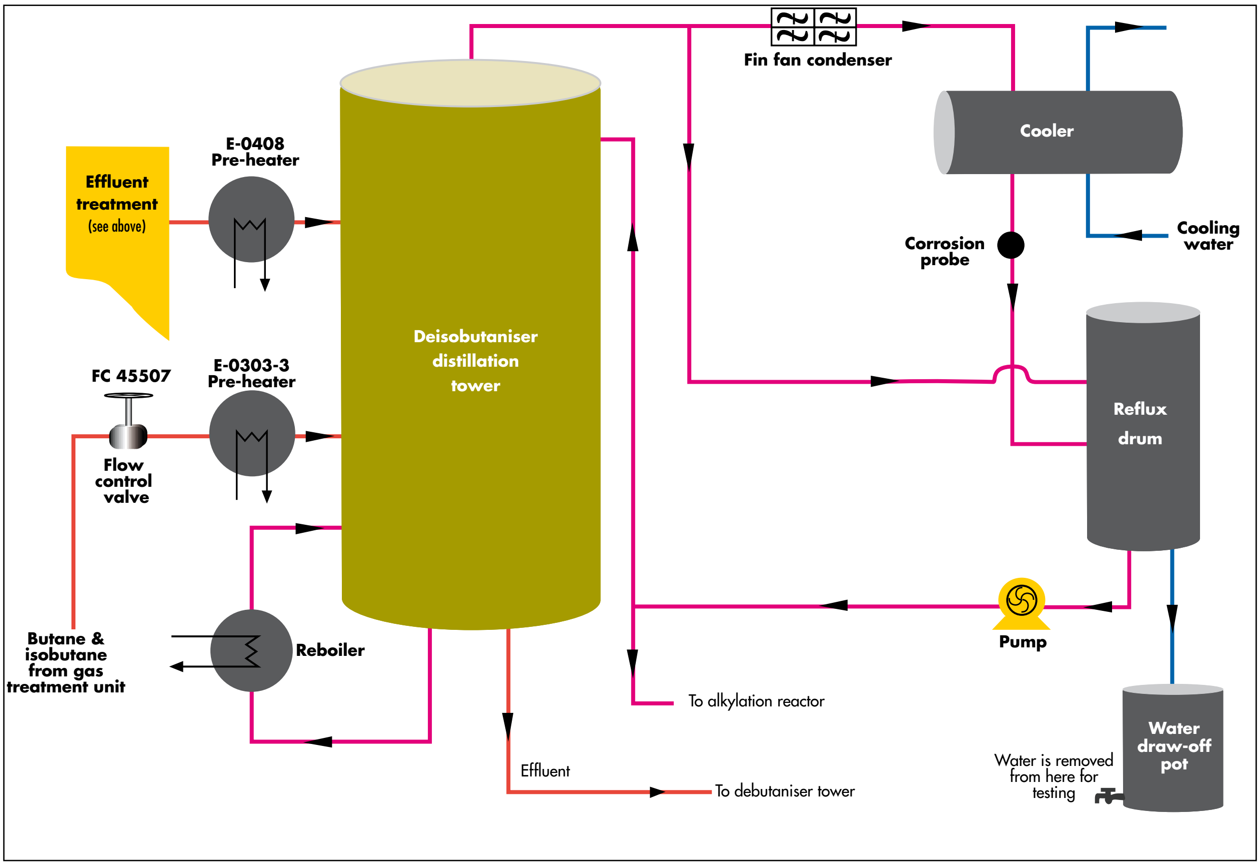


FIGURE 7. Deisobutaniser distillation tower and overheads



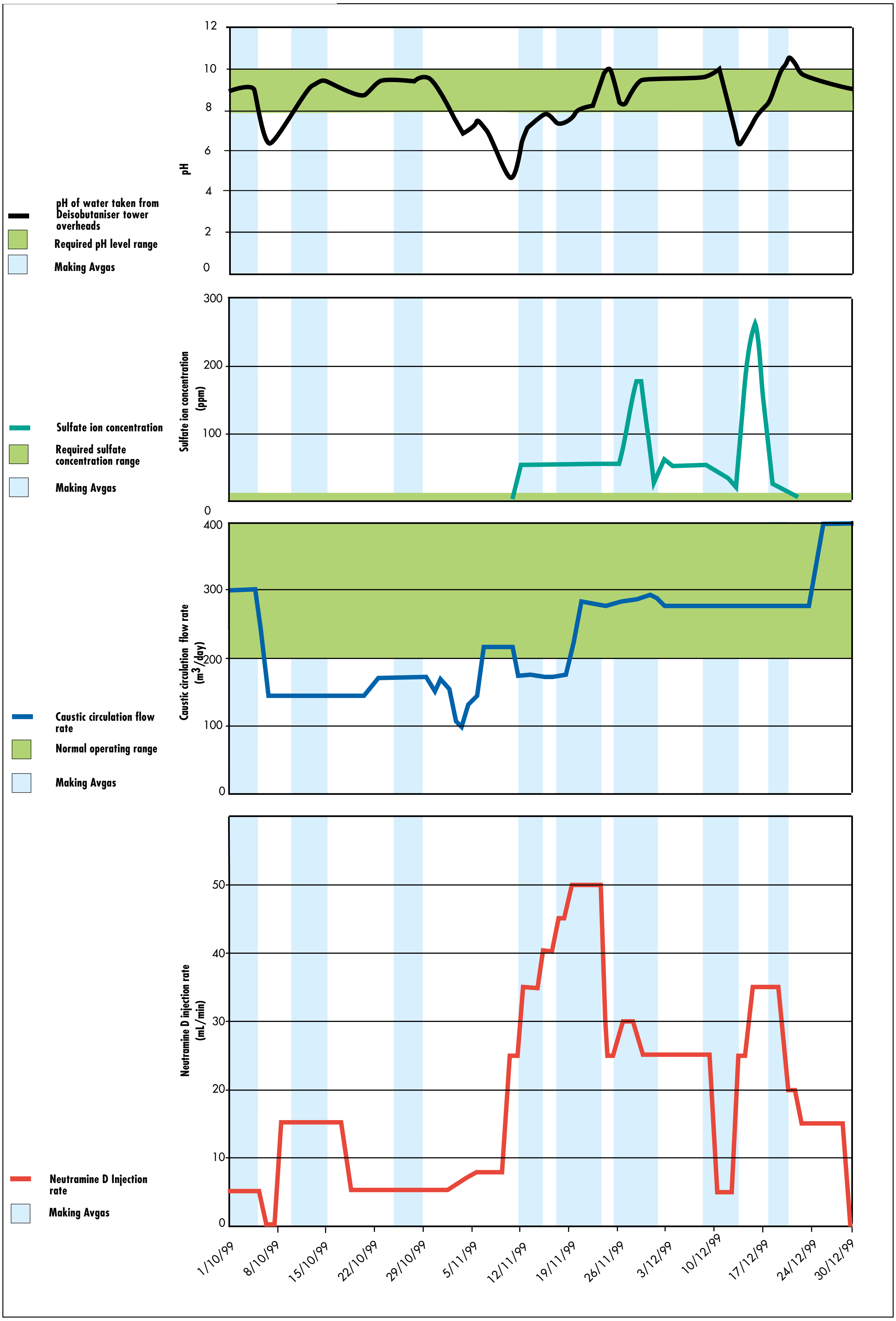
failed due to an airlock. Later that day, a detailed inspection of the unit revealed a leak of a flow control valve in the caustic circulation system. A bypass pipe with a valve was brought on line, the leaking valve was removed for repair and production continued. Normal caustic circulation flow rates could not be achieved with maximum pump output and the bypass valve fully open. It was following this event that pH levels stabilised; however, a higher than normal dosage of Neutramine D was still required.

On 20 November 1999, the caustic circulation flow rate increased to remain within the normal range, above the lower alarm limit. Process limits are described in section 2.1.2.2 The pH in the deisobutaniser tower had been effectively controlled in the past with the use of smaller changes in the injection rate of Neutramine D; however, in this case, larger changes in the injection rate had been required.

The alkylation process was complex, and a large number of parameters had to be maintained within predefined limits for normal operation. It was not unusual for components to fail at times in the plant, and for the system to be managed so that it could continue to operate. However, over a 5-month period from August 1999 until the contamination event, a number of planned and unplanned changes, variations and events occurred in the alkylation unit in addition to the pump failures described above. These can be summarised as follows:

- pH was twice found to be no greater than seven at the test point in the caustic wash circulation system. This indicated that any caustic that was being injected into the system was totally consumed before the test point in the circulation system.
- The chemical composition of the alkylation unit feedstock varied at times.
- The preheater for the effluent supply to the deisobutaniser tower did not operate to target at all times, and was not operating for a period. The preheater was not essential for continued operation.
- The steam supply to the preheater for the isobutane supply to the deisobutaniser tower was changed to manual control. Manual adjustment was not as precise as automatic adjustment, as it was not being continually monitored and changed, so the heat input to the deisobutaniser tower would not have been controlled to the same degree of accuracy. The preheater contributed to the consistent operation of the deisobutaniser tower, and less control would have been available of both the effluent downstream of the tower, and of the isobutane that was recirculated to the alkylation reactor. Variable quality of isobutane entering the alkylation reactor would have affected the process in the alkylation reactor.
- Planned maintenance was conducted on the effluent water wash system.
- The caustic circulation flow valve was bypassed. The system with the bypass valve in operation could not maintain a caustic circulation flow rate above the lower alarm limit.
- The automatic flow controller for supply of isobutane feedstock to the alkylation unit was bypassed, and the system was manually controlled. Manual adjustment was not as precise as automatic adjustment, as it was not being continually monitored and changed in response to small changes in system parameters.
- Planned maintenance was conducted on the Advanced Control Application Package.
- The ratio of isobutane to olefin feed was usually below the normal minimum limit. If the ratio was not maintained within normal limits, the chemical reactions in the reactor would have produced undesired compounds.
- Daily acid consumption was usually greater than the desired rate.

FIGURE 8. Process variations - Alkylation unit



- The acid analyser required repeated maintenance, and was off line at times. This would mean that less information was available on the quality of the acid in the reactor, so it would not have been possible to control the acid in the system with the same degree of accuracy.
- The isobutane drier did not operate consistently. This would lead to more water entrained in the recycled isobutane being injected into the alkylation reactor. The water would dilute the sulfuric acid, and a variation in the fresh acid injection rate would be needed to compensate for this change.
- The corrosion probe in the deisobutaniser overheads was unserviceable.

2.1.2 Control of Avgas manufacture

The objectives of the refinery were to maximise production performance in a safe, efficient, reliable and environmentally acceptable manner, while minimising costs and maximising profit. The refinery was controlled with the aim of achieving these objectives.

2.1.2.1 Equilibrium

A plant that processes fluids would normally be controlled to achieve the maximum efficiency in the process. Parameters such as temperature, pressure and chemical makeup, which are required to maintain the efficiency of a unit, would be monitored and optimised to achieve that efficiency. It would be a desirable aim to achieve a state of equilibrium within the plant in which all the parameters that could affect the efficiency of the process were maintained at their optimum levels. A plant would normally be managed by identifying the optimum levels of all the critical parameters, and defining an achievable range of operating limits for each parameter.

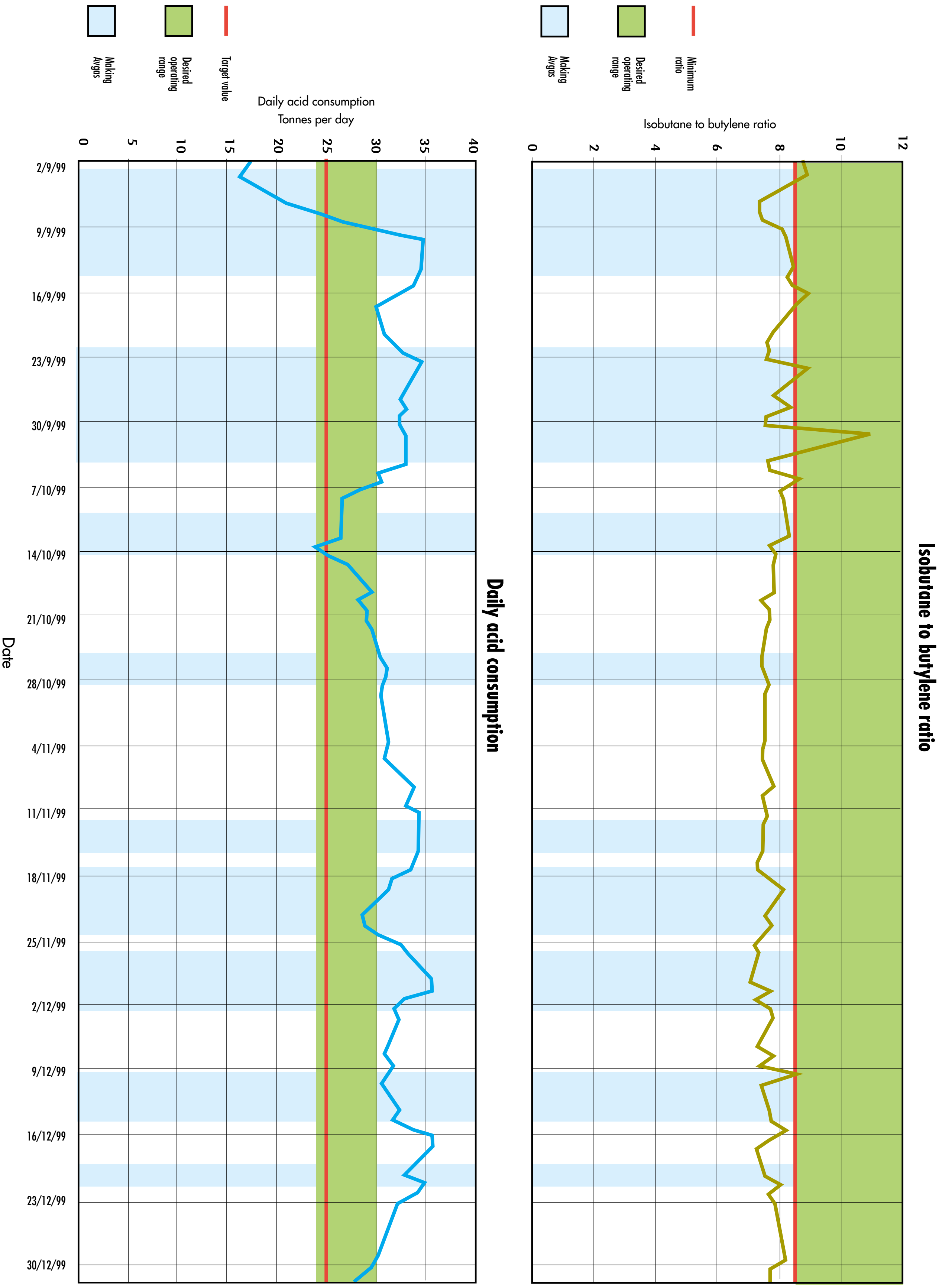
The Altona refinery was intended to operate with each critical parameter at, or as near as possible, to its optimum which were considered as target values. Additionally, each parameter had defined operating limits that were intended to define the limits on normal operations for the plant. The selection of normal operating targets and limits could be related to economics, safety, product quality, operating conditions of the plant, or any condition that could affect the desirability of an outcome.

2.1.2.2 Control room

All the refinery units, including the alkylation unit, were monitored from six computer-based consoles in the control room at the refinery. Various parameters of the operation were displayed in real time. The main control and information system was known as the Distributed Control System (DCS). A computer system known as the Advanced Control Application Package (ACAP) could automatically manipulate some of the operating control settings to optimise the performance of a refinery unit. The ACAP controlled various parameters within the alkylation unit through the DCS. Most settings could also be adjusted by the control room operator from the control room; however, some were monitored from the control room and settings had to be adjusted manually on site under instruction from the control room. The ACAP had many predefined high and low limits and parameter targets that it aimed to maintain. These high and low limits defined the optimal process range.

If at times the ACAP would not be able to meet the desired targets, it would highlight the target that could not be achieved. The DCS system initiated an aural and visible alarm on the control board whenever a measured parameter exceeded the prescribed limit.

FIGURE 9. Daily acid consumption and isobutane to butylene ratio



The alkylation console in the control room did not have the capacity to indicate any faults in the caustic circulation pumps, nor to indicate which caustic circulation pump was operating. The console displayed the flow rate downstream from the caustic circulation control valve (see Fig. 6). The injection rate of Neutramine D (see Fig. 4) and the pH of water extracted from the deisobutaniser overhead system (see Fig 7.) were not monitored by the DCS system or displayed on the console.

A diary or logbook was maintained in the control room for the control board that was used to control the alkylation unit. This book was used to record items of interest, and to assist in passing on necessary information to the next shift. There was no structure to the book, and no guidelines to define what should or should not be entered in the book. This meant that entries in the book were not consistent, and that the book could not be relied on for a complete transfer of relevant information.

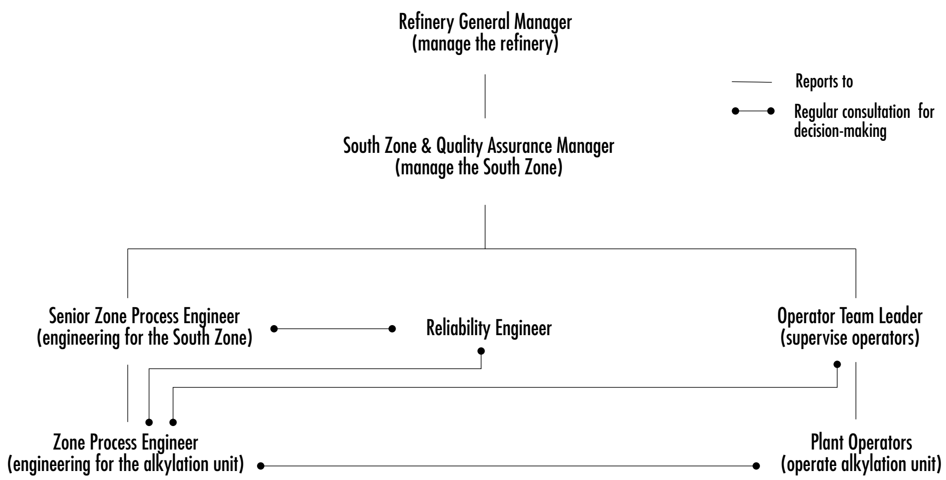
Piper Alpha

Deficient management of processes, including transfer of relevant information, on the Piper Alpha oil platform (UK) led to an undesired outcome:

On 6 July 1988, a fire occurred on an oil platform in the North Sea. A variety of maintenance activities were being undertaken, and all this activity was controlled from a central position. Before the fire, a contractor had been removing pressure safety valves for overhaul under the authority of the central maintenance controller. The management of the maintenance activities was found to be deficient, in that it did not ensure effective exchange of all the necessary operational knowledge between the different functional working groups on the oil platform. This deficiency led to an incomplete understanding of the situation by critical personnel at a time when there was a significant amount of change on the platform. A combination of planned and unplanned changes on the platform led to a situation when there was a significant amount of unusual but critical information that needed to be effectively managed. The critical personnel were not aware of information relating to the maintenance of the pressure safety valves that would have let them know that their actions were unsafe. These actions led to the initiation of the fire. The lack of a workable and robust system of managed information transfer was a contributing factor to the onset of the fire.

2.1.2.3 Roles of Avgas production personnel

FIGURE 10. Organisational chart



2.1.2.4 Plant operators

Teams of plant operators operated the alkylation unit. The operators worked in the control room at the computerised console, monitoring the parameters of the unit and controlling the process. Operators also worked on site under the instruction of operators in the control room. There was a very low turnover of operators at the refinery: the last recruitment of operators occurred in 1993. The operators were expected to gain a good practical knowledge of the operation of the refinery prior to working on the console. Each shift was supervised by a team leader.

2.1.2.5 Zone Process Engineer

The position of Zone Process Engineer for the alkylation unit was a developmental position for a new graduate engineer within the company. The Zone Process Engineer would normally hold that position for 6 to 24 months. The Zone Process Engineer's role was to:

- Monitor the performance of the assigned refinery process units.
- Make recommendations to optimise performance.
- Provide timely and cost effective technical support for complex problems and solutions.

The Zone Process Engineer fulfilled this role by ensuring that recommendations were made to optimise the quantity, quality and yield of the manufactured product, while aiming to minimise costs and maximise plant reliability. The Zone Process Engineer was expected to work closely with, and to advise, the operating team, and to help to solve any unusual problems as they arose. The Zone Process Engineer was expected to be aware of and to develop the knowledge of the capabilities and limitations of the plant, using computer simulations as appropriate. The Zone Process Engineer was expected to monitor parts of the plant that were critical to its operation, and to work with the Reliability Engineer to identify and manage vulnerabilities to the operation that were related to those parts of the plant. The Zone Process Engineer was expected to maintain appropriate records for the refinery unit under his responsibility.

The Zone Process Engineer reported to the Senior Zone Process Engineer, and also assisted in assessing the ability of the unit to run with differing feedstocks and in forecasting the consequences, helping in assessing lost opportunities, prioritising and managing work priorities for the refinery unit.

The Zone Process Engineer was expected to attend a daily planning meeting, to provide information to the meeting, and to provide input to the daily schedule.

2.1.2.6 Senior Zone Process Engineer

Two positions for Senior Zone Process Engineer (SZPE) existed within the refinery, each position covering approximately half of the operation, including a number of units. A person with considerable experience of process engineering normally held the position. The SZPE's role was to:

- Optimise and develop zone operations to maximise production performance in a safe, efficient and environmentally acceptable manner.
- Maximise the contribution of the refinery assets through application of process engineering technology throughout the zone.
- Ensure predictable operation of the plant through accurate assessment of plant capability and updated linear program.

The SZPE fulfilled his role by what were essentially similar processes to those that were being used by the Zone Process Engineer. The SZPE attended the daily planning meetings, and also attended a SZPE weekly meeting to discuss refinery-wide and strategic issues, as well as personnel and administrative matters. The SZPE reported to the South Zone and Quality Assurance Manager.

2.1.2.7 South Zone and Quality Assurance Manager

The position of South Zone and Quality Assurance Manager was held by one person with considerable experience in process engineering. The South Zone Manager's role was to:

- Manage and integrate the assets and resources to safely meet the production plan and expense targets for the zone with a focus on extracting the most value from the existing assets.
- Continuously improve zone performance by improving the skills and motivation of the zone team, quality of operations, equipment reliability and availability, and by defining and undertaking expense and capital projects.
- Manage the laboratory to improve quality assurance processes throughout the refinery and ensure that all products were 'right first time'.
- Provide leadership and inspiration to the people of Altona around continued development of the alignment and involvement process that underpins the culture of the plant.

The South Zone Manager fulfilled this role by ensuring that the operation of the plant aligned with the production plans for quantity and quality, and developing and working on plans to improve the performance of the plant and its operation. The South Zone Manager helped in the development of reliability strategies and in the utilisation of maintenance capabilities, and managed the quality assurance process to optimise the process of ensuring consistency of product quality.

The South Zone Manager was primarily involved in the development and monitoring of plans used to predict and monitor the operation of the plant, and in processes for enhancing the operation of personnel within the plant.

2.1.2.8 Reliability Engineer

The position of Reliability Engineer was not in the direct line of responsibility for operation of the alkylation unit. The Reliability Engineer analysed information that was obtained to enhance the predictability of equipment reliability. The Reliability Engineer provided advice as required to personnel in relation to enhancing the reliability of the unit, minimising breakdown maintenance, and maximising programmed maintenance.

