Bureau of Air Safety Investigation

Air Safety Report

INVESTIGATION REPORT
9701421

Bell Helicopter VH-CKP Tartrus Station, Qld

2 May 1997

COMMONWEALTH DEPARTMENT OF
TRANSPORT AND
REGIONAL SERVICES

Department of Transport and Regional Services

Bureau of Air Safety Investigation

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CONTENTS

1. FACTUAL INFORMATION

1.1 History of the flight

About 10 minutes after landing to evacuate the injured occupants of an ultralight aircraft that had been involved in an accident, the pilot returned to the helicopter to collect some first-aid equipment. While at the helicopter, and in preparation for the return flight, he slowly turned on the valve of the medical oxygen cylinder fitted inside the cargo compartment. He later recalled that shortly after opening the valve, he was thrown violently away from the helicopter onto the ground, suffering blast damage to his left lung, internal bruising, and a burst eardrum. The helicopter caught fire and was destroyed.

1.2 Personnel information

The pilot held a commercial helicopter pilot licence and a current medical certificate. He had 2,540 hours total flying experience, with 325 hours on the Bell 206.

1.3 Oxygen system description

The helicopter had been purchased in late 1995 and was subsequently fitted with a range of equipment, including a medical oxygen system for use in the emergency service role.

At the time of the accident, the oxygen system in the helicopter consisted of a ‘D’ size cylinder (1,500 L at 15,000 kPa) mounted in the forward upper corner of the cargo compartment, immediately behind the cabin. A medical regulator was attached to the head of the cylinder. Outlets from the regulator were both high pressure (15,000 kPa) and low pressure (400 kPa). The high-pressure outlet was connected by a 3/8-inch (9.5-mm) inner diameter flexible polyester-lined hose to a pressure gauge attached to a panel in the rear of the passenger cabin. The low-pressure outlet was connected to the oxygen outlets in the cabin by a standard medical oxygen flexible polymer-lined hose. Medical appliances could then be connected to the cabin outlets as required.

1.4 Oxygen system examination

Examination of the helicopter wreckage revealed that a fire had occurred within the oxygen system. This initiated a secondary fire which destroyed the helicopter.

Damaged oxygen system components recovered from the wreckage were examined by Defence Science and Technology Organisation (DSTO) specialists. The design of the oxygen system was also assessed. The specialists concluded that:

1. The oxygen fire was initiated in the high-pressure flexible hose situated between the oxygen system regulator (in the rear baggage compartment) and the pressure gauge (in the helicopter cabin).
2. Although the exact cause of the ignition was not established, particle impact or rapid compression of gas within the flexible hose were likely factors, with particle impact being the more likely.

3. The design of the oxygen system was not consistent with best design practice for high-pressure oxygen systems. In particular, the use of a long polyester-lined non-metal flexible hose, rather than a teflon-lined hose, running to a dead end (the cabin mounted gauge), was inappropriate.
4. The adaptor connecting the flexible hose to the regulator system appeared to be of poor quality. Fissures in the inner surface of the adaptor would have made thorough cleaning of this component difficult. This may have contributed to the ignition within the hose.
5. All other parts of the fixed oxygen system were suitable for use with oxygen and there was no evidence that they contributed to the ignition.

1.5 Regulatory aspects

Civil Aviation Order (CAO) 108.26 described the specifications and requirements for supplemental oxygen and protective breathing equipment for use on Australian registered aircraft. These did not cover systems such as medical oxygen systems. There was no information or guidance published by the Civil Aviation Safety Authority (CASA) for the design and construction of oxygen systems to be fitted or carried on aircraft, other than systems for supplemental oxygen use.

CASA advised that specified role equipment, such as medical oxygen systems, did not form part of the airworthiness requirements for the aircraft. While CASA did not specify requirements for particular equipment, it did require that equipment be fitted in accordance with the relevant engineering order or supplemental type certificate. CASA had no involvement in the process other than the requirement that an authorised person holding approval for design of modification or repair under Civil Aviation Regulation (CAR) 35 approve the installation.

1.6 Oxygen system installation

The oxygen cylinder was installed in accordance with Engineering Order HEO-18, which was purchased from a CAR 35 delegate. The order specified the method of mounting the oxygen cylinder inside the cargo compartment at the rear of the helicopter. The cylinder to be used was a 'D' size medical oxygen cylinder as used in ambulance vehicles. The engineering order contained no other detail concerning the design or plumbing for the system. However, the general notes concerning the system installation stated that the system was to be installed in accordance with the standard procedures of a major industrial gas company. It also stated that all pipes were to be cleaned and degreased prior to final installation.