2.1.2.9 Decision-making processes

The day-to-day management of the alkylation unit was the responsibility of the field operators, the operator at the console in the control room, the operator team leader and the alkylation unit Zone Process Engineer. The Zone Process Engineer was responsible for providing technical advice during abnormal operations.

Decisions that affected the operation of the refinery were made in a consultative manner. The person responsible for controlling a particular aspect of the operation would discuss any change and the factors that were related to that change with those who had knowledge of those factors, and other members of the team involved in the operation of that aspect of the refinery. Since 1995, the decision-making process for changes that fell within specified criteria should normally have been controlled through a company-documented *Management of Change* process. Changes to the operating parameters for temporary changes on a day-to-day basis were recorded, and conducted through a process of discussion supported by daily scheduled meetings. In addition to the *Management of Change* process, other defined changes would be managed by maintenance, reliability or project processes.

Mobil's *Management of Change* document, MOA-ES-005, version 2.0, appendix C, dated 19 December 1996, detailed situations for which the *Management of Change* procedure was recommended. This document specified that in relation to plant and equipment changes, replacement of equipment other than replacement in kind (that is, identical replacement), for example pumps and valves, should be subject to the documented *Management of Change* procedure.

This document was supported by the *Management of Change* procedures document MRAA-SAP-0002, revision 00.1, dated 7 July 1998. Section 7.1 of this document indicated that a change that was not a replacement in kind should be supported by the use of the documented company *Management of Change* procedure.

Prior to the failure of the remaining effluent treatment caustic circulation pump in November 1999, Mobil personnel had identified that the proposed use of pump G-A3-63 would result in a caustic circulation flow rate that was less than the lower alarm limit. When considering changing the system to use deep well pump G-A3-63 for caustic wash circulation, the engineering team discussed issues related to the process change to identify any potential downstream impacts but they did not use the company's structured *Management of Change* procedure. The considerations included an assessment of the effects on product quality. Product quality was monitored after the change by ensuring that manufactured Avgas met the specification tests.

The scope for the *Management of Change* process stated that it was to be used to manage change. It did not clearly identify the minimum significance of any change for which the procedure should be used, whether the procedure should be used for temporary or permanent changes, or if it should be used for unplanned, as well as for planned changes. The scope therefore provided insufficient information to enable consistent application of the procedure. When the *Management of Change* procedure was being applied, defined criteria were used for considering appropriate, defined hazard assessment methodologies. The selection process considered different types of change, and set criteria that required particular types of hazard assessment process.

The management structure was supported by a series of programmed hierarchical meetings, with daily production review meetings that reported up through a series of higher level meetings. The meetings were used to gather information and make decisions relating to the operations of the refinery, and to report on them to senior management within the company.

The Zone Process Engineer reported daily to a management meeting; however, the minutes of the meeting, and of the next higher level meeting that that meeting reported to, did not refer to the caustic circulation pumps. It is not known if the caustic circulation pumps were discussed, or if they were discussed but not minuted.

Prior to taking caustic wash circulation pump G-A3-33 off line in early November, the Zone Process Engineer had informed his Zone Manager. The Zone Manager indicated that it was desirable that the unit should continue operating. The Zone Manager decided to continue operations and to inform the weekly management team meeting of the situation. One of the reasons for this was that is was easier to control the process without any gross changes to the operating parameters, such as shutting the unit down. It was not possible to continue operating if there was no caustic wash circulation.

The depropaniser caustic charge pump G-A3-63 was identified as an alternative that could provide effluent treatment caustic circulation while both G-A3-33 and G-A3-34 were not available, even though pump G-A3-63 was a smaller capacity pump with a substantially lower maximum output than either of the normal circulation pumps. No documented procedures or methods existed to indicate that this circulation system had been developed for use in this way.

When refinery personnel were considering the implications of the use of pump G-A3-63 to provide caustic wash circulation at a lower flow rate, the Zone Process Engineer considered the downstream effects. He recognised that there would be a likelihood of increased acidity downstream from the caustic wash system that would require an increased Neutramine D injection rate to compensate. He expected that if there was any effect on the end product from this injection rate, it would be detected by quality assurance and specification tests downstream.

The corrosion control contractor who tested the pH levels and adjusted the Neutramine D injection rate during this period advised the Zone Process Engineer that the pH levels in the deisobutaniser tower water were indicating lower than the normal limits. The Zone Process Engineer stated that adjusting the Neutramine D injection rate was commonplace and that he did not disagree with the decision to increase the injection rate from around 10 mL/min to 50 mL/min in order to protect plant equipment from the resulting corrosion. The Zone Process Engineer indicated that he accepted the increased injection rate, at least in part, because he was aware that there had been times in the past when the injection rate had been similar to that occurring in November 1999 (see appendix E). He was therefore not concerned by this decision because of his expectation that it would not affect the end product. The Zone Process Engineer discussed the caustic circulation issue with his supervisor at the time. It is not known whether increased Neutramine D injection rates were discussed. Higher dosage rates of Neutramine D were normally required when starting up after a unit shutdown to return the pH levels to the required values.

2.1.3 Corrosion control

The alkylation unit of the refinery had vessels that contained significant quantities of low boiling point hydrocarbons that were under pressure. The units also contained significant quantities of potentially corrosive chemicals that were also under pressure; for example, if the sulfuric acid was diluted with water, then it would increase in corrosiveness. At certain stages of the process, the chemicals were heated. If the chemicals and the conditions within the alkylation were not maintained within predefined limits, a highly corrosive environment could have existed within a section of the unit. If corrosion resulted in a leak in the unit, a significant loss of containment of flammable liquids, gas or corrosive chemicals could have occurred from the pressurised system.

This potential meant that inadequate control of an alkylation unit could make it safety critical. The containment of potentially toxic or explosive chemicals relied on consistent and accurate maintenance of a non-corrosive environment within a system, and this in turn relied on an effective system to manage the control of operating parameters within the unit.

The refinery went through an exercise in 1991 to rationalise the suppliers of corrosion-control chemicals. One supplier was awarded a contract for the supply of corrosion-control chemicals to a number of points in the refinery, including the effluent leading to the deisobutaniser tower.

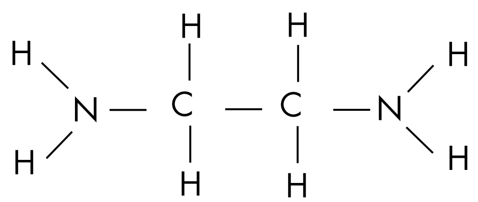
The corrosion control contractor initially recommended the use of Neutramine OH, a proprietary product containing an organic amine, for injection into the effluent stream prior to entering the deisobutaniser tower. In order to test its effectiveness in relation to corrosion control, injection of corrosion control chemicals was stopped and the resulting corrosion rates were monitored in order to establish a baseline corrosion level. Neutramine OH was then introduced to develop a model of its effectiveness. This process indicated that it was not providing the required level of corrosion control in the deisobutaniser tower overheads.

The corrosion control contractor then recommended Neutramine D as an alternative corrosion inhibitor for the deisobutaniser tower. Mobil tested the effectiveness of Neutramine D as a corrosion inhibitor and established that it was more effective than Neutramine OH in the deisobutaniser tower. Mobil also established that use of Neutramine D did not result in unacceptable amine salt deposition in the deisobutaniser tower. In April 1991, Neutramine OH was replaced with Neutramine D for corrosion inhibition in the deisobutaniser tower.

Properties of Amines

Amines are derived from the replacement of a hydrogen atom on ammonia (NH_3) with one or more alkyl groups. They exhibit alkaline behaviour by reacting with acids to neutralise them. Ethylene diamine, or technically 1,2-ethanediamine, is a colourless liquid at room temperature which has a strong ammoniacal odour. It melts at 11 degrees C and boils at 116 degrees C. It dissolves readily in water to form an alkaline solution but only dissolves very slightly in a mixture of hydrocarbons such as Avgas. If an organic mixture containing ethylene diamine is washed with water, then most, but not all, of the ethylene diamine will dissolve preferentially in water, and the ratio of concentrations of ethylene diamine in solution in the two solvents will remain constant. The ratio is known as the partition ratio.

Representation of the structure of ethylene diamine



The partition ratio of ethylene diamine in a mixture of water and alkylate products indicates that any excess ethylene diamine that did not chemically react with acids in the deisobutaniser tower would be largely but not completely extracted in solution in water removed from the deisobutaniser tower overheads. A small concentration of ethylene diamine would be expected to remain in the process stream.

Mechanisms of corrosion control

There are predominantly two categories of corrosion inhibitors used to control the corrosive characteristics of acids such as sulfuric acid. Neutralising inhibitors reduce acid strength by reacting with hydrogen ions (the acidic component), while filming inhibitors bond to metal surfaces, forming a physical barrier between the metal and the corrosive environment. Ethylene diamine is a neutralising inhibitor that reacts with acidic hydrogen ions to control corrosion.

The manufacturers of ethylene diamine advertise and sell the compound both as a corrosion inhibitor and as a complexing agent. It reacts with metal ions such as copper and zinc to form a complex molecule known as a chelate. The copper-ethylene diamine chelate has a distinctive purple colour when dissolved in water.

The accepted procedure that existed between the refinery operator and the provider of the corrosion control chemicals at the start of the contract required the supplier to control the injection rate of the corrosion inhibitors. The contractor was also required to conduct an analysis on Monday, Wednesday and Friday mornings. This was done by testing water that had been extracted earlier that morning by a refinery night shift operator from the overheads of the deisobutaniser tower to ensure that the environment within the tower was within specified limits. The required pH level for the analysed water was between 8 and 10. The analysed water was also expected to have a concentration of iron and copper ions of less than 5 parts per million (ppm) each and a concentration of sulfite and sulfate ions of less than 10 ppm each. The contractor would then adjust the Neutramine D injection rate to control the pH. The contractor was required to produce a written report for the Zone Process Engineer after each test, and a monthly report for the refiner. The contractor normally discussed operational aspects of the plant with the Zone Process Engineer when submitting test reports.

The corrosion control contractor also monitored the rate of corrosion by using corrosion probes located at specific sites within the refinery. One of these probes was located in the deisobutaniser overhead system; however, it had ceased to function prior to November 1999.

The contract between Mobil and the corrosion control contractor was signed in early 1991 as a two year contract, with an option of an extension for a further year. No evidence was found of a formal extension of the contract; however, the relationship between the two contracted parties continued in a similar manner after the end of the contracted period.

The contract indicated that the operational priority of the contractor was to ensure that corrosion within the deisobutaniser tower was maintained at an acceptable rate by controlling the pH of water from the deisobutaniser overheads. The corrosion control activities had been continuing without any apparent problems for several years.

The corrosion control contractor's activities directly affected the process stream, in that the contractor was contractually empowered to inject chemical directly into the process stream without initially referring to the refiner's process controller. The objective of the corrosion control contractor was to ensure that the pH of water that came from the deisobutaniser tower overheads was within limits, and this was controlled by varying the injection rate of Neutramine D.

The investigation found no formal procedures or contractual requirements to ensure that the contractor's activities would not conflict with any of the organisational objectives of the refinery company.

An example of the concepts of risks and hazards as they apply to organisational objectives:

Josephine Soap has a small business that sells lunchtime sandwiches on a light industrial estate.

The *organisational objectives* of the business are to manufacture sandwiches and to sell them, maximising profit, minimising loss, to do so safely, without risk to health or the environment, and meeting all the regulatory obligations in regard to pay, work conditions, tax, etc.

The objectives may be defined, such as cashflow projection, or undefined, such as the requirement to avoid an adverse impact on the environment.

As the business progresses, *outcomes* are achieved, such as an actual cashflow, that either will, or will not meet the objectives. A *desirable outcome* is one that helps to achieve the organisational objectives, whereas an *undesirable outcome* is one that hinders the achievement of the organisational objectives.

Hazards exist that have the potential to adversely affect the objectives of the business. A hazard may be physical, such as a slippery floor that could increase the chance of a customer falling over, or botulism in supplied sandwich filling. A hazard may also be organisational, such as poor industrial relations in the factory employing most of the customer base, so that the customers are often on strike, and not buying sandwiches.

The probability of the customers being away on strike is the *risk* of the undesirable outcome.

A *defence* is something that reduces the probability of an undesirable outcome. A hard defence may be something mechanical like a guard on the meat slicer. A soft defence would include contracting an accountant to ensure that mistakes are not made in calculating the cashflow, or ensuring that the supplier of sandwich fillings has adequate hygiene to reduce the risk of botulism in the product.

At the time of the introduction of Neutramine D, Mobil did not have a formal *Management of Change* process in place to control decision making and the actions related to the introduction of a new chemical to the refining process. The team who managed the change used their professional knowledge to develop a program of actions for the change. These actions included an assessment of the effectiveness of the new process, and a consideration of some undesired outcomes, such as instability of both the chemical and its products of reaction in the physical and chemical environment within the tower. Both Mobil and the corrosion control contractor assumed that the ethylene diamine was removed from the process stream in water removed from the deisobutaniser overheads. This assumption was consistent with the physical properties of the chemical. Processes were not in place to ensure that either Mobil or the corrosion control contractor identified all of the undesired outcomes that should have been considered.

2.1.4 History of Neutramine D injection and its consequences

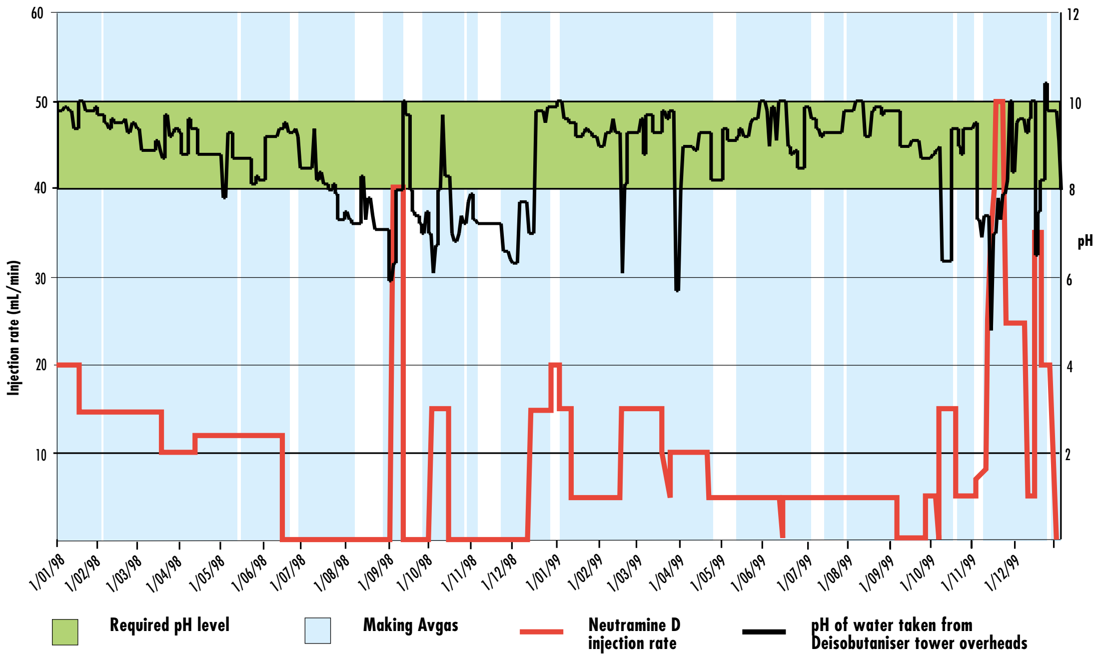
No conclusive evidence was found to confirm that Avgas had been contaminated with ethylene diamine before November 1999.

At the time the Neutramine D injection rate was increased in November 1999, the chemical had been in use in the refinery for approximately 8.5 years. Refinery personnel indicated there was no evidence before the contamination event that Neutramine D was anything other than an effective corrosion control chemical. A review of the history of Neutramine D injection rates from August 1995 to December 1999 indicated that the injection rate was over 25 mL/min on a number of occasions for limited periods during that time (see appendix E).

An engineer from a Moorabbin aircraft maintenance facility told Mobil's logistics aviation inspector during late December 1999 that he had seen heavier fuel system deposits over the last month or so. The inspector later told other Mobil personnel via email that the maintenance facility engineer had also told him 'that heavy deposits were also noted approximately 18 months ago ([the]…time frame…[that aircraft]…boost pumps were last failing at Moorabbin).' Personnel from a Bankstown fuel component overhaul facility also reported that they had observed heavier than normal deposits on copper and brass components during November and December 1999. It was also reported that copper and brass surfaces had exhibited 'sooting' for at least several years before the contamination episode. The sooting was not reported to Mobil before 16 December 1999.

On 2 September 1998, the Neutramine D injection rate was increased from 0 mL/min to 20 mL/min. On 4 September 1998, the injection rate was increased to 40 mL/min before being reduced back to 0 mL/min on 11 September 1998. The refinery was transferring light alkylate to tank 508 to make Avgas between 2 September and 7 September 1998. Records with dates of Avgas manufacture prior to 1 January 1998 were not examined. This information is illustrated on the graph of process variations (see Fig. 11).

FIGURE 11. Neutramine D injection rate and making Avgas in 1998 and 1999



Previous cases of sooting could have indicated that small concentrations of ethylene diamine were present in Avgas manufactured at Altona before the contamination event in late 1999. However, the chemical properties of ethylene diamine mean that its concentration in stored Avgas would have diminished over time (see appendix C). Samples of Avgas manufactured before the contamination in late 1999 were tested and no significant concentration of ethylene diamine was identified. It was not possible to confirm that contamination of Avgas with sufficient ethylene diamine to react with aircraft fuel system components had occurred before the contamination in late 1999.

2.1.5 Abnormal operations

When responding to abnormal conditions within the refinery, the *General Procedures Manual* was available for guidance.

The 'Alky Unit Upsets, Reactor Effluent Alkaline Wash Failures' section of the *General Procedures* Manual stated that if:

> Any of the alkaline wash systems have to be shut down and isolated due to failed pumps or bad leaks, replace the olefin feed with isobutane immediately.

Shutting down the olefin feed to the alkylation unit would stop the production of alkylate, as the alkylation reaction in the reactor could not proceed without the olefin feed. Shutting down the olefin feed could have resulted in significant upstream effects, including the possibility that the fluidised catalytic cracker which supplied olefins would have to be shut down.

The 'Alky Unit Upsets Alkaline Wash Circulation or Fresh Caustic Make Up' section of the *General Procedures Manual* stated that if:

> The circulation cannot be restarted within one hour then the unit must be shutdown per normal procedures.

Hence, the *General Procedures Manual* gave two different instructions in the event of no caustic circulation.

The computerised Advanced Control Application Package (ACAP) system lower and upper alarm limits for caustic wash circulation flow were 200 m^3/day and 650 m^3/day respectively. The *General Procedures Manual* did not give any instructions in the event of caustic circulation decreasing below the lower alarm limit. No instructions or advice were given until the flow rate reached 0 m^3/day, although the process was considered to be in an abnormal situation if the flow rate dropped below 200 m^3/day (as indicated by the presence of the alarm).

The operating team would have to identify a problem and analyse and develop a plan of action in each case when the flow rate dropped below 200 m^3/day. This process could not lead to a consistent method of planning action each time the flow rate dropped below 200 m^3/day, as there were no guidelines in the *General Procedures Manual* to direct the activity of the team in remedying the abnormal situation.

Daily work records indicated that refinery personnel operated in an environment of regular process and monitoring equipment anomalies and failures. A working environment with repeated alarm warnings can lead to habituation among those who operate in the environment, which in turn can lead to a desensitisation in relation to the alarms.

The refinery had well defined methods of operation for use when the processes were operating within their normal parameters. It also had well defined procedures for use in the event of an emergency, such as a loss of containment. Refinery personnel had developed numerous procedures that were used to start up or shut down refinery systems or units, when the unit would be operating for a limited period of time with the operating parameters outside their normal limits. However, the refinery did not have procedures in place for all abnormal operations, that is, when it was considered that the plant could continue to operate even though operating parameters were outside normal limits.

A process existed for developing procedural instructions after unintended abnormal operations that fell within certain specified categories, such as injuries, fires and loss of containment. The procedure was not designed to address all the undesired outcomes (such as product quality deficiencies) that could affect the refiner's objectives. The processes at the refinery were primarily designed to rely on the ability of the trained professional to develop an appropriate response at the time of the event of an unplanned abnormal operation.

Explosion at Flixborough

An abnormal condition at Flixborough (UK) was not managed in a controlled fashion and this led to an explosion:

On 1 June 1974, a flammable gas cloud ignited at a chemical plant at Flixborough in the UK. One unit in the plant had six reaction vessels connected to one another that contained cyclohexane at high temperature and pressure. Each vessel was 35 cm below its predecessor so that the cyclohexane would flow through them under gravity. The fifth vessel was found to have a crack, and it was removed for repair. As a temporary measure, a pipe with a double bend was manufactured and used to interconnect vessels four and six, using a flexible bellows at each end. The shape of the connecting pipe was such that it would experience a turning moment when under pressure. Some time later, when the pressure in the vessels increased slightly above normal, the pipe buckled and folded, releasing cyclohexane which then ignited.

The discovery of the crack in the fifth vessel was unexpected, and the consequent actions were decided on at an engineering meeting. No consideration was given at the meeting to the safety of the use of the replacement pipe in the plant. Calculations were undertaken to ascertain that the pipe would be of sufficient diameter to take the required flow, and that the straight pipe would withstand the internal pressure involved. No one appreciated, however, that the pressurised assembly would be subject to a turning moment that would impose a lateral (shear) force on the flexible bellows, for which they were not designed.

The management of the replacement of the cracked fifth reactor vessel with the temporary pipe was undertaken by a meeting of engineers, supervisors and managers. The meeting was focussed on resolving the situation efficiently. There was no indication of a structure to the considerations of the meeting, and it was evident that a number of considerations that were of relevance to the direct safety of the plant were not addressed. No guidelines were used to control the management of an abnormal situation at the plant.

2.1.6 Refinery maintenance practices

Maintenance procedures used within the refinery were intended to maximise the maintenance being conducted on a scheduled basis in preference to a breakdown basis. In order to attain this goal, refinery personnel used various methods, including the use of computerised reliability modelling tools, maintenance tracking systems and routine equipment monitoring. Approximately every two or three years, the alkylation unit was shut down to allow an inspection of the equipment and structures in the unit, and for repairs to be conducted as deemed necessary. The last shutdown of the alkylation unit was completed in 1997.

The alkylation caustic wash system incorporated two pumps for circulation, numbers G-A3-33 and G-A3-34 (see Fig. 6). The two pumps were piped in parallel so that either one could be used to circulate caustic. The pumps were installed in the refinery during original construction of the alkylation unit in 1954. All components of both pumps, except the pump cases, had been replaced at various pump overhauls.

Spares for major refinery components such as caustic circulation pumps were not normally stocked on site, and the normal maintenance method was to send such components to a contractor for overhaul. Over the life of such a pump, almost all components would be replaced a number of times.

Pump overhauls were normally expected to take about two weeks; however, it was not uncommon for overhauls to take longer as further necessary work was discovered on a pump during the overhaul. The overhauls conducted on pumps G-A3-33 and G-A3-34 in the second half of 1999 each took about six weeks because of such extra work requirements. The possibility was considered of authorising overtime to expedite the repair of pump G-A3-34 when indications of performance deterioration on pump G-A3-33 were found; however no overtime was authorised. As the overhaul progressed, it became clear that overtime would not have affected the overhaul time, however Mobil monitored the progress of the overhaul with greater frequency and detail.