The licensed aircraft maintenance engineer (LAME) who supervised the installation of the oxygen system advised the aircraft owner that he did not have the expertise to carry out the installation task. The owner then engaged a medical plumbing contractor to design the oxygen system, supply the components, and install them in the helicopter. The contractor designed and installed the system in accordance with accepted commercial practice relating to medical oxygen systems. The system included a copper line linking the regulator high-pressure outlet to the pressure gauge in the cabin. The medical plumbing contractor stipulated that the copper line be replaced at every 100-hourly inspection of the helicopter. This was because the line could develop cracking due to fatigue, as a result of either bending during cylinder removal/replacement, or movement during service. To overcome this difficulty, the helicopter maintenance organisation asked the medical plumbing contractor to provide a flexible hose that could remain in the helicopter as a permanent fixture. The contractor then ordered an oxygen-compatible high-pressure hose. The policy of the company that supplied the hose was to refer any aviation related order to a section of the company which had the necessary expertise to ensure that appropriate materials and practices were used in the construction of the hose. In this instance, however, the order did not indicate that the hose was to be used in an aircraft oxygen system. In the meantime, the helicopter was flown to Rockhampton where it remained until the accident flight.

The helicopter underwent a 100-hourly inspection in June 1996. A flexible hose was delivered for fitting at this time but it was too short and the fittings were incompatible with the existing system. The copper line was inspected and retained in the helicopter. At the next 100-hourly inspection in December 1996, no flexible hose was available. The copper line was again inspected and retained. A flexible hose was subsequently installed on 24 March 1997. The flexible hose supplied was an industrial brand thermoplastic hose of 3/8 inch (9.5 mm) inner diameter, consisting of two steel braid sheaths, polyester liners and cover. Its rated temperature range was -40°C to +121°C, and its working pressure was 34.5 MPa (5,000 lb/in^2). The hose manufacturer listed it as compatible with oxygen.

The oxygen system was not cleaned at this time, nor had it been cleaned previously. No other maintenance was conducted on the system up to the time of the accident, other than routine cylinder replacement.

At the time of the accident, the major industrial gas company referred to in the notes to the engineering order no longer existed, having been taken over by another company. As far as could be determined, that company had instructions available on the hazards associated with, and the handling of, various industrial gases, but did not publish any information concerning the design of gas systems.

1.7 Overseas practices

The US Federal Aviation Administration (FAA) has regulations and advisory circulars (ACs) relating to supplemental breathing systems for crews, as well as additional information specifically covering medical oxygen systems for aeroplanes and helicopters. The underlying philosophy is that all such equipment is considered to be part of the aircraft and is subject to the same design parameters and airworthiness considerations. Of particular interest to this occurrence are AC 43.13-2A Chapter 6—Oxygen System Installations in Non-Pressurised Aircraft, and AC 135-14A—Emergency Medical Services (Helicopter).

A US manufacturer of oxygen systems listed its criteria for medical oxygen systems as:

1. Oxygen bottles are no longer removable for filling. A fill bottle or cart is taken to the aircraft. This lowers the possibility of leaks developing due to repeated loosening and tightening of the regulator assembly.
2. No high-pressure oxygen is ever routed to the passenger compartment. Transducers are utilised for oxygen quantity monitoring with digital quantity gauges in the medical area.
3. Soft or flexible oxygen lines are no longer used. Hard metal lines should be used throughout the aircraft on permanently installed items.
4. Blowout pressure protection is provided at the fill port to protect against over-charging.
5. Separate analogue gauges are provided on each bottle for filling purposes.
6. A mechanical, positive, shut-off cable is located in the cabin area to provide positive shut-off at the bottle in the event of an oxygen fire.

7. A fill port flow limiter is installed in-line with the oxygen bottles to prevent heat build-up from filling too fast'.

The manufacturer added: 'All of these features add to the cost of medical systems but oxygen is a very dangerous gas to deal with in a closed environment like a helicopter and we feel every precaution should be taken'.

Internationally accepted authorities have promulgated design standards for oxygen systems. One group, the American Society for Testing and Materials, has published standards relevant to aspects of oxygen system design. They are G88—Standard guide for Designing Systems for Oxygen Service, G63—Standard guide for Evaluating Nonmetallic Materials for Oxygen Service, G94—Standard guide for Evaluating Metals for Oxygen Service, and G93—Standard Practice for Cleaning Methods for Material and Equipment used in Oxygen-Enriched Environments.

1.8 Local aviation industry knowledge and practice

Discussions with operators of emergency medical service aircraft indicated limited knowledge of the hazards associated with oxygen systems. While most were aware of the dangers posed by oil and/or grease and of the necessity to open valves on oxygen cylinders slowly, there was little other knowledge. Only a few of these operators had in place written instructions concerning system operation, maintenance, or cylinder changing procedures.

Some local emergency service helicopters had medical oxygen systems installed in accordance with a supplemental type certificate issued in the USA. These systems were apparently fitted in the USA before the helicopters were brought to Australia, and their design and construction appeared to accord with best industry practice. For example, hard metal tubing was used throughout, cylinders were not removable but were refilled 'in situ', and an emergency shut-off valve was positioned in the cabin. Systems fitted to other local aircraft had deficiencies similar to those identified in CKP.