The operator at the control panel in the control room monitored the caustic circulation pump output downstream of the flow control valve (see Fig.6). The pumps were also visually inspected during the daily work shift and during the monthly maintenance check. The reliability engineer was also expected to check the pump vibration levels once every five weeks. The frequency of vibration inspections was increased if no spare pump was available to replace the operating pump. The vibration inspection only occurred if the pump was operating at the time of the inspection. This was because it was considered that there was a direct relationship between the life of seals in pumps and the number of pump starts. Pump starts therefore had to be justified to manage pump maintenance scheduling. This meant that intervals between vibration inspections could be longer than planned if the component was not operating at the time of the reliability engineer's vibration inspection. For example, the depropaniser caustic charge pump G-A3-63, which was not used frequently, had its vibration levels checked once in 1996, once in 1997, once in 1998 and twice in 1999.

The refinery used a computerised work order processing system when managing work requirements for events such as equipment failure, deteriorated performance or preventive maintenance. Once an operator requested maintenance in the system, a work order number would be generated and the job would be tracked to completion. An operator could also request increased monitoring of a piece of equipment if one of the alternate systems was unavailable. An operator who generated a work request on the work order processing system would also assign a priority code to the work order. The priority could vary from an immediate response to an indication of a job for completion at the next unit overhaul.

The refinery operating teams met daily and weekly to discuss problems, formulate strategies and assign maintenance priorities. The work schedule was discussed at the daily works coordination meeting and maintenance was scheduled up to 12 weeks in advance. There were no stated intervals for individual component overhaul or retirement times for the pumps in the alkylation unit. Scheduling of component overhaul was based on factors such as a comparison of performance with original specifications, operational ramifications of conducting maintenance and a risk-based analysis of the component history.

Maintenance scheduling and reliability personnel used a number of tools to manage the frequency and type of equipment maintenance. The primary tools were assessments of equipment condition, such as visual inspections and vibration checks. These assessments gave information indicating the status of a piece of equipment at the time of the assessment, and shorter term predictions of equipment condition could be derived from this information, based on industry experience. This was supported by the use of mean time between failure (MTBF) data, which provided longer term information regarding the effectiveness of the condition-based maintenance management systems. MTBF rates were based on calendar time and did not indicate the actual time that the caustic circulation pumps had been operating or the number of pump starts. The DCS system did not indicate whether caustic circulation was provided by pump G-A3-33 or G-A3-34, and there was no instrumentation on the pumps to indicate its total operating time or number of starts. There was no schedule for the changeover of pumps, and no formal preference for the use of one pump over the other, although at the time one pump was known to have a higher output than the other. This meant that there was no predictable relationship between the MTBF data that was recorded, and the amount of work and wear that an individual pump was subjected to. The MTBF rates for the dynamic components in the unit were issued worldwide every quarter.

2.1.7 Quality assurance

As part of its ISO 9002 accreditation, Mobil had a quality assurance manual for the Altona refinery.

2.1.7.1 Validation

It is a normal process in a quality assurance context to conduct a practical validation to ensure that a designed change conforms to requirements. Australian Standard 9001:1994 – Quality systems – Model for quality assurance in design, development, production, installation and servicing, which replaced Australian Standard 3901 – 1987, specified in paragraph 4.4.8 that:

> Design validation shall be performed to ensure that product conforms to defined user needs and/or requirements.

The appended notes stated:

> 12 Validation is normally performed under defined operating conditions.
> 13 Validation is normally performed on the final product, but may be necessary in earlier stages prior to product completion.

Both Mobil's and the corrosion control contractor's personnel expected that the ethylene diamine would have been extracted from the effluent stream in the water that was extracted from the deisobutaniser tower overheads (see Fig. 7). This expectation was supported by an understanding that ethylene diamine would dissolve in water in preference to the products of reaction from the alkylation process. It was not possible to determine the origin of this expectation. No evidence was found to indicate that practical validation testing to verify this expectation was considered when Neutramine D was introduced.

2.1.7.2 Document control

The 'Document and Data Control' section of the quality assurance manual stated that all reference documents would be reviewed and approved for adequacy prior to issue, that a document revision control process existed, and that a process for control of obsolete documentation existed. The following deficiencies in the process were identified:

- The alkylation unit operations manual was last updated in 1991, and a number of changes to the unit had occurred since then. The manual had not been revised or removed as obsolete; rather, operators relied on their knowledge gained from experience of working on the plant for the latest updates.
- Most information relating to the unit was stored electronically. Inconsistencies were found between the layout of the displays on the Distributed Control System (DCS) and the layout of the unit equipment as indicated on the piping and instrumentation diagrams.
- More than one set of instructions had been issued for action in the event of particular emergencies. An example was found in the General Procedures Manual, where one set of instructions stated that, in the event of pump failure in the alkaline wash systems, the alkylation unit should be shut down immediately. Another set of instructions stated that, in response to the same event, the alkylation unit should be shut down within one hour.
- The 'Purchasing (Materials and Services)' section of the quality assurance manual identified responsibilities for the development and completeness of contracts for the purchase of services. However, no written contract existed between Mobil and the corrosion control contractor at the time of the contamination event.

2.1.7.3 Corrective and preventive action

ISO 9002:1994 section 4.14 required an accredited company to establish and maintain documented procedures for implementing corrective and preventive action. The 'Corrective and Preventive Action' section of the quality assurance manual detailed the company's policy and the respective responsibilities within the organisation in relation to this requirement in the standard. The quality manual also referred to other company documented procedures that could be referred to when fulfilling the function, such as the internal quality auditing procedure. The procedure did not achieve a successful outcome following the previous contamination episode in April 1999 (see section 2.1.9), in that recommendations from the subsequent investigation were not all carried out. The documented, accredited procedure did not achieve its stated policy of maintaining a system which 'implements actions to correct the present nonconformance and to prevent recurrences.'

2.1.7.4 Hazard Identification

The quality assurance manual described techniques to be used to analyse hazards to the production process, but the manual did not describe any methods or techniques to identify hazards to the objectives of the refinery that should be analysed.

The formal hazard assessment methodologies that were used at the refinery were hazard and operability studies, job safety analyses, 'what-if?' studies and quantitative risk assessments. These are tools that are used worldwide for identifying particular types of hazards. Job safety analyses are used to identify hazards to workers undertaking specific tasks with a greater hazard potential, and minimising the hazards to those workers. The other studies were primarily used by Mobil to identify catastrophic failures, such as explosions, containment failures and toxic cloud emission potential, within the process. The methodologies described were all aimed at analysing the hazards that may have led to particular outcomes that involved either explosive potential and/or risks to suburban areas adjacent to the refinery, or occupational health and safety issues. They did not initially address a formal identification of all the undesired outcomes, or categories of outcomes, that should be considered. The caustic wash circulation pumps were not assessed as critical because of the perceived lack of explosive or geographically widespread hazard potential.

When considering the implications of decreasing the caustic circulation rate, it was assumed that fuel would be fit for purpose if it passed the specification testing. The batches of fuel that were contaminated with ethylene diamine subsequently passed the specification tests, but were not fit for use in aircraft. A structured risk management procedure was not used to assess the process variations in the alkylation unit, and did not consider the possibility that the fuel could pass the specification tests but not be fit for purpose.

2.1.8 Risk management at the refinery

Reliability engineering personnel used a variety of methods to ensure plant equipment operated satisfactorily until the next scheduled preventive maintenance. These methods included hardware improvement, preventive routines, operational procedures and maintenance strategies. The reliability engineers used a database for recording maintenance information on components that could be accessed by Mobil reliability personnel worldwide. There was no information in this database regarding the caustic wash circulation pumps.

The reliability engineers also used a commercially available computerised reliability analysis tool called Raptor that had been used in the refinery since 1995. It was used to quantify the reliability of a piece of equipment, by monitoring repair time, spares availability and failure rate. It then assigned a level of risk from 1 to 3 (1 being the highest) for each component being monitored. The reliability engineers decided which components should be analysed using the Raptor system. This decision was based primarily on the perceived criticality of the component. The caustic circulation pumps were not assessed as critical items and hence were not subjected to a Raptor analysis prior to the failure of pump G-A3-33 in November 1999.

A containment failure due to corrosion in the alkylation unit downstream of the caustic wash system would be a significant hazard because of the potential for a release of a large volume of volatile and flammable compounds. The caustic wash system was a part of the system of managing that corrosion potential.

In November and December 1999, acid usage increased, the caustic wash system that was used to remove acid was less effective and pH tests from the sample point in the deisobutaniser tower were found to be outside normal limits. However, there was no increased monitoring of acidity downstream of the washing units once the pH excursions had been identified.

Each year, the reliability engineering section produced a 'top-ten' list of equipment that gave the greatest reliability concerns. The decision as to which items were placed on the list was based on factors such as the perceived criticality of the component, its maintenance history and its operating parameters. Maintenance and reliability personnel used the top-ten list as a tool to assist in prioritising maintenance strategies, with efforts focussed on improving the reliability of the equipment on the list. The caustic wash circulation pumps had never been on the top-ten list.

The risk assessment procedures used to assess the criticality of refinery equipment identified hazards to life and hazards to the continuing operation of the production process. Based on these considerations the caustic circulation pumps were categorised as being of a low risk. The risk assessment procedures did not incorporate a process to identify all the hazards that could adversely affect the organisation's objectives.

Australian Standard 4360:1999 addressed risk management. It defined a generic process whereby an organisation could identify and manage what it perceived to be adverse outcomes to its organisation. One of the early stages of the risk management process required the development of risk evaluation criteria, and deciding the emphasis to be based on operational, technical, financial, legal, social, humanitarian or other considerations. These criteria would be influenced by the organisational context under examination, looking at the goals, objectives and strategies of the organisation.

Following this process, a formal hazard identification would be conducted, to identify all hazards to the organisation in a structured, systematic process, that identified hazards both within and beyond the control of the organisation.

Standard 4360:1999 provided information on generic sources of risk. The example given in appendix D, section 5(h) of the standard identified sources of risk. It included product liability including risk from design error, substandard quality control and inadequate testing.

The use of a similarly structured, systematic hazard identification process could increase the potential to identify hazards such as the contamination of aviation fuels, and to manage the process to control such a risk.

The first version of this standard was published in 1995.

The Zone Process Engineer had received training in the application and use of risk management tools in his assigned work.

2.1.9 Previous Avgas contamination

In April 1999, Mobil agents noted particulate contamination and yellow-coloured water in the water drains from Avgas delivery equipment at Essendon and Moorabbin aerodromes in Victoria. At the same time, the Air BP agent at Merimbula aerodrome, who was supplied with Mobil Avgas, reported difficulty in pumping Avgas due to blocked filters on delivery equipment. On 22 April 1999, Mobil quarantined Mobil-supplied Avgas outlets at a number of aerodromes in NSW, Vic., SA and Qld. Between 22 and 25 April, tests were carried out on fuel from a wide variety of locations in Vic., NSW and Qld. The tests indicated that the fuel at the quarantined sites met the Mobil specification for Avgas, and the quarantine was lifted.

A subsequent internal investigation established that both Avgas tanks at Altona were contaminated with microbiological material. It appeared that dead bacteria had been transferred along the delivery path and had clogged fuel filters. The yellow-coloured water was attributed to unstable yellow dye coming out of the fuel into the water. It was also thought that the microbiological growth had been killed by water with a pH of 10 that was found in the tanks.

The internal Mobil investigation team that analysed the factors leading up to the quarantining of the fuel also identified a number of deficiencies in the procedures for Avgas quality protection. Their report issued in July 1999 contained the following recommendations intended to rectify those deficiencies:

1. Two aviation quality councils should be formed, one at a local level and the other at a national level. This recommendation required the local team to oversee implementation of the recommendations and to implement procedures that would ensure that only clean, dry, on-specification fuel was delivered into aircraft. The team also had the responsibility to monitor the existing Avgas production process in order to identify the reasons for phenomena such as the water in the fuel having a pH of 10.

   The national level aviation quality council was required to develop an aviation quality control and knowledge sharing network that would be tasked to respond to any quality issue. This team was also required to monitor the safety and quality health of the aviation production and distribution process to ensure that clean, dry and on-specification Avgas was delivered to customers. It was intended that the local team would be wound up when the national team was satisfied that the report recommendations had been implemented and correctly functioning sustainable quality controls were in place.

2. All potential sources of water in Avgas, such as process additives, corrosion inhibitors, dyes and caustic wash water should be investigated. The aim was to establish the normal characteristics of any water in the fuel, how it got there and why it had the characteristics that it did. The recommendation arose from deficiencies discovered regarding the refinery personnel's knowledge of the characteristics of any water suspended in Avgas and present in the supply chain.

3. The national aviation quality council should prepare a section of the six-monthly due diligence report to Mobil's Board of Directors regarding Avgas and Jet A-1 quality.

4. Avgas tanks at Altona and Yarraville should be progressively cleaned and the frequency of tank cleaning should be increased to an annual basis, with an ongoing assessment of the adequacy of the tank cleaning regime.

5. The Altona tanks should have a documented requirement for a full settling time to be applied for batches of Avgas after blending and prior to their transfer to Yarraville. There was also a requirement for documented control of settling times at Yarraville.

6. Daily dewatering of tanks should occur at Yarraville and this should be properly recorded. Also, all tank drains should be checked for sulfides and pH. This must be recorded to allow a picture to be built up of what is normal.
7. The Avgas tanks at Altona and the tank draining facilities at the Altona and Yarraville Avgas tank sites should be upgraded. The team also recommended that 'monitor' type filters be installed at Yarraville. These filters prevent a product from passing when they become contaminated with water.
8. Operational procedures should be amended, including the review of all procedures for their accuracy, relevance, simplicity and ease of compliance. In addition, it was noted that operator training regarding aviation procedures and record keeping needed to be part of a formally maintained system rather than the knowledge being 'passed down' on a 'father to son' basis.

Recommendation 6 required analysis of samples of all water drained from fuel tanks at Altona and Yarraville, in order to develop knowledge of the characteristics of any water present in a tank. The work sheet used for specification tests included a space for detailing pH from the test results of water samples. The Altona standing order documents had not been amended to reflect the intent of the recommendation at the time of the contamination at the end of 1999: they indicated that only dark or malodorous water, or water that was taken at the time of drawing a fuel sample for specification testing should be tested. Up until the end of 1999, the nominated officers for this recommendation had not received any reports of water tests from any tank water samples. The standing order documents for Yarraville did not require that any water drained from tanks 16 and 36 be collected and analysed. The implementation of recommendation 6 had the potential to assist in identifying contamination of the process stream by ethylene diamine; however, it had not been fully implemented by the time of the November/December 1999 contamination.

The internal Mobil investigation team noted in their report that while some aspects of Mobil's response to the April 1999 contamination occurrence had worked well, others had not worked so well and the investigation team described areas for improvement. These areas for improvement were additional to the formal recommendations. Two specific areas identified by the team were a need to increase awareness of the quarantining procedure and the need to develop a relationship and a point of contact with CASA. The quarantine and recall processes following the contamination event in December 1999 were effective. No action officer was assigned to any of the items that were identified as requiring improvement. No action was taken on these or any of the other identified areas for improvement, apart from the recommendations.

2.2 Aviation fuel standards

Aviation fuel standards were used by numerous organisations concerned with aviation fuel quality. These organisations included aviation fuel manufacturers and their customers.

Operating manuals for most piston-engine aircraft specify that the fuel to be used in the aircraft must be either aviation gasoline 100/130 or aviation gasoline 100LL. The Mobil refinery at Altona manufactured aviation gasoline 100/130.

Aviation gasoline 100/130 and other aviation fuels are global products that are bought, sold and used for similar purposes around the world, but there was no single global standard for any aviation fuel. A number of standards exist, with the two primary standards for this grade of Avgas being ASTM D910 – 97 issued by the American Society for Testing and Materials (ASTM), and Def Stan 91/90 issued by the Defence Standardization within the UK Ministry of Defence. These two standards are similar in their specification requirements, but not identical.

Major oil companies have developed their own in-house specifications for this grade of Avgas that meet or slightly exceed all the specifications of both the ASTM and the Def Stan standards. In this way, the fuel may be held to 'comply' with each of the two major international standards if it complies with an in-house specification, but the 'compliance' can be silent as to which standard it actually complies with. The Fuels Technical and Product Support section at Mobil was responsible for developing the internal specification that was intended to equal or slightly exceed the requirements of the ASTM and Def Stan specifications. The internal specification testing laboratory worksheet included a comparison with these specifications.

2.2.1 Details of specification tests

The standards comprise a textual description of the required specifications for the product. In conjunction with the specifications for Avgas, the standards organisations have produced a number of chemical testing procedures that should be used to ensure compliance with their specifications for Avgas.

Manufacturers of Avgas used numerous quality control checks and tests to maintain the quality of the product stream throughout the manufacturing process. These tests were in addition to the specification tests performed on samples taken from the final product. Some of the documentation associated with the tests that were used during specification testing of the final product made statements that indicated that they could have identified the presence of contaminants such as ethylene diamine.

2.2.1.1 Copper reaction test

One of the chemical tests that was used to assess the specification of a batch of Avgas was the copper strip test, as described in ASTM 130-94. ASTM D 910 – 97 paragraph X1.5.1 refers to this test and states:

> Copper Strip – The requirement that gasoline must pass the copper strip corrosion test provides assurance that the product will not corrode the metal parts of fuel systems.

ASTM 130-94 recognises in paragraph 4.1 that the main corrosive agents for metals in petroleum products are normally sulfur-based, but also that the test should 'assess the relative degree of corrosivity of a petroleum product'.

The copper reaction test procedure involves placing a shiny copper strip in a sample of Avgas, heating the sample for 2 hours at 100 degrees C and checking the copper strip for discolouration.

The test was conducted on the fuel that was subsequently identified as contaminated as a part of its testing before batch release. The sample of contaminated fuel passed the test. The test description states that if fuel passes the test, assurance will be provided that the product will not corrode the metal parts of fuel systems. The test did not provide the assurance that was described in this paragraph, as the contaminant reacted with and corroded copper in pure or alloyed form in aircraft fuel systems.

2.2.1.2 Water reaction test

Another of the chemical tests that was used to assess the specification of a batch of Avgas was the water reaction test, as described in ASTM D 1094 – 97. ASTM D 910 – 97 paragraph X1.7.5 refers to this test and states:

> Water Reaction – The water reaction method provides a means of determining the presence of materials readily extractable by water or having a tendency to absorb water. When the fuel

> consists essentially of hydrocarbon components, there is no measurable change in the volume of the water layer.

The water reaction test involves putting a sample of fuel in a container with a measured quantity of water containing a pH7 buffer, shaking the mixture and letting it stand. The sample is then visually examined at the interface of the two fluids for any blurring of the boundary, or any indication of a change in the relative quantities of sample and buffer.

The test was conducted on the fuel that was subsequently identified as contaminated as a part of its testing before batch release. Ethylene diamine will dissolve preferentially in water, or be readily extractable from Avgas by water. The contaminated fuel sample passed the test. The test description states that the test method provides a means of determining the presence of materials readily extractable by water or having a tendency to absorb water. The test did not provide the assurance that was described in this paragraph; however, the concentration of the contaminant in the contaminated fuel was such that it was not likely that this test method would have reliably identified the presence of the contaminant in the fuel.

Both the copper reaction test and the water reaction test described are acceptable as a part of the testing process for indicating that a batch of Avgas meets either (ASTM) D 910 – 97 or Def Stan 91-90.

2.2.2 Management of off-specification fuel

The refining companies normally had a small number of senior personnel who were authorised to release fuel that did not entirely meet a company's specification. When an off-specification fuel batch was released, then the details of the failure to comply with the specification should be appended to the documentation that was supplied with the fuel. The people who were authorised to release fuel that did not meet its specification would normally do so very conservatively. Procedural safeguards that they considered to be appropriate would be developed and laid down before the batch was released.

No evidence was found of guidelines that would be available to assist those people who were authorised to release off-specification fuel. They would make such a decision based on their professional expertise, and advice that was received regarding a particular situation as it developed.

2.2.3 Use of zero concentration in a specification

The standards for Avgas are primarily performance based, in that they specify physical and chemical properties that the product should achieve. The specifications do not identify the chemical constituents in detail. The chemical mixture in Avgas is highly complex, and may vary so long as the performance specification is met. An example of a chemical analysis of Avgas can be seen in appendix B.

The ASTM D910 – 97 specification stated that aviation gasoline:

> Except as otherwise specified in this specification, shall consist of blends of refined hydrocarbons derived from crude petroleum, natural gasoline, or blends thereof, with synthetic hydrocarbons or aromatic hydrocarbons, or both. (6.1)

Def Stan 91-90 stated that:

> The fuel shall consist wholly of hydrocarbon compounds and approved additives, only as listed at annex A (4.1) [of the standard].

Both standards listed similar permitted additives, which included octane enhancers, antioxidants and dyes. Neither standard included ethylene diamine as a permitted additive.

(An additive is a compound which is deliberately mixed into the product to change its properties. Ethylene diamine was not deliberately added to the product for this purpose, but was used as a part of the manufacturing process with an expectation that it would be removed from the process stream. It should not therefore be considered as an additive, but as a contaminant.)

Both standards stated the permitted chemical compounds in Avgas. The standards required a zero concentration of any chemical that was not one of the permitted compounds, so a batch of Avgas that contained any compound that was not a permitted additive or hydrocarbon did not meet the specification. A batch would not technically meet the specification even if a contaminant was of an immeasurably low concentration. As the concentration of a contaminant in a sample decreases, it becomes increasingly difficult and expensive, and then impossible to measure. It was therefore not possible to comply with the strict interpretation of the standard: it could not be seen as an achievable measure, but only as a target to be aimed for.

The concentration of ethylene diamine present in the contaminated Avgas was measurable, but the specification, by implying a measurable concentration of zero, becomes inapplicable in its strictly literal interpretation.

The Delaney Clause

Another example of such a requirement existed in what was known as the Delaney Clause.

The 1958, Delaney Clause of the American Federal Food, Drug, and Cosmetic Act prohibited the approval of food or feed tolerances (limits of concentration) for pesticide residues in ready-to-eat processed food (e.g. tomato sauce, apple juice), or animal feed if the pesticides were found to induce cancer in man or animals, regardless of the level of risk. That is, it enforced a 'zero-risk' standard for these chemicals by saying that no tolerance could be established (not even one molecule of the pesticide residue could be present). A decision in 1992 by the US Ninth Circuit Court of Appeals held that the Environmental Protection Authority (EPA) was required to follow a strict, legal interpretation of the Delaney clause. Subsequent to the decision, the EPA began a process of revoking all tolerances that were not consistent with the Delaney Clause.

The restrictions that were applied under the Delaney clause worsened in the years following its enactment. At the time the law was passed, it was possible to detect concentrations of chemicals of several parts per million; however, the improvement of techniques over the next forty years has enabled an improvement in test sensitivity of at least a millionfold. The test of the Delaney Clause was applied with rigour, irrespective of the degree of carcinogenicity of the chemical in question. The clause became even more difficult to apply when it was found that some naturally occurring compounds that are a normal part of some foods could be carcinogenic at large dose rates.

The Delaney Clause is no longer United States law. In July of 1996, the House and Senate unanimously approved the Food Quality Protection Act (H.R. 1627), which was signed by President Clinton on 3 August 1996. The reforms outlined in this Act amended the Federal Food, Drug, and Cosmetic Act and the Federal Insecticide, Fungicide, and Rodenticide Act. They represented a significant commitment toward modernizing food safety law, in part, by repealing the Delaney Clause. It was replaced with a unified safety standard of 'reasonable certainty that no harm will result from aggregate exposure to pesticide residue' for raw and processed foods.

The obligation to use a measurable concentration of zero had created an unworkable requirement in the practical sense.

2.2.4 Undefined parameters

The standards for aviation fuels describe some performance parameters that a sample of on-specification fuel is expected to achieve. A number of other performance parameters are also required in order for fuel to function as intended. Aviation fuels are normally manufactured by similar processes in different refineries, and if the defined performance parameters are met, then the undefined parameters (such as specific heat capacity or fuel lubricity) will normally remain reasonably constant. There is a reasonable expectation that these undefined parameters will be constant; however, there is no obligation for a fuel manufacturer to ensure that these undefined parameters remain constant. Aircraft designers, manufacturers and operators who rely on a number of these undefined parameters could have no assurance that those undefined parameters would always exist.

Undefined parameters

Problems have occurred in the past when undefined parameters for aviation fuel properties were not met.

In April 1994, the crew of a New Zealand registered British Aerospace 146 shut down the number 4 engine after it continued to lose power when it was reduced to flight idle setting at top of descent. The crew subsequently conducted a three-engine landing at the destination.

Maintenance personnel established that the engine failure occurred when the fuel control unit stopped delivering fuel to the engine. The drive splines in the integral high pressure fuel pump had failed as a result of a lack of lubricity in the Jet A-1 fuel that the aircraft was using.

The makers of the fuel pump had relied on the natural lubricating properties of Jet A-1 to provide the necessary lubrication to the rotating parts of the pump. However, changes to the manufacturing process had resulted in a reduction of the fuel's lubricity. The Jet A-1 specification did not require a lubricity test.

A significant number of other aircraft also experienced fuel component problems that were attributed to low levels of lubricity in Jet A-1. These problems resulted in a number of engine failures during ground-running, during the take-off roll and in flight.

Although this is not an example that relates directly to Avgas, the principle is the same, and in this case the potential for multiple engine failure, and risk to a large number of passengers, was significant.

A safety deficiency exists if an aircraft designer, manufacturer or operator is relying on an implicit property of an aviation fuel to ensure reliable operation of an aircraft. The implicit properties of fuel could be defined, and the maintenance of those properties could be referred to the maintenance of the explicit parameters that are tested.

2.2.5 Relevance of standard to ensuring fitness for purpose

The ASTM D 910 – 97 specification stated in its scoping paragraph, (1.1) that:

> This specification is intended primarily for use by purchasing agencies in formulating specifications for purchases of aviation gasoline under contract.

Def Stan 91-90 stated in its scoping paragraph, (1) that:

> This Defence Standard specifies the requirements for three grades (AVGAS 80, AVGAS 100 and AVGAS 130) of gasoline type aviation fuel intended primarily for use in aircraft reciprocating engines. Fuel provided to this Standard shall possess satisfactory performance and properties when used in appropriate aircraft or engines operated by the Crown or for which the [British] Civil Aviation Authority (CAA) is the certificating agency.

The ASTM specification was written with the intent of ensuring a fuel standard at the time of purchase, and not at the time of use in the aircraft.

The Def Stan scope stated that it was intended to specify the requirements of Avgas, and that it had been agreed by the authorities concerned with its use. This included the British CAA.

The Def Stan standard was designed to be a sensible balance between the commercial costs of testing, and the needs of the engine. The specification was designed to protect the end user from receiving a product that had been contaminated from a foreseen source. The standards were not designed to protect the end user from a contamination problem that was not considered probable, or that had not been considered.

The two main standards were very similar. They were designed to protect the end user from probable deviations from the specification. If an end user was to be protected from improbable deviations to the specification of supplied Avgas, then alternative processes to specification testing needed to be in place as well to provide protection from those improbable deviations.

Manufacturers of Avgas endeavoured to meet criteria that were not included in the standards in order to ensure that the Avgas was fit for purpose. As an example, one of the factors that was considered was the shelf life of the product. Work and testing was carried out to ensure that Avgas would be fit for purpose for a determined period of time after manufacture, and controls were put in place to ensure that fuel was not sold beyond that time. This process is not mentioned in the specification for fuel.

2.3 Oversight of aviation fuel quality

This section describes the role of the various regulatory authorities that might be considered as having a potential to have any form of regulatory oversight of aviation fuel quality. It also describes the relevance of that oversight to the consistent maintenance of aviation fuel quality.

The degree to which there is a societal acceptance of a failure in a complex system is dependent on the likely outcome of that failure. If a failure of a complex system is likely to cause a significant risk to life, then this will be considered as less acceptable than an outcome that would cause inconvenience, or some monetary loss alone. For an engine to become unreliable as a result of the action of the fuel on the engine is not a desirable outcome; however, the degree of undesirability depends on the system in which the engine is operating. A multiple engine failure of an aircraft in flight is one of the least desirable situations in which such a failure could occur, as the potential risk of injury is greater than any other commonly used engine-based public transport system.

The recognition of the importance of safety in flight is indicated by the sophisticated process of regulatory oversight that is required before flight is permitted to continue. The function of the regulatory system is to ensure that all the systems necessary to ensure safe flight exist and are maintained. However, as was seen following the accident involving the ferry *Herald of Free Enterprise*, some methods of regulatory oversight may not be effective in ensuring that organisational defences are in place that can enhance a consistently safe outcome in a complex process.

Herald of Free Enterprise

Effectiveness of various methods of oversight in ensuring regulatory compliance:

On 6 March 1987, shortly after it departed Zeebrugge, Belgium, for the cross-channel trip to Dover, England, the passenger and vehicle ferry *Herald of Free Enterprise* capsized and sank in shallow water. The ferry capsized after seawater entered the vessel past the bow doors which had not been closed before the ship sailed. The subsequent judicial investigation identified significant underlying organisational deficiencies in the company that operated the ferry and concluded that all levels of management must share responsibility for the disaster. British police investigated the circumstances of the accident and subsequently charged the owners of the company with corporate manslaughter. However, after 27 days of a trial expected to last 6 months, the judge instructed the jury to find the defendant not guilty and dismissed the case.

The wording of UK laws, as in Australia, meant that it would be extremely unlikely that a corporation could be successfully criminally prosecuted in such a case. A corporation is responsible for setting up and maintaining organisational safety defences in its activities, so in reality, the likelihood of successful retrospective criminal action for a criminal consequence, such as unlawful death, that could be attributed to an organisational responsibility, is remote. The structure of law is such that it is easier to successfully prosecute an individual, as the intent behind any act would be easier to determine. It would therefore be more likely that the only successful prosecutions following events such as the *Herald of Free Enterprise* accident would be against individuals who failed to comply with procedure, rather than organisations that administered and managed the procedure. This example, and others like it, have shown that the threat of retrospective criminal prosecution or civil litigation against organisations that undertake complex activities is largely ineffective in ensuring regulatory compliance.

2.3.1 Quality assurance for the Department of Defence

The Defence Quality Assurance Organisation (DQAO) was formed in 1988. Before then, four separate organisations purchased fuel on behalf of the Australian Department of Defence. As part of the purchasing process, DQAO conducted audits on refineries that manufactured and sold fuel to the Department of Defence. In 1998 the function of DQAO became a part of the Defence Acquisition Office (DAO), and DQAO was disbanded. DAO was then responsible for all major Defence acquisitions, including fuel. After this time refineries were no longer audited on behalf of the Department of Defence.

Support Command Australia was responsible for the quality of fuels for the Department of Defence during the period leading up to the contamination. The Joint Fuels and Lubricants Agency, a technical section of Support Command Australia, dealt directly with refineries that manufactured and sold fuel to the Department of Defence. The suppliers were required to supply details of batch numbers, test reports and release notes. A National Association of Testing Authorities (Australia) accredited third-party laboratory normally tested fuel that was sent to a military base on behalf of the Department of Defence. Third parties did not test aviation fuel for compliance which was supplied to the Department of Defence at locations other than military bases. Defence forces would also purchase fuel from civilian sources as required.

2.3.2 Civil Aviation Safety Authority

The Civil Aviation Safety Authority (CASA) was the agency responsible under the *Civil Aviation Act 1988* for regulating Australian civil aviation.

Section 9 of the *Civil Aviation Act 1988* stated that:

> CASA has the function of conducting the safety regulation of the following:
> civil air operations in Australian territory; [and],
> the operation of Australian aircraft outside Australian territory.

Section 9A of the *Civil Aviation Act 1988* stated that:

> In exercising its powers and performing its functions, CASA must regard the safety of air navigation as the most important consideration.

The degree to which CASA had overseen the manufacture of different products of an aircraft's system varied; however, it did not normally oversee product manufacture back to its raw materials. The normal procedure was to oversee the final manufacture of a product (such as a seat belt) in order to satisfy itself that the manufacturer had sufficient systems in place to ensure that the product was airworthy.

CASA did not oversee the manufacture or distribution of aviation fuels at the time leading up to the contamination.

2.3.2.1 Regulatory requirements for aviation fuel quality

CASA controlled a number of documents that specified the requirements for civil aviation operations. These documents included the *Civil Aviation Act*, the *Civil Aviation Regulations* and the *Civil Aviation Orders*. A number of sections within these documents related to aviation fuel.

Civil Aviation Regulations (CAR) 1988 s.30 (1) stated that any person engaged in the distribution of aircraft materials (aircraft fuel fell within the definition of aircraft material), may apply for a certificate of approval. All of the manufacturers of Avgas in Australia distributed fuel.

The former Civil Aviation Authority issued certificates of approval until 1990 to the refineries that manufactured aviation fuel. The issue of a certificate of approval placed an obligation on the authority to satisfy itself that the product for which the certificate of approval was issued would remain airworthy.

CAR 1988 s.36A stated that CASA may give written directions requiring the use of aircraft materials of identified specifications for particular purposes connected with the maintenance, servicing or operation of aircraft.

CASA had not given any written directions relating to any specification for Avgas to be used in aircraft maintenance, servicing or operation.

Civil Aviation Order 20.9 para. 3.1 Issue 5 dated 2 July 1997 stated:

> The pilot in command of an aircraft shall ensure that the aircraft is not flown unless the aviation fuel, aircraft engine lubrication oil, aircraft engine power augmentation fluid and aircraft hydraulic system fluid used in connection with the servicing or operation of the aircraft complies with the specification and grade required or approved for the purpose by CASA.

Note 1 appended to this subsection stated (in part):

> The specification and grade of aviation fuel and aircraft engine lubricating oil required to be used for the relevant engine is specified in Civil Aviation Order 108.4.16

Note 3 appended to this subsection stated that a pilot could assume that any fuel that was in an aircraft, other than that which he had caused to be put in that aircraft, complied with the required specification and grade.

Civil Aviation Order 108.4.16 specified the fuel and oil grades to be used in different aircraft engine types. It was superseded in February 1972 by *Civil Aviation Order* 108.46, which also gave details of other approved fluids such as greases and miscellaneous hydraulic fluids. This order was removed without replacement on 15 November 1995.

CASA had not required or approved a specification for Avgas. In general, operational documentation for Avgas powered aircraft manufactured in the USA, Australia and France do not include a specification for the fuel to be used in the aircraft.

Civil Aviation Regulations 1988 s.138 required a pilot to comply with operational documentation in each civilian-registered aircraft, which would specify the appropriate grade(s) of fuel to be used in that aircraft.

Civil Aviation Order 104.2 required that fuel supplied to regular public transport (RPT) aircraft should be under the cover of a release note. A release note was a certification of the quality of the fuel. The order was repealed on 15 May 1991, and as a consequence of this, the then Civil Aviation Authority (CAA) discontinued its auditing functions on fuel distribution facilities. The authority requested the manufacturers of aviation fuels to ensure that they no longer referred to the authority in any documentation referring to the supply or delivery of those fuels.

The reasoning for the repeal of the order was that the CAA considered that the refining companies were capable of self-regulation as they had sufficient systems in place to ensure control of product quality. Also, international practice indicated that there was no need for release notes. Finally, it was also felt that if any concessions were required against a certificate of approval, then the regulator had to refer back to the applicant for an expert opinion, thereby rendering the input from the regulator a bureaucratic irrelevance.

At the time that the CAA discontinued oversight of fuel, the Defence Quality Assurance Organisation (DQAO) conducted audits of aviation fuel manufacturers' production and distribution systems (see section 2.3.1). The fact that this auditing was being conducted was included as additional justification for the removal of any oversight by the CAA. No change was made to the arrangements for oversight of fuel quality by CASA when the auditing function of DQAO ceased in 1998.

The CAA also considered that it did not have the expertise to comment on the manufacture of fuel, and therefore relied on the expertise and management capacity of the manufacturers to ensure the continued airworthiness of aviation fuel. No indication was found that the CAA had considered the effect on aviation safety of the repeal of the order.

2.3.2.2 Reporting requirements

None of the companies that manufactured Avgas in Australia listed CASA as a point of contact if Avgas were quarantined. There was no regulatory oversight of the manufacture and distribution of aviation fuels by the Authority, so no formal mechanism therefore existed for the Authority to become aware of fuel supplied to the public that was not considered to be fit for purpose.

2.3.2.3 Oversight arrangements in other countries

The UK Civil Aviation Authority (UKCAA) had a contractual relationship with the Defence Evaluation and Research Agency (DERA) to maintain the fuel standards for use by UK civil-registered aircraft. DERA fulfilled this contractual obligation by ensuring that the standards that it maintained for the UK defence forces were compatible with the UK civil aircraft fleet, and represented the interests of the UKCAA at the relevant expert bodies.

The US Federal Aviation Administration (FAA) delegated quality control and specification development of aviation fuels to the petroleum industry. The FAA considered fuel to be an operating limitation that should ensure that an aircraft engine would perform as expected. As such, it was expected that either the pilot or the operator would ensure that the limitation was adhered to. This position led the FAA to consider that it was appropriate for it to only address fuel quality once fuel had entered an aircraft.

2.3.3 Workcover Victoria

2.3.3.1 Occupational health and safety legislation

Victorian health and safety legislation could have been used for the oversight of aviation fuel quality.

Workcover Victoria was responsible for regulatory oversight of occupational health and safety at the refinery that manufactured the contaminated fuel.

Australian occupational health and safety legislation was based on the recommendations of the Robens Report from the UK. The occupational health and safety acts were different in each Australian state; however, the principles behind each of the acts were the same.

The Robens Report

The Robens Report had a profound effect on the way that occupational health and safety legislation was written:

A committee in the UK chaired by Lord Robens issued a report in 1972 that commented on the relevance of occupational health and safety legislation at the time. The report found that there was an excess of prescriptive legislation. It recommended that legislation be simplified, so that instead of stating in detail how work systems should be established, it should state the goals that should be achieved in relation to occupational health and safety.

The report recommended a statement of the basic and overriding responsibilities of both employers and employees. The reasoning behind the recommendation to change from a prescriptive system to one that was performance based was explained in the report:

'A positive declaration of the over-riding duties, carrying the stamp of parliamentary approval, would establish clearly in the minds of all concerned that the preservation of safety and health at work is a continuous legal and social responsibility of all those who have control over the conditions and circumstances under which work is performed. It would make clear that this is an all-embracing responsibility, covering all workpeople and working circumstances unless specifically excluded'.

The achievement of these goals was intended to rely on the effective management of individual workplaces, either through established methods, or by developing appropriate alternatives. A law that reflected these recommendations was enacted in the UK in 1974, and a similar law was enacted in Victoria in 1985.

Victorian workplaces operated under the *Occupational Health and Safety at Work Act (OHSA) 1985*. Section 24(3) required Mobil to take all practicable steps:

> To ensure that its manufactured substance shall, so far as is practicable, be safe and without risks to health when properly used.

The legislation was intended to apply to workplaces within Victoria; however, it was silent as to the location in which a manufactured substance could 'fail to be safe and without risks to health when properly used', in order for the regulation to be breached.

The word 'practicable' was defined in the Victorian OHSA 1985 Act as:

> Practicable having regard to-
> - the severity of the hazard or risk in question;
> - the state of knowledge about that hazard or risk and any ways of removing or mitigating that hazard or risk;
> - the availability and suitability of ways to remove or mitigate that hazard or risk; and
> - the cost of removing or mitigating that hazard or risk.

As of the time of the fuel contamination, Workcover Victoria had not used section 24(3) of the Act to initiate prosecution of any manufacturer.

The Act was structured similarly to the UK *Health and Safety at Work Act 1974*. The UK Act had similar powers to ensure that an employer had a duty of care to require that the activities of an employee or subcontractor did not endanger the health and safety of others who were not employees or subcontractors. The UK regulator of this Act did not, as a policy, prosecute controllers of workplaces for manufacturing products that could be dangerous to a customer who purchased that product, although the Act gave the regulator the power to do so.

Workcover Victoria, in its regulatory oversight of the Mobil refinery at Altona, had not ensured that Mobil, in accordance with section 24(3) of the OHSA Act, had addressed the need for the manufactured product to be safe when properly used. Workcover believed that it was not the lead agency for issues relating to aircraft safety or product liability issues, and that any regulatory oversight of such an issue would be best dealt with by regulators that covered product liability or civil aviation safety.

2.3.3.2 Control of Major Hazards Facilities legislation

New legislation known as the *Occupational Health and Safety (Major Hazard Facilities) Regulations 1999* was in the process of being developed in Victoria. It was based on *European Council Directive 96/82/EC* (commonly known as the Seveso II directive). The EC directive was developed following the inadvertent release of a toxic cloud from a chemical factory in Seveso, Italy in 1976.

This proposed legislation was designed to provide for greater regulatory capacity at major hazard facilities, such as the Altona refinery, to ensure that:

- Hazard and major incident identification, safety assessment and control measures were in place.
- Safety management systems were established, implemented and effective to the highest management position within the organisation.
- Safety cases were prepared.
- Major hazard facilities were licensed.
- Obligations existed for all employees on a major hazard facility.

The main purpose of this legislation was to address the possibility of major events that may have caused significant loss of life or damage to property, commonly from explosions or toxic releases. It did not cover major incidents that could occur outside the facility as a consequence of hazards within the facility. The new major hazard facilities regulations would also not have addressed all the types of hazard that might lead to contamination of fuel.

The Mobil refinery at Altona would have been defined under the Act as a major hazard facility. Under the proposed restructuring of Workcover Victoria, the Major Hazard unit of Workcover Victoria intended to assume responsibility for all aspects of occupational health and safety regulation at the refinery.

Workcover Victoria believed that an act that contributed to an unsafe event in an aircraft in flight would fall within the regulatory purview of CASA. They also believed that if an aircraft lost power in flight, CASA should be the prosecuting body, should that be considered appropriate.

The new major hazard facilities regulations would have required an enhanced safety management system. They would not have included a requirement to ensure that the manufactured product would have been safe when properly used.

2.3.4 Trade practices legislation

The regulators that administered the applicable trade practices legislation were, respectively, the Australian Competition and Consumer Commission (ACCC) and the Victorian Office of Fair Trading and Business Affairs (now known as Consumer and Business Affairs Victoria). The commonwealth Department of the Treasury also had an advisory role.

The ACCC was the federal body that administered the enforcement sections of the *Trade Practices Act 1974* (the TPA). One of the functions of the commission was to investigate allegations of unfair trading practices, including misleading or deceptive conduct. The Department of the Treasury administered the policy sections of the TPA.

Part V, Division 2 of the TPA deemed implied conditions into contracts for the supply of goods. Goods had to be of merchantable quality, fit for their intended purpose, free from defects and matching their description or sample. If any goods did not meet these conditions, then consumers were entitled to compensation. The conditions were not intended to prescribe the behaviour of suppliers, but provided an opportunity for consumers to seek compensation for any damage or loss incurred by a breach of one of the conditions. The TPA did not provide for the ACCC, or any other public body, to enforce these conditions on the supply of goods, it only provided a mechanism for the recovery of compensation by a consumer. The only disincentive provided by this legislation against the honest supply of defective goods was the threat of retrospective civil action.

The TPA empowered the federal Minister for Financial Services and Regulation to:

- Issue a warning notice to the public relating to the safety of specified goods.
- Require that goods met a specified standard before they could be supplied to a consumer.
- Prohibit the supply of specified goods to a consumer.

The use of these powers was at the Minister's discretion, and there was no obligation on the Minister to utilise these powers in relation to the supply of any unsafe goods. The Department of the Treasury administers the product safety provisions of the TPA and advised that up until late 1999, there had been no consideration of the possible use of ministerial powers under the TPA in relation to aviation fuel safety (i.e. to issue a warning, or a requirement to comply with a specified standard, or to issue a prohibition on supply to consumers).

The Office of Fair Trading in Victoria operated under the *Fair Trading Act 1999*. The Office did not audit the refinery or its product. If the Office received an allegation that there had been deceptive or misleading conduct in the supply of aviation fuel, then they might have investigated and prosecuted for this under their Act.

The activities of the ACCC were similar to those of the Office of Fair Trading, and there was a Memorandum of Understanding between the two bodies that assigned responsibility to the ACCC for issues that were national or international in character, or that covered large regional areas.

The Office of Fair Trading and the ACCC have indicated that neither would be likely to prosecute if there were an unintentional or accidental sale of a product that did not meet its description.

2.3.5 Summary

The intent of the legislation under which the different regulatory bodies operated differed widely.

CASA's stated primary focus was delivering aviation safety to the Australian public. It was required to regulate the systems that were critical to aviation safety. It was also required to satisfy itself that the organisational capacity of organisations that maintained and flew aircraft maintained an adequate, managed control of safety critical systems. At the time of the fuel contamination, CASA did not regulate fuel production or supply to ensure that these safety critical systems were managed so that they remained both safe and resistant to human error. CASA had not prescribed any specification for any grade of Avgas.

Workcover had a prime function of ensuring occupational safety and health in a workplace, followed by a function of ensuring public safety as affected by actions in the workplace. The major hazards facilities regulations that were being introduced were intended to enhance the regulatory capacity to ensure that organisational systems were in place to manage the prevention of major incidents and to control them if they occurred. These enhanced regulatory capacities were intended to address a limited group of undesired outcomes, which would not have included major incidents arising from the use of a product outside a workplace, such as in an aircraft.

The powers of the federal Minister for Financial Services and Regulation to warn of, prescribe standards for, or prohibit the supply of unsafe goods to consumers under the *Trade Practices Act 1974* had neither been considered by the Department of the Treasury nor used to enhance the safety of aviation fuel.

The Office of Fair Trading regulated commercial transactions in which there was misleading or deceptive conduct on the part of the vendor. The regulatory function did not primarily address the need for safety in relation to a sold product. This was also the case with the ACCC.

None of the regulators intentionally used their powers to prevent the supply of unairworthy fuel to aircraft, and there was a diffusion of responsibility among them.

3. ANALYSIS

3.1 Introduction

The purpose of this analysis is not to review all of the detail described so far in the report, but to identify and examine key issues. That process is necessary in order to gain an insight into the potential impacts on the system of safe aviation and hence what defences are needed to protect that system. The factors that contributed to the failure of the whole system at the time of the contamination event are key to that understanding.

The key issues are discussed in terms of their relevance as defences in the system of safe civil aviation, and relate to:

- manufacture
- standards
- oversight

These key issues should not be seen as individual subjects in their own right, but as interrelating parts of the complete system of civil aviation. It is necessary for all of the individual parts of the system to function adequately, and for the relationship between these aspects to be correct and appropriate.

To re-emphasise, the purpose of the investigation was not to determine blame or liability, but to understand how and why events unfolded as they did. A series of apparently unrelated safety events may be regarded as tokens of an underlying systemic failure of the safety system. The investigation, while not an audit, having determined the facts as best it can, needs to look beyond the actions at the operational level, in order to understand the organisational processes and management decisions that influenced those actions. The investigation can also provide an insight into the safety health of the organisations involved, and any consequent effect on the wider safety system. Such a process facilitates the development of effective recommendations aimed at improving aviation safety.

The findings from the Avgas contamination investigation are just as relevant to the supply of fuel to high capacity airliners, because although the manufacturing processes differ, the defences that ensure the quality of Jet A-1 fuel are similar to those for Avgas. It is unacceptable for public transport systems to not be consistently safe.

No redundancy existed within an aircraft in flight to provide an acceptable outcome if the power systems were rendered ineffective by fuel that was not fit for purpose. This had a significant potential to compromise the safety of an aircraft in flight. If an aircraft was supplied with fuel that was not fit for purpose, then any power failure would probably have affected all the power systems in an aircraft at or near the same time in flight. Consequently, it was essential that fuel be manufactured that was consistently fit for purpose, and distributed without compromising that fitness for purpose.

The expectation that high capacity passenger aircraft could operate safely over extended sectors is primarily based on the effectiveness of multiple systems redundancies in the design of modern jet airliners. However, in the absence of similar levels of system redundancy in the supply of fuel, the effectiveness of all other redundant systems would ultimately be dependent upon the quality of the fuel supplied.

Since 1991, the possibility of aviation fuel quality being compromised by the manufacturing process had not been formally considered by regulators or aircraft operators. There was no indication that the fitness for purpose of aviation fuel as supplied by a refinery had been considered in the development of procedures used in civil aviation to ensure safety. The aviation safety systems did not recognise that fuel could be not fit for purpose for reasons other than those that would be identified by a pre-flight fuel drain.

The manufacture of aviation fuel is currently one of the more complex aspects of the system of aviation. The historical reliability of manufacture of aviation fuels had been creditable. However, aviation fuel quality had a significant potential to contribute to the development of an accident, as it was not normal to expect to be able to always identify fuel that was unfit for purpose in flight. Nor was it usual to have a system of redundancy within an aircraft to allow for an alternative fuel supply in flight in the event that one supply was found to be not fit for purpose.

3.2 Manufacture

3.2.1 Management of the process

Effective control of the process of Avgas manufacture was maintained by the use of an operating system designed to run efficiently and to be tolerant to process change. This would be best supported by an organisational process that would manage the system and react effectively to any changes to the system. The operating system was intended to operate in equilibrium, so that it should be able to function adequately, and to a limited extent with minimal input from the organisation that controlled the system. The organisational and management controls that supported the system were intended to monitor the operating system and provide inputs to optimise its effectiveness.

Both the refinery operating system and the organisational control of the operating system needed to work effectively for the consistent and reliable achievement of the organisation's objectives. A number of organisational and management processes existed to support Mobil in maintaining the complex process of operating the Altona refinery, and in achieving its desired outcomes. However, these did not prevent the contamination of Avgas in November 1999.

3.2.1.1 Knowledge of the processes

The refiner did not have an adequate system for managing knowledge of the alkylation unit processes.

The mixture of fluids entering the deisobutaniser distillation tower in the Altona refinery alkylation unit was extremely complex. To make confident predictions of the distillation characteristics of individual components in this mixture would have required mathematical modelling that would normally be enhanced by modern computerised modelling programs. The accuracy of a model is enhanced by the quality and detail of the information used to develop the model; however, neither the fresh caustic injection rate in the caustic wash system, nor all of the pH tests on the caustic circulation system, were recorded. The minutes of the meetings that were used to manage the plant were not complete, in that there was no reference to some of the actions that were taken as a result of the decisions from those meetings. The modelling could have been more complete if all information that related to the operation of the alkylation unit had been used to its maximum benefit to improve the understanding of the process.

The modelling would have led to a design that should then have been followed by practical validation to confirm that the outcome would be as expected. There was no evidence found within the refinery to indicate that there was a recognition of the need for validation of the designed change to the process, despite the physical properties of ethylene diamine indicating that not all of it would be extracted in solution in water. The refinery only relied on assumptions derived from the physical properties of ethylene diamine to ascertain its point of extraction from the process stream, without performing any form of validation of its model. This was not in accordance with normal quality assurance procedures that were used to control design or development changes. The quality assurance process at the Mobil refinery did not clearly cover quality assurance of design or development, or changes to either of those processes.

Ethylene diamine was sold not only as a corrosion inhibitor, but also as a chelating agent. The compound should therefore not have been considered as of little consequence if small concentrations had remained in the end product. It would have been reasonable to have considered the potential for adverse consequences to an end user from contamination and to have validated the process to ensure that none of the ethylene diamine remained in the end product.

3.2.1.2 Operating system

No formal system existed to consider the cumulative effects of the number of planned and unplanned changes that occurred within the alkylation unit before and during the contamination episode.

A number of problems developed within the alkylation unit which, by themselves, could have been controlled and managed. It was apparently not recognised that the cumulative effect of an abnormal number of process upsets could be greater than the sum of the changes due to the individual upsets. The changes due to one upset could have affected the predictability and management of the effects of the next upset. The increased number of problems would have led to a situation in which the knowledge of the total process was degraded. This would have made it increasingly difficult to manage the process effectively, and control of the process would therefore not have been as consistent or reliable.

A similar deficiency existed before the fire on the Piper Alpha oil platform. A significant number of changes were occurring at the time, and control of the activities on the platform was degraded. Satisfactory management of changes within a complex operation was identified as a deficiency that was a contributing factor to the fire. This fire occurred over 10 years before the Avgas contamination episode; however, the lessons that could have been learnt from this fire had not been universally implemented to reduce the probability of an undesirable outcome from inadequate control of the number of changes to a continuous process, and the control of information relating to those changes.

3.2.1.3 Documentation of procedure

The operation of a complex process would normally be too much for one person to remember reliably, so it would be appropriate for the procedures in the operation to be controlled using accurate documentation. This documentation would ensure that any person within the organisation could provide a consistent and correct input into the process. The documentation should describe the activities of operators who control a complex process, such as pilots of large aircraft; however, it should also cover the activities of any individual who had the capacity to affect the complex process. This would include maintenance activities, and the activities of those who managed the process or could change the process. Mobil had documented procedures in place.

If the documented actions for a process were to be effective in ensuring a consistent and appropriate approach to achieving the organisation's desired outcomes, then the procedures needed to be correct, appropriate, up to date, complied with and workable. Several deficiencies were identified in the documentation of actions within the refinery.

- *Completeness.* Some of the procedures that were used to operate the alkylation unit were not documented. As an example, no documented process of management or procedure existed for operating the effluent treatment section of the alkylation unit with a caustic wash flow rate below the lower alarm limit.
- *Consistency.* Documents that described the procedures to be used in the alkylation unit were not necessarily accurate or consistent. This could be seen in the General Procedures Manual, which contained two different instructions for actions in the event of effluent treatment caustic wash system failure. There were no instructions to ensure consistent information recording in the alkylation unit logbook.
- *Compliance.* Not all of the procedures prescribed for use at the refinery were followed. For example, the procedures stated that vibration checks on certain components should be conducted on a calendar basis; however, this did not always happen. Also, a sample of water was not taken from the deisobutaniser overheads for testing at a scheduled time.
- *Application.* A number of the documented procedures were not easy to apply in practice.

  If a procedure was not workable in a practical sense, then it would not be likely to be followed. For example, it was expected that any water drained from a tank during specification sample-taking would be collected for analysis, even though these samples were normally taken after any water had been drained from the tank during the daily water drain. The likelihood, therefore, of obtaining such a sample would not be great. Similarly, the *Management of Change* procedures were intended to provide a structure to the consideration of any process change. It was necessary to define the circumstances when the *Management of Change* procedures should be used, and for that definition to be appropriate. The scope for the process was not explicit in considering the significance of a change, nor the degree of permanency of a change for which the process should be applied. An effective *Management of Change* process would have increased the probability of fuel contamination being satisfactorily considered at the time of change to the process in the caustic wash circulation system. If this had occurred, there would have been less chance of a particular outcome from the change being overlooked.

3.2.1.4 Quality assurance

The processes that were laid down in the refiner's quality assurance system did not ensure that the product supplied for sale was fit for purpose.

The refinery had an accredited production quality assurance system. Such a system should be designed to provide a documented organisational control of the processes of manufacture and test for a manufactured product to ensure the reliability and consistency of that manufactured product.

In November and December 1999, Mobil sold Avgas that was not fit for purpose.

3.2.1.5 Change control

When the implications of the changes to the caustic circulation system were being considered, there was no indication that the effect on the quality of the final product was considered, beyond the need to meet the specification.

In late 1999, the refinery personnel planned and operated the plant with the effluent treatment caustic wash circulation flow rate below the lower alarm limit. The effluent treatment caustic wash system formed an integral part of the whole Avgas production process, and as such, a change in the composition of the effluent caused by a reduction in the caustic wash flow rate could have affected subsequent processes during manufacture. Despite this, no changes were made to the quality control systems for the final product. In addition, no formal risk management exercise was conducted to assess the risks that could result from the planned abnormal operation.

3.2.1.6 Maintenance

The potential reliability offered by parallel redundant caustic circulation pumps was rendered largely ineffective because the maintenance management system did not ensure that the reliability of the backup pump was predictable.

This was due to the combination of:

- condition-based maintenance only providing an indication of failure once a component had started to deteriorate;
- incomplete data gathering to support a meaningful Mean Time Between Failure (MTBF) prediction;
- no procedure to control or monitor the usage of each of the parallel pumps; and
- inconsistent management of the system of vibration checking.

The refinery was designed to accommodate failure of equipment such as a caustic circulation pump by plumbing two pumps in parallel so that one could be used in the event of a failure of the other. However, there was an ineffective system to control the use of the caustic circulation pumps to ensure that the backup pump remained reliable, or to determine a valid measure of the working life of individual pumps. Consequently, the MTBF data stored in the computerised maintenance scheduling system could not provide an adequate indication of the reliability of the two pumps. A more complete MTBF analysis including pump starts, pump hours in use, and maintenance intervals could have enhanced the predictability of pump reliability, beyond that provided by condition-based assessment. This practice therefore diminished the defence of having a reliable alternative pump available.

This investigation did not identify any management system that compensated for the irregular nature of vibration checks on pumps G-A3-33 and G-A3-34. Clearly, if a pump is not checked regularly, any increase in vibration levels may not be identified prior to failure. The irregular nature of the program of vibration analysis was not consistent with the refinery's stated objective of conducting maintenance on a scheduled basis rather than responding to breakdowns.

3.2.1.7 Feedback

The management structure did not ensure that critical information was consistently available to appropriate personnel through effective feedback systems.

A managed feedback process would be one in which instructions were clearly laid out, followed, and the actions reported on. The managed process of implementing regular pH testing of water drains was deficient. Recommendation 6 from the internal investigation following the contamination episode in April 1999 required pH testing of all water drains from both the Yarraville and Altona tanks; however, it is not known if this was carried out, as no test results were reported back to the nominated officers. If the tests had been carried out, then the reporting process could have been considered as deficient, as the purpose of the tests was to provide information to the nominated officers. The system that was in place did not ensure that the initial instructions were practical and correctly carried out, or that regular and on-going monitoring or checking of the new procedure was conducted.

The refinery was managed by a structure of hierarchical management meetings in which information was processed, decisions made, and reports passed to higher level meetings within the hierarchy. The decisions made in these meetings were not fully recorded: for example, there was no complete record of decisions that were made in relation to the alkylation effluent caustic wash system in late 1999.

It would have been reasonable for an effective managed feedback process to specify what information had to be provided to the next level of management. This would have enhanced the consistency of information available for decision making.

3.2.1.8 Learning Organisation

There was evidence that process variations and their consequences were not adequately recorded and analysed to maximise the knowledge of the process.

Not all activities within the plant were consistently recorded. Some activities, such as specification testing, were recorded in a consistent manner by the use of forms. However others, such as information that was used to assist in shift handover were recorded in a diary, and the person making the entry decided the detail to be recorded. Sample taking was not recorded in detail, and it was not possible to identify from the record the person who took a sample.

Opportunities to learn from the analysis of previous incidents were lost because recommendations arising from those incidents were not followed through to completion.

Information relating to the effectiveness of previous use of Neutramine D could also have been used as a comparison at the time of the contamination to assess the normality and degree of control that existed over the process at the time. Previously, the use of high doses had returned the pH to normal limits in a short time; however, in this case, it was necessary to continue the high dosage for an extended period of time to maintain the pH within normal limits.

3.2.1.9 Control of Contractors

The contractual relationship with the corrosion control contractor was not managed effectively.

A documented tool was not used to clarify the nature and limitations of the relationship between Mobil and the corrosion control contractor at the time of the contamination, as no current written contract was in place. Consequently, the degree of control over the contractor could not have been as rigorous as would have been the case if both parties had maintained a defined agreement.

No clear formal authority relationship therefore existed between Mobil and the corrosion control contractor. Despite this, the contractor had access to the process stream, and the authority to directly affect that stream. The contractor's key performance indicator, as understood by both parties, was to control the pH of water from the deisobutaniser tower overheads. The key performance indicator did not address the downstream effects of the contractor's activities, and the two parties did not have a consistent understanding of whose responsibility it was to consider those downstream effects. Because there was no formal structure to ensure that possible downstream effects were considered, the refiner had not ensured that those concerns were effectively addressed.

This failure to manage the refinery's contractual arrangements was not in accordance with the requirements of ISO 9002, paragraph 4.3. Mobil had been accredited under ISO 9002.

3.2.1.10 Objectives

There was no process to ensure that the contractor's objectives did not adversely affect the refiner's objectives.

The stated objectives of the oil refining company were to maximise production performance in a safe, efficient, reliable, legal and environmentally acceptable manner, while maximising profit and minimising costs. The corrosion control contractor's objective in the alkylation unit was to ensure that the pH of water that came from the deisobutaniser tower overheads was within limits by varying the injection rate of Neutramine D. The contractor's objective was based on its understanding of the written contractual arrangement between the two companies, which had not been formally renewed since 1991.

The two organisations intended to work together effectively, however the achievement of the contractor's objectives had the potential to adversely affect the refiner's objectives. This was the case for a period of time in late 1999. The contractor's activities were not managed in such a way that they did not conflict with the refiner's objectives.

3.2.1.11 Problem solving

Problem solving processes were not effective in identifying problems, or in developing effective solutions to the problems. This was evidenced by the following events:

- Pump G-A3-33 was showing signs of reduced reliability before pump G-A3-34 was removed from service for overhaul. The use of pump G-A3-63 as an alternative was being considered four weeks before pump G-A3-33 was finally taken off line. Pump G-A3-63 would not have been needed as an alternative for pump G-A3-33 if pump G-A3-34 had not been delayed in its overhaul; however, at the time when pump G-A3-63 was first being considered as an alternative, it was not known how long G-A3-33 would last, nor how long the overhaul on pump G-A3-34 would take. The opportunity to at least commence a *Management of Change* exercise on the use of pump G-A3-63 was not used from the time when it was first considered as an alternative. Even if the pump had not been used at that time, a completed *Management of Change* process would have been of benefit if the possibility of needing that pump had arisen again in the future.
- The reduction in caustic wash circulation flow rate was not acted on as if it was safety critical. Instructions requiring a shutdown of the alkylation unit following a failure of the caustic wash system (which could be precipitated by an inability to circulate caustic), indicated that the caustic wash system was safety critical for the alkylation unit. A reduced caustic wash circulation flow rate could lead to increased acid carryover, which although not necessarily safety critical, would lead to changes in the process downstream.
- Neutramine D had proven to be effective in the past at controlling pH with small increases in dose rate. Dramatic increases in dose rate were necessary over an extended period of time (see Fig. 8) to control pH during the contamination episode. The change of the effectiveness of the Neutramine D indicated a process problem that was neither adequately identified nor addressed.

- No conclusive evidence was provided to the investigation team of any widespread significant contamination occurrences from ethylene diamine in the past, despite the occasional previous high injection rates of Neutramine D. Consequently, it is likely that additional factors influenced the concentration of ethylene diamine in the final product released from the refinery in late 1999. The need for an increased injection rate of Neutramine D to control pH in the deisobutaniser tower indicated that the physical and/or chemical conditions in the alkylation unit had changed. However, refinery personnel did not adequately appreciate the potential for those conditions to reduce the ability of the process to effectively remove the ethylene diamine from the product. Due to the complex nature of the process, the capacity for one aspect of the process to adversely impact on another was not clearly identified. The need for an increased Neutramine D injection rate was not only an indication of a potential problem in the manufacturing process, but also directly contributed to the contamination of Avgas.

3.2.2 Extraction mechanisms for ethylene diamine

Neutramine D had been used for some time in the manufacture of Avgas, however there had been no indication of a mass contamination of aircraft prior to December 1999. Therefore it is likely that extraction mechanisms for ethylene diamine in the amounts used had been working adequately in the manufacturing process.

On occasion, the Neutramine D injection rate was high enough that, had no extraction mechanism been working, a fuel contamination episode would have been likely to occur. Although a higher rate of ethylene diamine injection occurred in August 1998, it is unlikely that the physical and chemical conditions in the alkylation unit were the same as those in November 1999. It is probable that the difference in conditions in the alkylation unit in August and September 1998 contributed to a more efficient extraction process at that time, and a subsequent lack of significant contamination.

The product that was manufactured during late August and early September 1998, a period of higher Neutramine D injection rates, remained for some time in the tanks at Altona during August and September 1998. Thirty–six millimetres of rain fell in the Altona area during that period, and some of that rainwater would have entered the light alkylate storage tank. It is possible that even if there had been ethylene diamine contamination of the light alkylate then it could have been unintentionally extracted into the water during the subsequent blending process in the Altona tanks. This process could have reduced the concentration of any ethylene diamine remaining in the fuel supply .

3.2.3 Knowledge/rule based information processing for abnormal operations

There were no preconsidered rules or guidelines to support decision making processes in the event of all foreseeable abnormal operations.

The decision to halve the caustic wash flow rate on 5 October 1999, knowing that this would activate a system alarm, indicated that refinery personnel were comfortable operating with this alarm activated even though this would be an indication of abnormal operation.

Mobil's professional engineers normally managed abnormal situations by assessing the available information and developing a response. Because the documented guidance regarding management of abnormal situations was incomplete, engineers relied on group knowledge and experience of unit operations to develop a consensual approach. Mobil normally used this knowledge-based information processing activity to manage unanticipated abnormal events.

Information Processing

The way that people think about problems, or process information, can be categorised in order to help in understanding the way that decisions are made. The thinking process may be separated into:

- skill-based information processing
- rule-based information processing
- knowledge-based information processing

(Rasmussen 1983)

Skill-based information processing is used for tasks that are repeated frequently, are well learned, and require little conscious thought or decision making. Such actions include cleaning your teeth, signing your name, or a skilled pilot landing an aircraft.

Rule-based information processing is used for tasks that are repeated less often but have either been specifically learned, or for which detailed rules, instructions or checklists are readily available. When using rule-based information processing, a person will use procedures to undertake a task. This type of operation would include cooking something new using a recipe from a cookbook, or abnormal procedures that a person has been trained to cope with, but does not frequently experience.

Knowledge-based information processing is used for tasks for which a person has received no direct training, and has little or no prior experience. A person will work out and develop their best solution on the basis of their knowledge of subjects relating to a problem.

Knowledge-based information processing has the greatest potential for error, all other things being equal, as a person has no guidelines for information processing that would be inherent in rule-based, or skill-based information processing. There is also a greater potential for insufficient or inappropriate information to be used in developing a solution (as a lack of guidelines could lead to lack of awareness of wrong, or missing important information), or a course of action to address a particular situation.

The development of rules or guidelines for foreseeable abnormal operations prior to the onset of an abnormal event would have enhanced the opportunities for greater consideration of appropriate actions, and to have gathered knowledge and experience from other sources to develop and validate an approved sequence of actions. The failure of the caustic circulation pumps was foreseen; however, the rules and guidelines that existed were inadequate as a defence for use in the abnormal operations that occurred when insufficient caustic circulation was available. The operating team managing the plant were required to deal with an abnormal alkylation unit caustic wash flow rate using knowledge-based rather than rule-based methods in their response to the developing abnormal situation. A rule-based approach would have allowed well designed procedures to have been applied in a timely fashion to the unusual but foreseeable situation. The use of rule-based information processing in preference to knowledge-based information processing in an abnormal situation is considered to be less prone to human error, and therefore less prone to an undesired outcome.

A similar deficiency existed before the explosion at Flixborough in 1973, as identified in the findings of the court of inquiry. The engineering team that developed the plan to continue operating after an abnormal event did not appreciate design problems which 'set the scene for disaster'. The team did not have a structure, rules or procedures to follow in developing the solution to an abnormal event: knowledge-based information processing was used when the individual experts used their specialist areas of expertise to provide input to the solution. The team did not, however, identify that certain necessary areas of expertise were missing from the team. Factors relating to those areas of expertise were not considered. Had they been considered, they would have increased the probability of identifying the relevant design problems.

The Flixborough explosion occurred over 25 years before the Avgas contamination episode. The lessons that could have been learnt from this explosion had not been universally implemented to reduce the probability of an undesirable outcome from an abnormal event.

3.2.4 Risk management

The Altona refinery operated within a structured risk management regime that was inadequate, in that it only identified hazards to address an overly narrow defined group of undesired outcomes, and consequently only maintained defences that were relevant to those outcomes. Procedures were not in place to identify all the potential undesired events.

A rigorous process of risk management as described in Australian Standard 4360:1999—Risk Management, would first identify the organisation's objectives and all the hazards that could affect those objectives. An organisation's objectives can best be identified by a process of examining the relationship between the organisation and its environment, considering 'environment' in the widest possible sense to include stakeholders and anyone or anything that may influence or be influenced by the organisation. After defining its relationship with its environment, hazards to that relationship may then be identified.

Management of change procedures had been used as planning tools designed to provide a consistent approach to planning and implementing changes in order to minimise unexpected or negative outcomes. There was no requirement in Mobil's management of change procedures to define all the negative outcomes that should be considered in the hazard identification process. Their procedures only included a requirement for personnel to consider whether a hazard identification assessment was required. Although Mobil's management of change procedures used hazard identification tools that were consistent with accepted industry practices, they would only have been successful in identifying hazards that could increase the risk of predefined unacceptable outcomes, such as an uncontrolled release of a chemical.

The reliability engineers did not assess the caustic wash circulation pumps as critical because of the perceived lack of explosive or geographically widespread risk potential. Despite this, the caustic wash system had the potential to affect the quality of the product, the operation of the unit, and to adversely affect the safety of the refinery. A failure of the circulation system could allow corrosive action downstream that could lead to an uncontrollable loss of containment. Also, the refiner's *General Procedures Manual* stated that a rapid shutdown of the unit was required if the caustic wash system failed, which indicated the criticality of the system to the safety of the unit.

Neutramine D was used in the alkylation unit before the introduction of the *Management of Change* procedure. Given the specific nature of the defined unacceptable outcomes, it is unlikely that the *Management of Change* procedure and the associated hazard identification processes that were in place at the time of the contamination would have identified the introduction of Neutramine D as a hazard.

Ensuring that fuel met its specification, by itself, did not provide adequate assurance that the fuel would be fit for purpose. The hazard identification process did not therefore adequately address the risk of aircraft becoming unreliable as a consequence of using product from the refinery. This was evidenced by the refiner not adequately considering the downstream effects of the high injection rate of Neutramine D that occurred in late 1999.

3.3 Standards

The use of standards, by themselves, did not ensure the fitness for purpose of aviation fuels.

Aviation fuel standards were a defence that was used as only one of a number of measures to ensure that fuel was fit for purpose. Other defences were required, including control of manufacture, control of the plant used for manufacture, and control of the distribution system to ensure that fuel remained fit for purpose until it was used.

In order for standards to have been effective as a defence, it was necessary for users of the standards to have known not only what protection a standard would provide, but also the limits of that protection and, more importantly, what protection a standard would not provide.

3.3.1 Limits of application

The aviation industry generally had an invalid expectation that fuel that met a relevant specification during manufacture would always be fit for use in aircraft.

The standards were intended for use at a specific point within the Avgas manufacturing process. The manufacturers of aviation fuel recognised this, and used the standards only as one of a number of tools with the intention of ensuring that their product was fit for purpose. They applied extra requirements of their own to satisfy themselves that the fuel was fit for purpose by addressing fuel properties not covered by the standards.

In order for aviation fuel to be consistently fit for use in aircraft, other requirements such as control of storage and distribution needed to be managed to ensure that fuel remained fit for purpose following the point at which the fuel was tested for compliance with a standard. Neither of the two main standards referred to other requirements that were necessary in order for fuel to remain fit for purpose.

The ASTM standard did not imply fitness for purpose in aircraft, as it stated that its intended application was for the purchasing of Avgas under contract. The Def Stan standard stated that if fuel was supplied to that standard, then it should possess satisfactory performance in appropriate aircraft and engines. Although this was the defined expectation in the Def Stan standard, it did not address all the requirements for aviation fuel to be fit for purpose.

The standards did not state the limitations on what could be assumed about fuel that had met a specification during manufacture. Such a statement would have reduced the likelihood of end users of aviation fuel inappropriately expecting a fitness of purpose from the product. Despite this, most regulatory agencies only required that Avgas complied with a specified grade or grades, without any additional requirements to ensure that fuel quality had been maintained.

3.3.2 No single requirements

No single standard existed for each grade of aviation fuel that was sold on the world market. A number of standards existed, and the manufacturers then used these to develop individual company standards. The individual company standards were not identical, even though they were predominantly the same.

Fitness for purpose after manufacture was supported by each major manufacturing company maintaining individually controlled procedures.

Aviation fuel that complied with a variety of different specifications was manufactured and distributed. This meant that there was a potential for fuel to meet one specification and not another if there were several different specifications for the same fuel grade and distribution activity. A standard is intended to set minimum requirements for a product in order to achieve a consistent defined performance from that product. However, differences in standards could have led to less consistency in the marketplace for aviation fuel. Aviation fuel was marketed globally. Therefore, a single international standard could have been a more effective defence for the consistent manufacture, distribution and supply of each individual aviation fuel. Most aircraft operational documentation for piston-engine aircraft only specified which grade(s) of fuel to use in aircraft, without referring to a specific standard.

3.3.3 Requirements of the standard not achievable

The literal requirements of the standard could not be achieved. It was therefore not possible to produce a product that would accurately reflect the requirements of the standard.

The Avgas specifications did not state the maximum acceptable concentrations of undesired compounds in the product, either individually or collectively. The Avgas specifications stated that only hydrocarbons and approved additives were permitted in fuel. The standards therefore required a zero concentration of any other compound in Avgas.

If an established rule, in any form, is perceived as an unachievable target, then the users of that rule would develop an expectation that it was not a strict requirement, but a desirable aim. The degree of effort that should be expended to approach that unachievable target would have been a matter for professional judgement on the part of the person responsible. Professional judgements would differ, whereas the consistent application of an achievable literal description would be preferable, as it should not change. This is similar to the problem arising from the enactment of 'The Delaney Clause' (see page 37) in America that specified zero concentrations of certain chemicals in food products.

Manufacturers could not make Avgas that complied with the literal interpretation of the standards because of the zero concentration requirements. They therefore produced Avgas by applying their own interpretation of the standard that was as close to the literal interpretation of the standard as they considered appropriate. This was a 'workaround' that was used as a normal procedure.

In order to have developed a standard that could have been literally achieved, it would have been appropriate for the professional judgements regarding the application of the standard to have been documented and managed. This would have provided an opportunity to have achieved a specification that accurately reflected the intent of the standard.

3.3.4 Undefined, or implicit properties

Some of the properties of aviation fuel that were necessary to ensure fitness for purpose were not defined in the standards.

The specifications had been developed so that the defined properties could be tested in each batch of fuel prior to sale. A number of other properties were necessary for aviation fuel to be fit for purpose; however, they were not defined in the specification, and they were not normally tested in each batch of fuel prior to sale. Consistency of fitness for purpose of aviation fuel would have benefited if these implicit properties were defined, even if they were not tested on all batches of fuel.

The manufacturers of aviation fuel had sufficient product knowledge and expertise to normally ensure that the necessary undefined properties were achieved.

3.4 Oversight

Regulatory oversight had the capacity to be an effective defence against an unacceptable outcome by performing an auditing function that would have acted as a preventive measure. Effective oversight might have identified deficiencies in a process and required appropriate remedies.

3.4.1 Aviation safety oversight

Effective regulatory oversight would have reduced the probability of the fuel contamination occurrence.

CASA, in company with other national aviation regulatory agencies such as the US Federal Aviation Administration, could not satisfy itself that fuel supplied to aircraft would be fit for purpose. In order for fuel to be fit for purpose, it needed to be effectively managed from manufacture to end use. The organisations that controlled the manufacture and distribution of aviation fuel in Australia had sole control without oversight or external regulation of fuel quality. The only legislated requirement for a fuel quality check relied on the end user draining a fuel sample from the aircraft at defined times before flight. This requirement did not identify the contamination of fuel in December 1999.

There were references to specifications for fluids used in aircraft being required or approved by CASA in the *Civil Aviation Orders*. Despite this, documentation controlled by CASA only specified the grades, and not the specifications of Avgas to be used in aircraft.

In 1991, the then Civil Aviation Authority (CAA) withdrew from oversight of fuel quality. This was inappropriate given its mandated responsibility that when performing its functions it 'must regard the safety of air navigation as the most important consideration' (*Civil Aviation Act 1988* s.9a).

The CAA stated that it discontinued issuing certificates of approval to fuel manufacturers because it considered that it did not have the competence to adequately comment on the manufacturing and distribution processes. However, as competence to adequately comment has no relationship to the potential for inadequate fuel quality to dramatically affect the safety of flight, this reasoning could not be seen as logical or valid.

There was no indication to suggest that the Authority considered the safety implications of the removal of regulatory oversight for fuel. The function of the Authority was to conduct safety regulation of civil aviation and the impact on safety should have been considered when making decisions that could affect safety.

The Authority had the capacity to assess and audit the organisational capacity of aviation organisations to satisfy itself that they had procedures in place to ensure that aspects of their operation which were critical to aviation safety were documented, controlled, workable and resistant to human error. This process could also be used to assess the organisational capacity of the manufacturers of aviation fuels. The Authority could then satisfy its regulatory obligation to ensure that this safety critical aspect of civil aviation was being controlled in a way to ensure that the manufacturing and distribution processes had the same organisational safeguards in place as any other manufacturer which supplied a safety critical component of the civil aviation system.

The nature of the function of CASA required it to utilise a diversity of expertise to enable it to effectively regulate the wide range of safety critical systems in civil aviation. Aviation fuel quality was a safety critical system in aviation, so it would have been reasonable for CASA to have ensured that this system was monitored by competent personnel.

Regulatory requirements that involved proactive management and auditing systems were more likely to be effective at ensuring the maintenance of a safety critical activity than the threat of reactive criminal prosecution and civil litigation. Mobil was not subject to any form of regulatory oversight with regard to aviation fuel quality prior to the fuel contamination event. Effective regulatory oversight of the refinery could have identified deficiencies in Mobil's management and quality assurance systems and hence reduced the probability of the contamination of Avgas.

The potential consequences of the supply of contaminated aviation fuel are unacceptable to government and society. All the individual systems that had the potential to be critical to the safety of an aircraft in flight should have been subject to regulatory oversight to ensure that the entire system of civil aviation remained safe. Fuel is a manufactured product for which quality is critical to aviation safety, and which should have been considered as but one safety critical component of an aircraft in flight. Consequently, aviation fuel should have been regulated for fitness for purpose in a similar fashion to any other safety critical aspect of flight.

The conscious abrogation of any responsibility for regulatory oversight of a requirement for flight that was safety critical removed an essential organisational element in the system of safe aviation.

No formal relationship existed between CASA and the fuel manufacturers. No procedure existed for CASA to ensure that it was informed of any safety critical issue relating to the fitness for purpose of aviation fuel. Early advice of such a safety critical issue could not be expected by CASA, and it could not therefore have been confident of its ability to generate a timely response to maintain aviation safety in such a situation. For example, Mobil were first notified of the possible contamination of their Avgas 5 days before they advised CASA, as described in section 1.1. The potential for a serious accident in the intervening period was significant.

3.4.2 Ambiguity between regulators and laws

There was no legislated obligation for regulatory agencies, apart from CASA, to ensure that aviation fuel was fit for purpose beyond the normal contractual obligations in a commercial transaction.

Occupational health and safety (OH&S) and fair trading regulators had the potential to provide some form of oversight over the quality of aviation fuel. OH&S regulators considered that the responsibility for this lay with the fair trading regulators, despite the fact that these regulators primarily concerned themselves with dishonest trading. However, none of those agencies provided a consistent legislated oversight that ensured that manufactured products would be safe when correctly used.

Perceptions varied between the regulatory bodies as to the obligations of the other regulatory bodies, and it was possible for each regulatory body to consider that some regulatory responsibilities would fall to another agency. This diffusion of responsibility contributed to ineffective regulatory oversight.

4. CONCLUSIONS

4.1 General

The supply of aviation fuel to aircraft is safety critical in relation to the fitness for purpose of the fuel, however the systems of manufacture, distribution, supply and use in aircraft are not supported by the defences that are normally incorporated into safety critical aviation systems.

The deficiencies that have been identified in relation to the supply of Avgas that was fit for purpose also have the potential to affect the fitness for purpose of other aviation fuels, like Jet A-1.

4.2 Manufacture

Ethylene diamine was not completely extracted during Avgas manufacture in Mobil's Altona refinery, which led to a contamination of Avgas. The extraction was expected to occur during manufacture in the deisobutaniser tower.

The refiner's knowledge of the process within the alkylation unit was incomplete.

The process of managing change at Mobil did not consider the effectiveness of the extraction mechanism for ethylene diamine from the Avgas process stream.

Mobil did not have a process in place to identify the adverse consequences of the cumulative effects of multiple planned and unplanned process changes on the degree of control of the alkylation unit.

The refiner's procedures were not effective in ensuring that decisions were fully implemented, or that progress with recommendations was regularly reported and reviewed.

The refiner's risk management process considered an overly narrow defined set of undesirable outcomes. This did not allow Mobil to identify all the undesirable outcomes, (such as hazards to aviation safety) that could prevent them producing products that were fit for purpose and from achieving their broader organisational objectives.

The refiner had not satisfied itself that all compounds that could be in the process stream during manufacture, (with particular attention to process chemicals that were introduced during the manufacturing process), would not adversely affect the systems in which the final product was intended to be used.

The refiner did not conduct any specific practical validation of their assumption that ethylene diamine would be extracted during manufacture following the introduction of Neutramine D injection in 1991.

The process of contracting out the corrosion control at the Altona refinery alkylation unit was not managed to ensure that the fulfillment of the contractor's objectives would not adversely affect Mobil's objectives.

Mobil did not define or clearly document procedures for managing process deviations outside some of the limits for normal operations within the alkylation unit.

The processes for monitoring the reliability of plant equipment did not provide the best possible indication of reliability.

The refiner's use of its accredited quality assurance system was not effective in ensuring product quality.

Following up a recommendation arising from a previous contamination event could have allowed Mobil the opportunity to identify ethylene diamine contamination.

4.3 Standards

A clear understanding did not exist among the manufacturers, regulators and users of aviation fuel that compliance with a fuel standard, by itself, would not provide assurance that fuel would be fit for purpose.

Despite aviation fuels being a global commodity, no single global standard existed or was used for each main grade of aviation fuel.

It was impossible to comply with the literal interpretation of the major international standards for aviation gasoline because they did not specify maximum permissible concentrations of undesired compounds, either singly or collectively.

Accepted definitions did not exist for all the physical and chemical properties of aviation fuels that were required to ensure that aviation fuels were fit for purpose.

4.4 Oversight

Despite the criticality to safety of aviation fuel quality, no regulatory requirements for fuel quality testing existed beyond the requirement to assess water content in a sample of fuel drained from an aircraft before the first flight of a day, or after refuelling.

There was a diffusion of responsibility among the various regulatory bodies that had the potential to oversee aviation fuel manufacture, quality assurance, supply and use.

There was no indication to show that the then Civil Aviation Authority considered the effect on safety when it made a safety related decision concerning the oversight of fuel quality.

5. RECOMMENDATIONS

R20000115

The Australian Transport Safety Bureau recommends that Mobil Oil Australia review its understanding of process interrelationships and of its ability to control processes when considering planned and unplanned changes to a process within a refinery unit.

R20000116

The Australian Transport Safety Bureau recommends that Mobil Oil Australia review and clarify its procedures for managing refinery units during abnormal operations.

R20000117

The Australian Transport Safety Bureau recommends that Mobil Oil Australia review its processes for assessing the reliability of individual components within a refinery and their potential to contribute to undesired outcomes.

R20000118

The Australian Transport Safety Bureau recommends that Mobil Oil Australia review its procedures to ensure that in safety critical areas, decisions are fully implemented and progress in following up recommendations and implementing decisions is regularly reported and reviewed.

R20000119

The Australian Transport Safety Bureau recommends that Mobil Oil Australia establish as a part of its management of change process a mechanism for systematically identifying undesirable outcomes that should be considered in hazard or risk assessment processes.

R20000120

The Australian Transport Safety Bureau recommends that Mobil Oil Australia review the effects, as contaminants of the end product, of all chemicals that could be in the process stream, with particular attention to process chemicals that are introduced during the manufacturing process. As a part of the hazard assessment processes, the review should include the expected products of reaction as possible contaminants of the end product.

R20000121

The Australian Transport Safety Bureau recommends that Mobil Oil Australia develop quality assurance processes comprising practical validation of end products to ensure that they are not inadvertently rendered hazardous.

R20000122

The Australian Transport Safety Bureau recommends that Mobil Oil Australia review its processes for managing the contractual arrangements for contracts that have the potential to significantly affect its fuel quality and safety objectives.

R20000123

The Australian Transport Safety Bureau recommends that Mobil Oil Australia review the effectiveness of its processes to ensure that it fulfils the requirements of its accredited quality assurance system, including its processes for the management of contractual relationships.

R20000124

The Australian Transport Safety Bureau recommends that the American Society for Testing and Materials include a description of the limitations of applicability of standard D910 – 97 in the scope of the standard.

R20000125

The Australian Transport Safety Bureau recommends that the Defence Evaluation and Research Agency (UK) include a description of the limitations of applicability of Defence Standard 91 – 90 issued 8 May 1996, in the scope of the standard.

R20000126

The Australian Transport Safety Bureau recommends that the American Society for Testing and Materials review standard D910 – 97 in relation to the maximum permissible quantities of undesired compounds in Avgas, either individually or collectively.

R20000127

The Australian Transport Safety Bureau recommends that the Defence Evaluation and Research Agency (UK) review Defence Standard 91 – 90 issued 8 May 1996, in relation to the maximum permissible quantities of undesired compounds in Avgas, either individually or collectively.

R20000128

The Australian Transport Safety Bureau recommends that the American Society for Testing and Materials develops and promulgates definitions for necessary physical and chemical properties of aviation fuels that are not currently defined, whether these are expected to be tested as a part of batch specification or not.

R20000129

The Australian Transport Safety Bureau recommends that the Defence Evaluation and Research Agency (UK) develops and promulgates definitions for necessary physical and chemical properties of aviation fuels that are not currently defined, whether these are expected to be tested as a part of batch specification or not.

R20000131

The Australian Transport Safety Bureau recommends that the Civil Aviation Safety Authority, either by itself, or in cooperation with other organisations, develop a process to satisfy itself that fuel that is fit for purpose is consistently supplied to aircraft.

R20000133

The Australian Transport Safety Bureau recommends that the Civil Aviation Safety Authority ensure that prior to any significant devolution or change in regulatory process, appropriate measures are taken to ensure that aviation safety is not diminished.

R20000130

The Australian Transport Safety Bureau recommends that the Civil Aviation Safety Authority identify and adopt an appropriate specification for each grade of fuel that is approved for use in Australia, or in aircraft on the Australian Civil Register.

R20000132

The Australian Transport Safety Bureau recommends that the Civil Aviation Safety Authority develop appropriate lines of communication to ensure that it is made aware in a timely manner of information relating to the management of situations related to fuel quality that could affect the safety of flight.

R20000186

The Australian Transport Safety Bureau recommends that the Civil Aviation Safety Authority review its relationship with other regulatory bodies to clarify the limits of their respective regulatory powers and responsibilities with respect to aviation fuels, to ensure that aviation safety issues are effectively regulated.

R20000187

The Australian Transport Safety Bureau recommends that Workcover Victoria review its relationship with other regulatory bodies to clarify the limits of their respective regulatory powers and responsibilities with respect to aviation fuels, to ensure that aviation safety issues are effectively regulated.

R20010017

The Australian Transport Safety Bureau recommends that the Department of the Treasury review its relationship with other regulatory bodies to clarify the limits of their respective regulatory powers and responsibilities with respect to aviation fuels, to ensure that aviation safety issues are effectively regulated.

R20010018

The Australian Transport Safety Bureau recommends that the Australian Competition and Consumer Commission review its relationship with other regulatory bodies to clarify the limits of their respective regulatory powers and responsibilities with respect to aviation fuels, to ensure that aviation safety issues are effectively regulated.

R20010019

The Australian Transport Safety Bureau recommends that Consumer and Business Affairs Victoria review its relationship with other regulatory bodies to clarify the limits of their respective regulatory powers and responsibilities with respect to aviation fuels, to ensure that aviation safety issues are effectively regulated.

6 SAFETY ACTION

Following the interested party process, the ATSB was advised of the following safety actions.

Mobil Oil Australia advised that, in response to the contamination, they had:

1. Immediately ceased manufacturing Avgas at Altona refinery, quarantined all Altona produced Avgas and re-called all potentially contaminated Avgas.
2. Immediately advised CASA and governments of a potential issue with supplied Avgas over a limited period and worked closely with CASA and the industry to safely return all potentially affected aircraft to the air. This included the development of new fuel testing programs to enable the detection of extremely low levels of contamination.
3. Immediately discontinued using EDA and is in the process of remediating equipment that had been in contact with EDA.
4. Conducted a thorough review of Altona refinery's Product Quality Management System procedures for the manufacture of Avgas.
5. As part of the Victorian Major Hazardous Facilities Safety Case, completed a risk and hazard analysis of the alkylation unit. This included a review and rationalisation of operating alarms and abnormal situation management guidelines.
6. Under the Triennial Audit by the independent [company name supplied], has been granted, in October 2000, continued certification of Quality Systems Standard, ISO 9002, with no non-conformances noted.
7. As part of actions planned prior to the Avgas incident, implemented a new electronic Corrective Action Request system at Altona refinery.

The American Society for Testing and Materials (ASTM) advised that, in response to the interested party process:

> These recommendations were discussed at the Subcommittee J meeting on December 6, 2000. Subcommittee J agreed to the following replies, which use the same numbers as the original ATSB letter.

1. ATSB recommended a description of the limitations of applicability of ASTM D 910 in the scope of the standard. Subcommittee J on Aviation Fuels agrees with your recommendation and will rework the limitations of applicability. The Subcommittee expects to take the opportunity to revise the present scope and, quite likely, will add a new section on significance and use, which takes the ATSB recommendation into account.
2. ATSB recommended a review of D 910 in relation to the maximum permissible quantities of undesirable compounds in Avgas. [Name supplied]'s comments on the report have touched on the difficulties of setting any limits on presently unknown materials. Furthermore, any quantitative limits have to be justified by technical reasons that include an assessment of the effects of the material on engine or aircraft performance. Subcommittee J already has been addressing this problem for jet fuels, but to obtain a consensus any solution has to meet the needs of both producers and users. Once a workable solution is found, there should be no difficulty in transferring it to D 910.

3. ATSB recommended that definitions for necessary, but currently undefined, physical and chemical properties be developed for aviation fuels, regardless of whether these properties are to be included in batch testing. Subcommittee J is currently embarked in a major effort to define all explicit and implicit properties required for the satisfactory performance of jet fuels. The work is directed to allow the evaluation of novel fuels that may differ from current fuels either by their non-petroleum origin or through differences in processing. Subcommittee J expects this effort will aid in the identification of such implicit properties for Avgas, although a direct read-across is unlikely.

   Based on the above response you can see that the ATSB recommendations are receiving serious consideration in ASTM and I expect Subcommittee J will keep you advised of progress.

The Australian Competition and Consumer Commission (ACCC) advised that:

> The Commission has formalised its relationship with a number of agencies in respect of its responsibilities in consumer protection. Currently the Consumer Protection Unit is in the process of examining further processes to clarify the Commission's role in the context of aviation fuel and other transport regulatory issues.

The Defence Evaluation and Research Agency (DERA) has advised that it is in discussions with the Aviation Fuels Committee, Executive Committee, as to suitable wording to be placed in the specifications, in the light of the Australian Avgas contamination event.

These safety actions have addressed in part some of the deficiencies that have been identified in the report. Any formal responses to the recommendations that will be issued in conjunction with this report will be published in the Bureau's Quarterly Safety Deficiency Report.

APPENDIXES

Appendix A: Terms of reference

Terms of reference for systemic investigation into the circumstances of aviation gasoline contamination

The Australian Transport Safety Bureau (ATSB) performs its functions in accordance with the provisions of the *Air Navigation Act 1920*, part 2A. Section 19CA of the Act states that the object of an investigation is to determine the circumstances surrounding any accident, serious incident, incident or safety deficiency to prevent the occurrence of other similar events. Under Section 19CB (1) (b) and (d) the Director of Air Safety Investigation, ATSB may investigate any safety deficiency affecting Australian registered aircraft and any other aircraft operating within Australia.

The ATSB investigation into the circumstances of the contamination of aviation gasoline supplies from the Mobil Altona, Victoria refinery, has identified the processing and distribution by Mobil of contaminated fuel for use in aircraft as a safety deficiency.

With a view to identifying recommendations to minimise the probability of the occurrence of similar events in the future, the investigation is being widened to examine the following:

1. the existing standards for aviation gasoline;
2. the details of risk analyses undertaken prior to and during the production of aviation gasoline at Mobil's Altona refinery;
3. the adequacy of the production control, distribution control, and recording processes used by Mobil and other refiners;
4. the current arrangements for the oversight of aviation gasoline quality, including the procedures followed by Mobil and other refiners to disclose information with potential aviation safety implications; and
5. any other matter of material relevance to the above.

The results of the ATSB investigation will be made public. If appropriate, progressive findings and interim recommendations will be issued.

Note: The Civil Aviation Safety Authority (CASA) will be examining the potential for continuing airworthiness problems that may arise as a consequence of both the fuel contamination event, and subsequent actions taken to rectify the consequences.

The terms of reference were addressed in the following manner:

1. The report of the investigation addressed the relevance of the existing standards for aviation gasoline by examining their effectiveness as a defence in enhancing the reliability of the fuel supply system by ensuring the supplied product is fit for purpose.

2. The report of the investigation addressed the methods that were used in conducting risk analyses as a part of the management processes used in controlling the operation of the refinery, and any changes to the operation of the refinery.

3. The report of the investigation addressed the methods used to control production processes in the refinery, and the methods by which information was recorded and used to maximise the efficiency of the refinery. These methods were also examined at some other major Australian refineries.

   Control of distribution methods was not found to have been a factor in the fuel contamination event; indeed, the contaminated fuel was successfully tracked and recalled. The report did not therefore address the control of distribution of aviation fuel.

4. The report of the investigation addressed the methods by which oversight of aviation fuel manufacture was provided by a number of regulatory agencies. The report identified the differing areas of oversight that could have had the potential to enhance the safety of aviation fuel that is provided to aircraft, and the impact that each form of oversight could have had on enhancing the probability of fuel being supplied that remained fit for purpose. The report provided comment on the diffusion of responsibility from the variety of regulatory potential.

5. The report of the investigation addressed the relevance of deficiencies in the supply of airworthy Avgas to other safety critical aviation systems, including the supply of fuel to turbine powered aircraft.

Appendix B: Chemical analysis of Avgas

Chemical analysis of a typical sample of Avgas from the Altona refinery

Listing of major components by volume per cent

Component	*Volume per cent*
2,2,4-trimethylpentane (iso-octane)	21.04
2,3,4-trimethylpentane	19.24
2,3,3-trimethylpentane	17.35
2,4-dimethylhexane	10.44
2,3-dimethylbutane	6.51
2-methylbutane	5.5
2,4-dimethylpentane	4.12
2,3-dimethylhexane	4.05
2,2,5-trimethylhexane	2.93
butane	2.88
2,3-dimethylpentane	2.88
3,4-dimethylhexane	0.64
2,3,5-trimethylhexane	0.47
2,2,6-trimethyldecane	0.36
2,2,6-trimethyloctane	0.27
2,2,6-trimethyldecane	0.22
2,2,3,4,6,6-hexamethylheptane	0.19
2,5-dimethylheptane	0.14
toluene	0.13
3,3,5-trimethylheptane	0.11
2-methylheptane	0.1
2,5-dimethyldodecane	0.1
2,3-dimethylheptane	0.09
2,4,4-trimethylhexane	0.08
2,3-dimethyloctane	0.08
2,6,7-trimethyldecane	0.07

Avgas also contains small amounts of intended additives. These components of Avgas may include the following:

Tetraethyl lead	- improves the octane rating of the fuel
1,2-dibromoethane	- scavenges lead from exhaust gases on combustion
Dye	- yellow and blue dyes to colour Avgas 100/130 green
Antioxidants	- prevent the formation of gums and lead compounds

Appendix C: Chemical behaviour of ethylene diamine

As part of their response to the contamination of Avgas, Mobil, the Civil Aviation Safety Authority and the Australian Transport Safety Bureau each commissioned different organisations to conduct a variety of tests to determine the behaviour of ethylene diamine in Avgas and aircraft fuel systems. Some of the conclusions reached following these tests are presented here. Care should be taken in evaluating these conclusions, as they are not supported by the full detail contained in the associated reports.

1. The concentration of ethylene diamine in Avgas in storage containers reduces over time. It was postulated that this could be attributed to ethylene diamine being adsorbed to the surfaces of containers, reacting with carbon dioxide and water from air to form ethylene diamine carbamate or its reactions with trace metals in the containers.
2. Ethylene diamine reacts with copper to form complex compounds. The formation of copper-ethylene diamine complexes is accelerated when copper is in brass, compared with pure copper. The copper-ethylene diamine complex dissolves in water to form a purple solution.
3. Mobil routinely retained samples from batches of Avgas before they were distributed. Subsequent testing of these samples established that the maximum concentration of ethylene diamine in samples taken at Altona was 30 parts per million (ppm) and 2.5 ppm in samples taken at Yarraville.
4. A brass strip immersed in a solution of iso-octane and 100 ppm ethylene diamine was not discoloured by copper complex formation after 3 days at room temperature.
5. A brass strip was immersed in liquid comprising 10 mL of 100 ppm ethylene diamine in iso-octane and 5 mL of deionised water. Within 1 hour, the water phase was purple and the part of the brass strip in the iso-octane phase was discoloured. After 48 hours, the water phase was a darker purple, the part of the brass strip in the iso-octane was discoloured and the part of the brass strip in the water phase was also discoloured. The part of the brass strip in the water phase was more heavily discoloured than the part in the iso-octane phase.
6. Ethylene diamine has a high affinity for water and will preferentially partition into water from fuel. It is postulated that any ethylene diamine in fuel tanks may concentrate in any water present in the tanks and result in a highly alkaline solution. Experimentation revealed that as little as 2 ppm of EDA into pH 6.08 water will increase its pH to 8.65.

Table 8:
pH increase with EDA additions to water

Water EDA addition	*pH*
Melbourne tap water	7.64
Melbourne tap water + 1 ppm EDA	8.10
Melbourne tap water + 2 ppm EDA	8.48
Melbourne tap water + 3 ppm EDA	8.75
Deionised water	6.08
Deionised water + 2 ppm EDA	8.65
Deionised water + 4 ppm EDA	9.10

7. It was estimated that the contaminated Avgas had greater than 0.4 ppm of ethylene diamine.

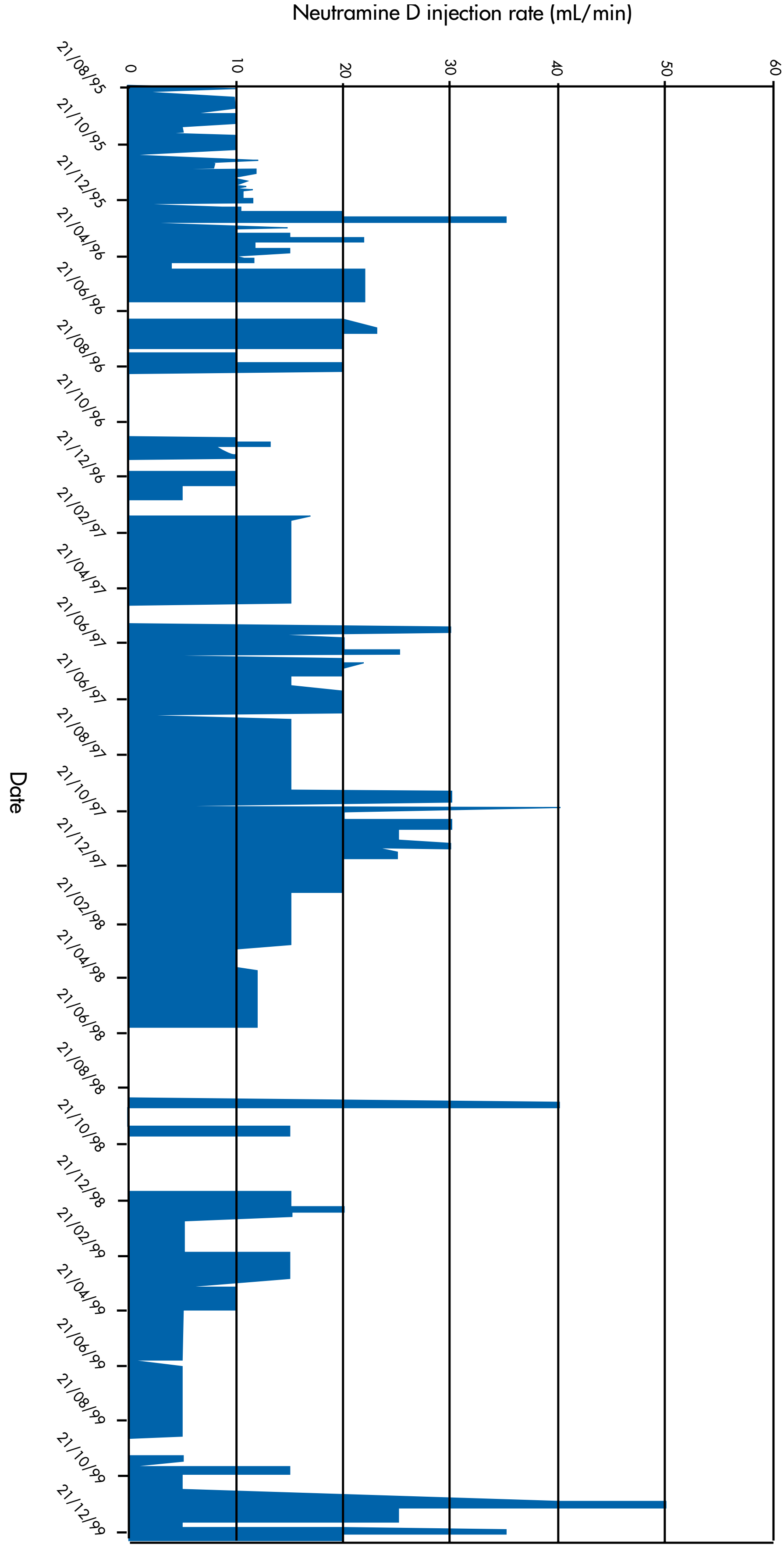
Appendix D: Organic chemistry naming conventions

The International Union of Pure and Applied Chemistry (IUPAC) is recognised as the world authority on chemical nomenclature, terminology, standardised methods for measurement, atomic weights and many other critically evaluated data. The IUPAC system of naming chemical compounds is intended to provide an unambiguous name for each chemical to allow clear written and oral communication between chemists. While there are systematic names for almost all chemical compounds, many are also identified using traditional names. Many of the names used in this report are traditional names, and the following table identifies the traditional name and its corresponding systematic name.

Traditional name	***Systematic name***
Ethylene diamine	1,2-ethanediamine
Iso-octane	2,2,4-trimethylpentane
Isobutane	2-methylpropane
Butylene	but-2-ene
Propylene	prop-1-ene

Appendix E: Figure 12. History of Neutramine D injection rates

This diagram depicts the rates of Neutramine D injection from 1995 to 1999.



Appendix F: Octane rating

To function correctly, engines require fuel of particular performance characteristics. Under normal circumstances, the fuel-air mixture in a spark-ignition engine cylinder ignites when the spark plug activates. However, a fuel-air mixture can ignite spontaneously when compressed, resulting in a characteristic 'knocking' or 'pinging' sound, a reduction in efficiency and the potential for mechanical damage. The ability of a gasoline-type fuel such as Avgas to resist spontaneously igniting when compressed in an engine cylinder is referred to as the octane rating.

An octane rating indicates the knock resistance of a fuel relative to two particular hydrocarbons. Heptane has a very low resistance to knocking and is assigned an octane rating of zero. Iso-octane, or 2,2,4-trimethylpentane has a high resistance to knocking and is assigned an octane rating of 100. The octane number of a fuel is the same as the percentage of iso-octane in a mixture of iso-octane and heptane that has the same knock resistance as the fuel being tested. Alternative methods are used to determine octane ratings above 100.

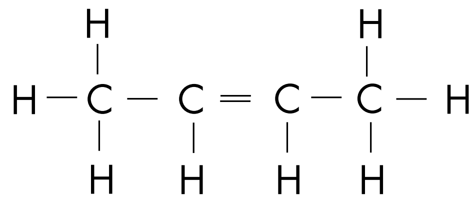
Appendix G: The petroleum refining and Avgas production processes at Altona.

Crude oil is a naturally occurring mixture of a wide variety of compounds. The compounds consist primarily of molecules with one to more than sixty carbon atoms (C_1-C_{60+}). Many different compounds exist for each carbon number, depending on the structure of the molecule. Each carbon atom is bound to as many as four hydrogen (H) atoms. These molecules are collectively known as hydrocarbons. The size and shape of their constituent hydrocarbon molecules determine the characteristics of the refined products. Crude oil also contains other compounds that would be considered impurities if present in a finished product.

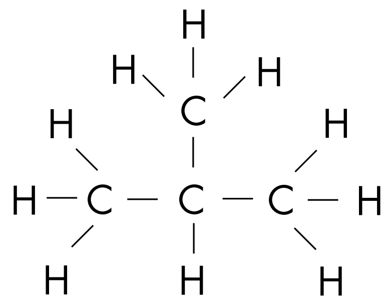
The structure of each hydrocarbon molecule determines its properties.

For example:
- More double bonds increase the boiling point.
- The longer the carbon chain the higher the boiling point.
- More branching decreases the boiling point.
- More double bonds increase the chemical reactivity.

Butylene
A straight chain hydrocarbon with 4 carbon atoms (C_4) and a double bond



Isobutane
A branched hydrocarbon with 4 carbon atoms (C_4)

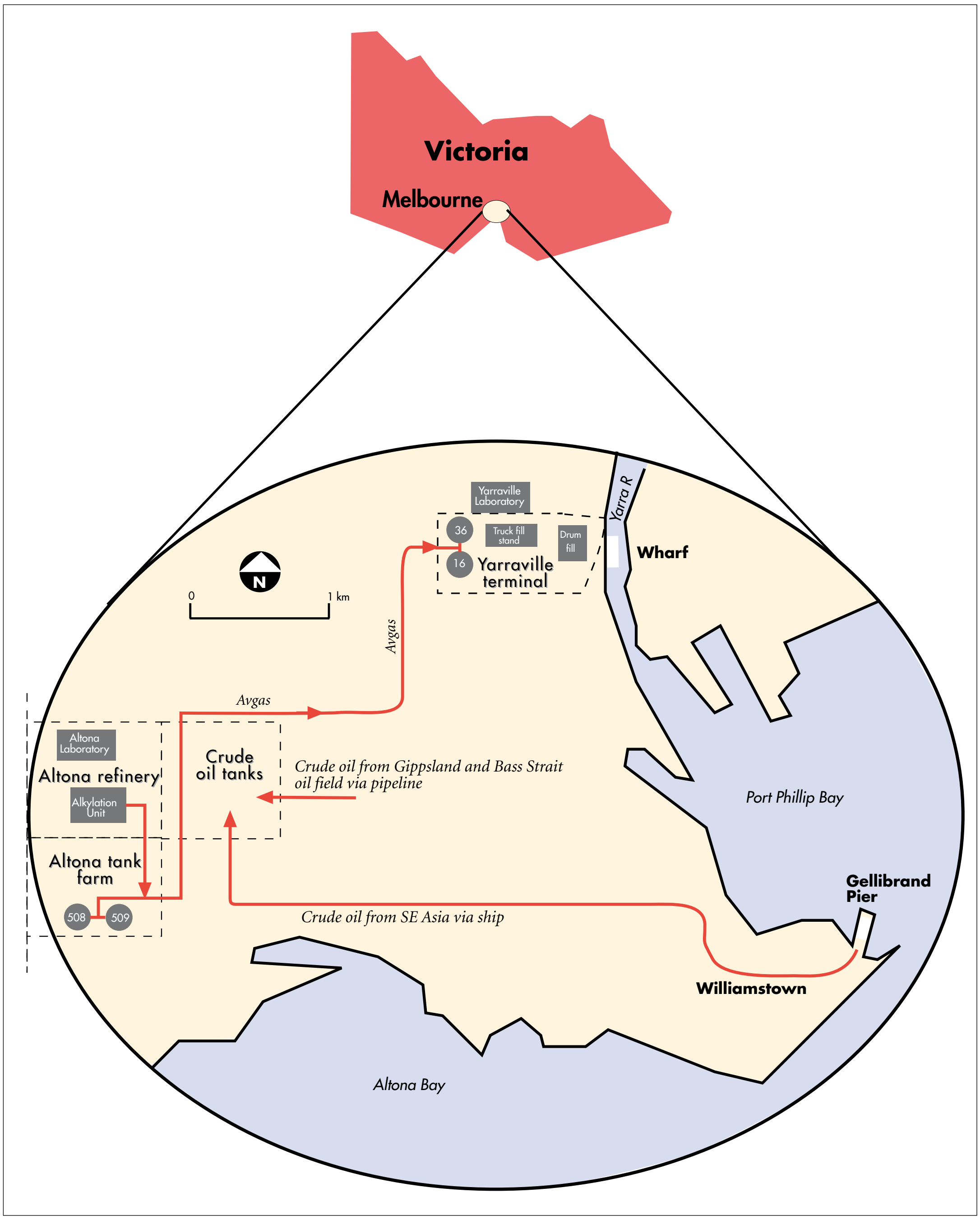


Oil refining utilises the properties of the different hydrocarbon compounds in developing saleable products from the mixture naturally present in crude oil. Processes within the refinery:

- Separate the compounds in crude oil according to their boiling point range by distillation.
- Create new molecules by breaking up or joining naturally occurring compounds from the crude oil by processes such as alkylation, catalytic cracking and reforming.
- Remove contaminants.
- Blend specific combinations of compounds.

An outline of the processes in the refining of crude oil is shown in Fig. 2.

FIGURE 13. Map of Altona area



G.1 Distillation

Crude oil that entered the refinery was initially separated into numerous streams by distillation. An outline of the distillation process is shown in Fig. 3. The overhead and the bottoms streams underwent further extensive processing. Streams that boiled off at intermediary temperatures generally required less treatment and were fed off as end products or for blending to make fuels.

G.2 The overhead stream

The overhead stream from the crude distillation process boiled off at the lowest temperatures. It included hydrocarbon compounds that were gaseous at room temperature as well as liquids with low boiling points. These hydrocarbon compounds comprised molecules with approximately one to 12 carbon atoms. One of the products that was available following further processing and separation was isobutane, a hydrocarbon compound containing four carbon atoms. Isobutane was one of the two primary feedstocks used in the alkylation unit.

G.3 The bottoms stream

The bottoms stream contained hydrocarbon compounds comprising molecules of approximately 30 to 60 carbon atoms. These molecules were chemically broken up in the catalytic cracker into smaller molecules and separated. The products of this reaction included C_1-C_{12} molecules which were processed and separated. Propylenes and butylenes (three and four carbon atom molecules containing a double carbon bond) were separated and processed. Propylene was separated from the butylene before it was fed to the alkylation reactor as the olefin feed.

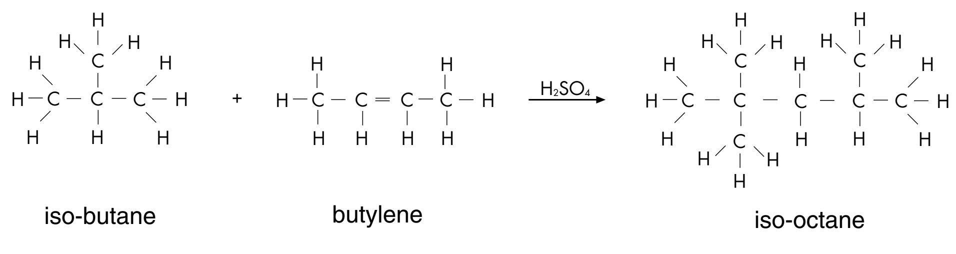
G.4 Reactant storage

Isobutane and the olefin feed could be stored in storage spheres before being passed into the alkylation reactor. This storage capacity provided a buffer for feedstock should the alkylation unit need to be shut down, so variances between demand and supply of feedstock to the alkylation unit could be accommodated. The storage spheres also held a reserve of isobutane that was required when the unit was shut down. The capacity of the storage spheres would allow sufficient supply for 60 hours of operation of the alkylation unit if they were full to start with. The storage spheres normally contained some feedstock.

G.5 The Alkylation unit

In the alkylation reactor isobutane and butylene chemically combined to form iso-octane, a high quality fuel and the basis of aviation gasoline (Avgas). A diagram of the alkylation reactor is shown in Fig. 5, and an outline of all the main components of the alkylation unit is shown in Fig. 4. This reaction required the presence of an acid catalyst, sulfuric acid (H_2SO_4). The process required accurate control of the environment within all parts of the unit, including temperature, pressure and chemical composition.

Diagrammatic representation of the desired alkylation reaction



The alkylation reactor worked by circulating an excess of isobutane with concentrated sulfuric acid, and injecting a stream of the olefin feed. The ratio of isobutane to olefin feed in the reactor needed to be greater than 8.5:1 in order for the reaction to proceed as desired. Sulfuric acid did not naturally mix with the other compounds and was the densest fluid in the reactor. It would naturally tend to separate and settle to the bottom if left undisturbed, so it was necessary to stir the mixture intensely in order that the catalyst came into intimate contact with the reactants. The quality of the acid in the reactor was continually monitored by an analyser, which was supported by regular laboratory testing of samples. The rate of acid usage was monitored and recorded.

A small quantity of undesired compounds would also form in the reactor. Some of the sulfuric acid would react with the hydrocarbons to form acidic monoalkyl sulfates and neutral dialkyl sulfates.

Alkylation occurred in seven reaction zones of the alkylation reactor. At the end of the reactor, the sulfuric acid was allowed to settle and most of it was removed. Further separation of sulfuric acid then occurred in a hydrocarbon settler. The remainder of the reactor process stream included the desired product iso-octane, unreacted isobutane, butane and a very small amount of propane as well as entrained sulfuric acid and alkyl sulfate compounds. This mixture was known as effluent and continued for further processing.

G.6 Effluent treatment

The effluent was treated to remove unwanted chemicals prior to further processing. An outline of the effluent treatment process is shown in Fig. 6.

The effluent was washed with an aqueous alkaline solution of sodium hydroxide (NaOH), referred to as caustic. The caustic wash was intended to react with any acidic compounds in the effluent and to neutralise them. This process removed sulfuric acid and monoalkyl sulfates from the effluent. The caustic solution was immiscible with and denser than the effluent. The remaining caustic was then allowed to settle, and was separated in a similar fashion to the process used for separating the sulfuric acid. The separated caustic was then recirculated through the caustic wash system, and its quality was maintained by a process of continual replenishment and the use of regular pH testing by operators to adjust the rate of fresh caustic injection into the wash system. The pH test results were not regularly recorded, and the rate of fresh caustic injection was not recorded.

The effluent was then washed with water to remove any remaining caustic, dialkyl sulfates and water soluble compounds. The water and its solutes were then separated. At this stage, the majority of the effluent was excess isobutane that needed to be separated and returned for recycling through the alkylation reactor. This happened when the effluent was fed via a preheater to the deisobutaniser distillation tower, where it was further heated as a part of the separation process.

G.7 Distillation theory

The theory of distillation is relatively straightforward, particularly in relation to a mixture of two components that do not interact with each other. However, if the components of a mixture do interact with each other (for example ethylene diamine and water have a strong affinity for each other), the distillation behaviour of the mixture can be remarkably different from the distillation behaviour of the two individual components. As a mixture becomes more complex, with increasing numbers of components with varying levels of interaction with each other, it becomes increasingly difficult to reliably predict the distillation characteristics of the components. Such predictions are usually performed using computer models.

The deisobutaniser distillation tower separated isobutane from the butane and isobutane mix, and unreacted isobutane from the effluent stream. The isobutane in the tower was then fed to the alkylation reactor. Isobutane came off in the overhead stream, and the remainder of the effluent continued to the debutaniser tower. Water also came off at the top of the deisobutaniser tower. An outline of the processes in the deisobutaniser tower is shown in Fig. 7.

Neutramine D, a product containing ethylene diamine in solution with water, was injected into the effluent flow prior to entering the deisobutaniser tower. Dialkyl sulfates should have been removed from the effluent by the water wash; however, when the effluent was heated in the deisobutaniser tower, any dialkyl sulfates that remained would have been likely to break down into acid products that would have accelerated corrosion in the plant. Neutramine D was intended to react with any acid that was carried over or formed from the breakdown of dialkyl sulfates, and to neutralise it.

Removal of butane from the effluent was the next stage of the separation process. This occurred in another distillation tower, called the debutaniser tower. The effluent from the debutaniser tower bottom stream continued to the rerun distillation tower.

The rerun distillation tower separated the purified reactor effluent into light (overhead stream) and heavy (bottom stream) alkylate. The light alkylate, with a primary constituent of iso-octane, was the basis of aviation gasoline. With the addition and mixing of tetraethyl lead, dyes and other required additives, the product became ready for specification testing as aviation gasoline.

G.8 Rundown from alkylation unit to tank farm

When the refinery was manufacturing Avgas, light alkylate that came from the rerun tower overhead was transferred via a pipeline to one of the two Avgas tanks at the Altona tank farm. When Avgas was not being manufactured, the light alkylate from the rerun tower overhead was blended to make other refinery products, in particular automotive gasoline. Alkylate typically made up less than five per cent of automotive gasoline. The tank farm was a large area adjacent to the refinery. It contained a number of tanks, the product blending area and waste water treatment areas. The two Avgas tanks, numbered 508 and 509, each had a capacity of approximately 2.5 million litres. The tanks had roofs that were designed to float on the contents of the tank, and the bottoms of the tanks were in the shape of a cone, with the apex pointing up, known as a 'cone-up bottom'. Some rainwater could have been expected to enter the light alkylate. After a required quantity of light alkylate had been transferred from the alkylation unit, the tank was allowed to settle and was dewatered. A sample was then taken to the laboratory for testing. Based on this initial test, a blendsheet was prepared which detailed the quantity of dye, antioxidant and tetraethyl lead required to ensure the resulting Avgas complied with the Mobil specification. The product was blended by circulating it through a pipe as the required blending compounds were injected at a controlled rate. When the blending had been completed, the tank of Avgas was again settled and dewatered, before a further series of samples were taken. These samples underwent a complete laboratory analysis to ensure that the product met the Mobil Avgas specification. If the samples met the specification, the batch was assigned a unique batch identification number. The batch was certified and then transferred via one of two pipelines that were used for gasoline type products including Avgas from the refinery to the logistics section at Mobil's Yarraville terminal for distribution.

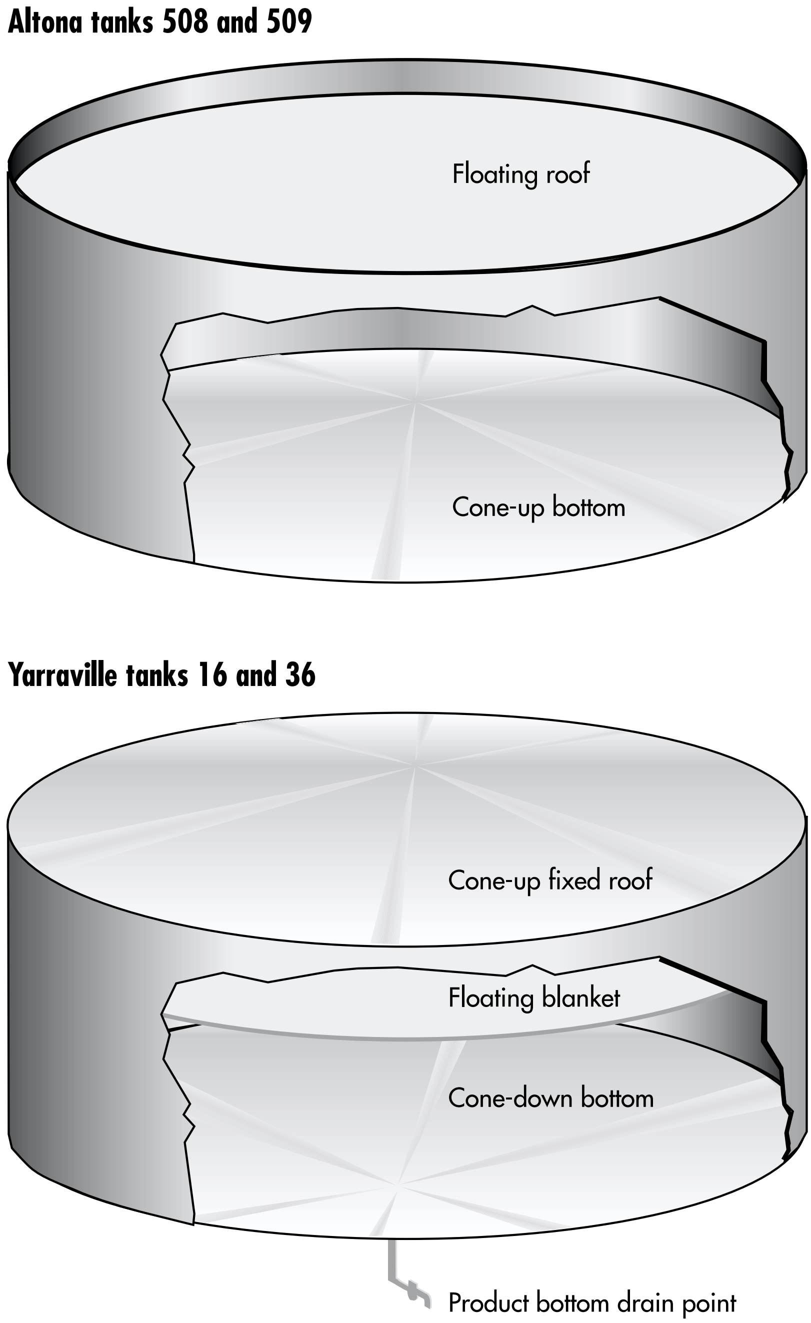
G.9 Batch release note procedures

The Mobil company batch release note procedures at Altona were designed to ensure that the distribution of a batch of Avgas could be controlled so that it was all tracked to its point of sale.

G.10 The Yarraville terminal and distribution methods for Avgas

The Yarraville terminal fulfilled a variety of distribution control functions. It had a large number of refinery product tanks, a tank truck fill stand, a drum fill area, a tanker wharf and a laboratory. There were two Avgas tanks at Yarraville, numbered 16 and 36. These

FIGURE 14. Avgas storage tanks



Altona tanks 508 and 509 incorporated floating roofs and cone-up bottoms while Yarraville tanks 16 and 36 had cone-down bottoms and fixed roofs with floating blankets. Tanks 508 and 509 at Altona were not ideal storage units for Avgas. It is preferable that the bottom of the tank be shaped to allow water in the tank to be removed from a single drain point, which provides for better extraction of settled water. The floating roof did not provide an effective shield against the ingress of rain into the tank. In addition, a floating roof can produce corrosion and particulate material as it moves up and down against the sides of the tank.

tanks had solid roofs, and the bottoms of the tanks were in the shape of a cone, with the apex pointing down, known as a 'cone-down bottom'. The water drain point was at the bottom of the cone. A blanket floated on the top of the Avgas in the tank to reduce evaporation. For a diagram of the Avgas storage tanks at Altona and Yarraville, see Fig. 14. When the transfer of a batch of Avgas from the Altona tank farm had been completed, the product was allowed to settle for the prescribed period. It was then dewatered and samples were taken for field specification testing at the Yarraville laboratory. From these tanks, Avgas was loaded into tank trucks (known as bridgers), drums or ship for distribution. For a map showing the locations of all the relevant units in the Altona area see Fig. 13.

G.11 Extraction mechanism

The design of the tanks at Altona was such that the process for water draining was less efficient than in the tanks at Yarraville. At Altona, any water that had entered the product would be mixed with the product during the blending process. Ethylene diamine dissolves preferentially in water compared to Avgas, so it is probable that ethylene diamine in the Avgas could have been extracted by the water during the blending process. Water was extracted more efficiently in the Yarraville tanks because of their design. It is probable that if any ethylene diamine had reached the tanks, then it would have dissolved preferentially into water during blending in the tanks at Altona and then have been extracted in water that was drained from tanks at Yarraville.

G.12 Settling, blending and sample taking procedures

Mobil standing order document MRAA-BLEG-0034, titled *Routine Aviation Quality Checks*, detailed the procedures required at Altona and Yarraville tank farms to ensure Avgas quality was maintained. The procedures can be summarised as follows:

Daily	-	The tanks were to be dewatered until dry, clear and bright Avgas was obtained.
Blending	-	The tank was allowed to settle for 45 minutes per metre of product depth before a sample was taken to determine the blending requirements.
	-	After settling and sampling, the tank was to be dewatered until dry, clear Avgas was obtained.
	-	The Avgas was then to be blended and circulated.
Specification sampling	-	Before taking product samples for specification testing, the tank was to be settled for one hour, and was to be dewatered until dry, clear and bright Avgas was obtained.
	-	Required samples were then to be collected and any water found prior to sampling (Altona only) was to be forwarded to the laboratory.
Transfer	-	Prior to transfer, the tank was to be dewatered until dry, clear and bright Avgas was obtained.

There was no requirement to record the process of sample taking. The dewatering procedure involved drawing samples from the bottom of the tank until the sample was dry, clear and bright. When the daily checks had been completed, the operator was required to detail the results on the Daily Quality Checks form in the Aviation Quality Control Diary. Both Altona and Yarraville operators were required to complete the form. The check form indicated that the general appearance of the product should be 'clear and bright', where clear indicated that there was no sediment and bright indicated that the sample was not hazy. The operator was required to use water detecting paste to determine that the sample was dry. The check form also stated that:

> Any water observed must be recorded, even after it has been removed. An estimate is to be made of the volume removed from the tank…Avgas is to be checked with Water Detecting Paste. If water is dark or foul smelling send a sample to the Lab for analysis and inform the [Zone Team Leader] immediately.

Dark or foul smelling water could indicate the presence of microbiological material.

Altona standing order MRAA-BLEG-0034 stated that if 'any water is found prior to [product] sampling [for fuel specification testing], the water must be sampled and sent to the Laboratory with the product samples and the blend sheet…'. The procedure was amended to include collection and subsequent pH testing of all tank water drainings following microbiological contamination of the Altona tanks in March/April 1999 (see section 2.1.9). The Altona laboratory had not received any water for pH testing between the time when the amended procedure was introduced and the end of 1999. There was no requirement to test the pH of water samples taken from tanks 16 and 36 at Yarraville.

Operators at Altona and Yarraville indicated that they rarely saw much water when dewatering Avgas tanks. The Altona daily quality check forms indicated that no water was observed in the tank drainings from either tank 508 or 509 during November 1999. The Yarraville daily quality check forms for November 1999 indicated that water was observed in tank drainings from tank 36 on most days when an entry was recorded in the diary.

It rained in the Altona area between 6 November and 10 November 1999. The amount of rainfall would have deposited approximately 5,000 L on the floating roof of each Avgas tank at Altona. The floating roofs had a water drain that was independent of the tank contents unless there was a mechanical defect. Mobil standing orders required that the floating roofs on the Avgas tanks were drained after it had rained. Records indicate that water was not taken from the Avgas tank drains during this period, despite the tank design allowing ingress of water when it rained. Avgas was transferred from Altona tank farm to Yarraville on 11 November 1999. On 12 November 1999, 1,200 L of water was drained from tank 36 at Yarraville when conducting water drains on the Avgas.

Water could have entered the Avgas during manufacture, in the tank at Altona or in the tank at Yarraville. If water entered the Avgas prior to transfer to Yarraville, then the circumstances would have been consistent with the water draining mechanism being more efficient at Yarraville when compared with the mechanism at Altona. If the water draining mechanisms were less efficient at Altona, then less confidence may be attributed to a statement that the Avgas was dry at Altona.

The design of the Avgas tank dewatering equipment at Altona and Yarraville did not allow an operator to collect volumes of water smaller than approximately 100 mL. The Altona operator indicated that the water drained from the tank prior to taking product samples for specification testing was rarely if ever as much as 100 mL.

Ethylene diamine dissolves preferentially into water rather than Avgas. If there was a small quantity of water in a tank of Avgas, then virtually all of any ethylene diamine that was in the Avgas could be expected to transfer to the water during the blending process. This would concentrate the ethylene diamine into the water. Low concentrations of ethylene diamine have a marked effect on the pH of any water in which it is dissolved (see appendix C).

G.13 Chemical testing and specification testing

Mobil's laboratories at Altona and Yarraville conducted specification testing on all the batches of Avgas that were manufactured at Altona. The Altona lab conducted the full range of specification testing and issued the initial batch release note once the samples had passed the required tests. The Yarraville lab completed further tests on the Avgas before the fuel was released from Yarraville; however, not all the specification tests were repeated again. This process was titled a field certification. The field certification tests included both the copper strip test and the water reaction test. Both of these tests were therefore normally carried out twice on a batch of Avgas before it left the distribution depot.

Appendix H: Variations in Alkylation unit operation prior to detection of contamination

October 1997

Effluent treatment caustic circulation pump G-A3-33 was overhauled

5 August 1999

Both effluent treatment caustic wash circulation pumps G-A3-33 and G-A3-34 were hot water washed in an attempt to improve perfomance. A vibration check was also conducted on G-A3-33, and although it was high, it was considered acceptable to leave the pump running.

14 August 1999

Pump G-A3-33 circuit breaker tripped.

15 August 1999

Pump G-A3-33 circuit breaker tripped.

18 August 1999

A reliability engineer checked the vibration of pump G-A3-33 and determined that the level of vibration had reduced.

19 August 1999

The pH of the caustic wash was noted to be six when the normal range was around 12. A pH of six is not caustic, and there could have been no significant quantity of caustic in the sample. The caustic mix tank was recharged.

26 August 1999

Pump G-A3-33 circuit breaker tripped.

10 September 1999

Caustic circulation flow rate was reduced to 300 m^3/day in an attempt to prevent pump G-A3-33 circuit breaker tripping.

20 September 1999

Effluent treatment caustic circulation pump G-A3-34 was removed from service due to a reduction in output. Pump G-A3-33 began operating as a spare. In accordance with the normal maintenance procedures, pump G-A3-33 was subject to increased monitoring and more frequent vibration checks. Subsequent inspection of pump G-A3-34 established that the reduced output was the result of badly worn impellers. The pump was completely overhauled.

22 September 1999

Deisobutaniser overhead fin fan cooler 17B isolated. A distributed control system (DCS) alarm activated.

23 September 1999

A work request was initiated for calibration of the water wash circulation control valve FC45417. The distributed control system (DCS) display indicated that the valve was open between 30% and 40%; however, the valve was actually open between 75% and 80%.

24 September 1999

Operators noted higher than normal vibration levels in pump G-A3-33. The pump was subsequently washed with hot water in an attempt to improve performance.

25 September 1999

DCS alarm activated.

27 September 1999

The pH of the caustic wash was noted to be seven when the normal range was around 12. Operators suspected that the tank had been diluted. A pH of seven is not caustic, and there could have been no significant quantity of caustic in the sample. The isobutane drier also malfunctioned.

28 September 1999

The acid level in the isobutane drier dropped. The acid level in the reactor was also found to be dropping. An electrically operated valve in the isobutane drier was found to be in bypass mode, but the control screen said that it was in service. The isobutane drier was bypassed.

29 September 1999

The sulfuric acid analyser malfunctioned for a short time.

30 September 1999

A high concentration of ethane was in the feedstock for the alkylation unit. The corrosion control contractor released his monthly report that stated that a work order request had been initiated for replacement of the expired deisobutaniser overhead corrosion probe.

1 October – 30 November 1999

The ratio of isobutane to olefin feed in the alkylation reactor was continuously less than the minimum of 8.5:1, except for one occasion during this period.

1 October 1999

The caustic wash for the feed treatment did not recharge after dumping. The acid level in the isobutane drier was established, but the isobutane outlet valve did not open.

2 October 1999

DCS alarms activated.

3 October 1999

Numerous DCS alarms activated.

5 October 1999

Pump G-A3-33 circuit breaker tripped and the flow rate was halved to 150m^3/day. Pump G-A3-63 was considered as a possible replacement for pump G-A3-33, should this become necessary. The electrically operated valve on the isobutane drier was repaired and the isobutane drier was returned to service. The acid level in the isobutane drier dropped and the drier was bypassed again.

7 October 1999

Neutramine D injection pump G-A4-55 was logged as 'OK now'. (There was no indication of a problem.) The reboiler on the deisobutaniser tower was removed from ACAP control in order to change the conditions within the tower.

8 October 1999

A work request was submitted to check a valve and the acid level controller on the isobutane drier. Operators noted a problem with the braided hose connected from the fresh caustic tank to the caustic wash drum suction point.

9 October 1999

Pump G-A3-33 was transfused with oil.

10 October 1999

Operators noted that effluent treatment caustic injection pump G-A3-87 had a leaking seal. The pump was shut down and the spare effluent treatment caustic injection pump G-A3-88 began operating. Operators also noted that pump G-A3-88's pressure safety valve was opening at a lower than normal pressure.

12 October 1999

Operators removed the pressure safety valve from effluent treatment caustic injection pump G-A3-88 for repair; however, the pump remained running.

13 October 1999

The deisobutaniser effluent preheater was bypassed. The acid analyser line ruptured.

15 October 1999

Pump G-A3-33 was again transfused with oil. The isobutane drier was bypassed and then returned to service. The acid analyser was returned to service.

20 October 1999

The effluent treatment water wash drum in the alkylation unit was removed from service until 21 October for scheduled maintenance.

22 October 1999

Neutramine D injection pump G-A4-55 was found to be leaking. The water wash drum static mixer was cleaned and returned to service. The deisobutaniser preheater was returned to service.

25 October 1999

Neutramine D injection pump G-A4-55 was repaired.

27 October 1999

DCS alarms activated. Instrument technicians worked on the acid analyser. Fin fan cooler 17B returned to standby status.

28 October 1999

DCS alarms activated.

29 October 1999

Pump G-A3-33 was transfused with oil and the circuit breaker tripped. Operators also noted that the effluent treatment caustic wash level controller LC45244 needed tuning. Fin fan cooler 17B operated while fin fan cooler 17D was repaired and returned to standby status.

30 October 1999

Pump G-A3-33 circuit breaker tripped and the thermal overload protection device was replaced.

31 October 1999

The corrosion control contractor released his monthly report that stated that a work order request had been initiated for replacement of the expired deisobutaniser overhead corrosion probe.

1 November 1999

Pump G-A3-33 circuit breaker tripped and an immediate priority work order request was initiated for it to be reset. The Neutramine D injection rate was raised to 6 mL/min.

2 November 1999

Pump G-A3-33 was removed from service after the circuit breaker tripped again when the pump malfunctioned. Following manipulation of appropriate valves, the depropaniser feed treatment caustic wash charge pump G-A3-63 was plumbed into the effluent treatment caustic circulation system. Pump G-A3-63 was a different type of pump to pump G-A3-33 and pump G-A3-34 and its maximum output was substantially lower.

3 November 1999

The deisobutaniser overhead water sample had a pH of 6.9, the Neutramine D injection rate was raised to 7 mL/min. The ACAP system was taken off line for a period for maintenance.

4 November 1999

The electric acid transfer pump was removed. The air driven acid transfer pump was repaired, and could be used, but there was a hole in the braided hose.

5 November 1999

Pump G-A3-34 was returned to service and the caustic flow rate increased to 200m^3/day at maximum pump power. The deisobutaniser overhead pH was 7.5 and the Neutramine D flow rate was raised to 8 mL/min. The spent acid pump was leaking from its flexible hose. Problems were found with the isobutane drier. A temporary procedure was developed for the operation of the isobutane drier.

6 November 1999

The acid analyser failed.

8 November 1999

No water sample was taken from deisobutaniser overhead, despite this being a normal day for testing. The ACAP system was taken off line for a time. The operation of a valve in the isobutane drier was checked.

9 November 1999

The operation of valves in the isobutane drier was checked after suspicion of abnormal operation.

10 November 1999

The Neutramine D injection pump was found to have failed, due to an airlock. The pump was bled and it started to work again. The deisobutaniser overhead pH was 4.8 and the Neutramine D injection rate was subsequently raised to 25 mL/min. Operators noted a leak in caustic circulation flow control valve FC45405. Caustic circulation flow was subsequently established through a bypass valve. Normal caustic circulation flow rates could not be achieved with maximum pump output and the bypass valve fully open. No change was made to the frequency of pH monitoring. The isobutane drier was returned to service, and the alkylation reactor automatic acid level controller LC 45223 was bypassed

11 November 1999

The isobutane drier was considered to be borderline in its effectiveness, and the acid analyser was still under maintenance.

12 November 1999

Very high concentrations of sulfate and sulfite ions were found in the deisobutaniser overhead water and the Neutramine D injection rate was raised to 35 mL/min. The alkylation reactor automatic acid level controller LC 45223 was still bypassed. The isobutane drier was bypassed.

15-24 November 1999

Sulfate concentrations remained very high, and Neutramine D injection rate was maintained at or above 40 mL/min. pH remained close to the limits for most of this period.

19 November 1999

Propane was found in the deisobutaniser overheads. The electric spent acid pump was returned to service. Avgas batch P30L9AL passed the specification tests.

24 November 1999

A leaking coil was found on the acid analyser. The ACAP display indicated that isobutane was being supplied to the alkylation unit through flow control valve FC 45507 even though the valve was blocked off.

24 November – 20 December 1999

Sulfate concentrations remained high, and the Neutramine D injection rate was maintained at around 25 mL/min; pH remained within the limits for most of the period.

25 November 1999

Brown sludge was recovered from the deisobutaniser reflux system. It was considered to have originated from outside the alkylation unit. Avgas batch P313L9AL passed the specification tests.

26 November 1999

Reactor effluent pump G-A2-36 would not start, but tripped immediately. Pump G-A2-35 was brought on line.

27 November 1999

The caustic wash coalescer was found to have a leaking elbow.

30 November 1999

The corrosion control contractor released his monthly report that stated that a work order request had been initiated for replacement of the expired deisobutaniser overhead corrosion probe. Avgas batch P316L9AL passed the specification tests.

1 December 1999

Maintenance was performed on the acid analyser.

8 December 1999

The reactor acid recycle pump G-A2-70 drain was leaking acid.

Acid recycling was operated manually with flow control valve FC 45240, and the pump was changed to G-A2-71.

13 December 1999

The fresh caustic injection pump G-A3-88 stopped working, and pump G-A3-87 was put on line. The automatic flow control valve FCV 45507 that controlled supply of isobutane to the alkylation unit was bypassed to manual operation.

14 December 1999

Reactor effluent pump G-A2-36 was returned to service. The refrigerant analyser was bypassed, as it was giving unreliable readings.

15 December 1999

Maintenance was performed on the acid analyser. The seal on the non-return valve on reactor effluent pump G-A2-35 was plugged. The automatic controller on the steam supply to the preheater for isobutane supply to the deisobutaniser tower was bypassed. The steam supply was controlled manually.

16 December 1999

Reactor effluent pump G-A2-35 was isolated and removed for repair.

18 December 1999

Caustic injection pump G-A3-87 was leaking. The heating of the supply of isobutane to the deisobutaniser tower was manually increased.

20 December 1999

The indication of flow rate through acid recycle flow valve FCV 45240 was considered unreliable. Maintenance was conducted on the deisobutaniser overheads analyser.

21 December 1999

The acid analyser was flushed.

22 December 1999

Pump G-A3-33 was returned to service. It was found to be satisfactory mechanically, but problems continued with the electrics.

24 December 1999

Pump G-A3-33 was fully functional and available for service.

31 January 2000

The corrosion control contractor released his monthly report for December/January, which stated that the expired deisobutaniser overhead corrosion probe had been replaced.