2. ANALYSIS

The investigation revealed significant deficiencies in the control, design, construction, installation and maintenance of medical oxygen systems for use in aircraft. The lack of specifications and requirements at the regulatory level resulted in the CAR 35 delegate and the helicopter owner deferring to non-aviation industrial sources for guidance and expertise. As a result, the design and construction of the oxygen system in CKP did not meet international aviation industry best standards in a number of areas. The absence of specific regulatory control for these systems within Australia may also have contributed to a culture within the industry which did not place an appropriate level of importance to design standards for, and hazards associated with, these systems. There was appropriate information available from overseas sources on medical oxygen systems in aircraft. However, the level of awareness of this information within the local aviation industry was low.

A detailed analysis of the oxygen system components and initiation of the fire is contained in Defence Science and Technology Organisation (DSTO) report DSTO-DDP-0203 (see appendix).

3. SIGNIFICANT FACTORS

1. There were no regulatory controls or guidelines concerning medical oxygen systems for use in Australian registered aircraft.
2. The level of knowledge within the Australian aviation industry of medical oxygen system design standards, operation and hazards was low.
3. The design of the oxygen system was inadequate, and inappropriate components were used.
4. The oxygen system had not been adequately cleaned.

4. SAFETY ACTION

As a result of the investigation into this occurrence, the Bureau of Air Safety Investigation issued the following interim recommendation:

IR970104

The Bureau of Air Safety Investigation recommends that the Civil Aviation Safety Authority:

(i) conduct an audit of all emergency medical service oxygen-equipped aircraft to determine the equipment standards in Australian registered aircraft;

(ii) issue design standards for emergency medical service oxygen equipment installations;

(iii) issue maintenance requirements for emergency medical service oxygen equipment;

(iv) provide surveillance requirements for emergency medical service oxygen equipment in the Aviation Safety Surveillance Program;

(v) ensure flight crew are provided with appropriate instructions in the use of emergency medical service oxygen equipment in aircraft flight manuals or company operations manuals; and

(vi) provide educational material to the aviation industry on the installation, operation and maintenance requirements of emergency medical service oxygen systems.'

The following response was received from the Director, Civil Aviation Safety Authority on 6 August 1998:

I refer to BASI Interim Recommendation, IR970104, in relation to the Bell helicopter accident at Tartrus Station, Queensland on 2 May 1997. This incident has clearly revealed some deficiencies in current CASA procedures regarding medical oxygen systems used in aircraft. These deficiencies require correction.

Issue design and maintenance standards for EMS 02 equipment installations (Recommendations ii and iii)

Role equipment such as that installed in EMS aircraft is installed on the basis of 'No Hazard, No Interference.' There are at present two Australian standards which relate to aircraft oxygen systems:

CAO 20.4, Provision and Use of Oxygen and Protective Breathing Equipment,

CAO 108.26, Systems Specifications - Oxygen Systems

Neither of these standards are directly applicable to EMS 02 systems, addressing instead supplemental oxygen for high altitude flight. However, Federal Aviation Administration AC 27-1, Certification of Normal Category Rotorcraft contains a section on EMS02systems. Unfortunately, this US AC has no legal standing under Australian law.

Thus, while much information is available, it is not clearly presented, is fragmented, and in some cases is out of date. I therefore intend to expedite the issue of a CAAP providing integrated design guidelines for this type of installation. This CAAP, expected to be issued by September 1998, will cover the design, installation and maintenance of Emergency Medical Services Oxygen Systems.

Provide surveillance requirements for EMS 02 equipment in ASSP. (Recommendation iv)

The ASSP program does not at present specifically address surveillance of aircraft internal role equipment, such as medical oxygen systems. This deficiency will be addressed, and the ASSP amended as necessary to include this type of equipment.

Conduct an audit of all emergency medical service 02 equipped aircraft to determine the equipment standards in Australian registered aircraft. (Recommendation i)

Because there is at present no readily available standard against which to audit existing EMS 02 installations, and because very few CASA (or industry) people have the knowledge or experience of oxygen systems necessary to conduct such an audit, I do not believe that an audit is appropriate at this stage.

Issue of the CAAP and clarification of ASSP requirements are expected to have a beneficial effect, resulting in improvements and upgrading of existing systems. However, should routine surveillance reveal widespread problems or raise further concerns, additional action will be taken to overcome the problems.

Provide educational material to the aviation industry on the installation, operation and maintenance of EMS 02 systems. (Recommendation vi)

CASA is planning to conduct an educational seminar in the latter part of this year involving CASA staff and industry personal, including designers, operators and other interested parties. Your assistance in conducting this seminar would be much appreciated, including a presentation on this incident and the BASI finding. The CAAP will also assist in this regard.

Ensure that flight crew are provided with appropriate instructions in the use of EMS 02 equipment in Aircraft Flight Manuals or Company Operations Manuals. (Recommendation v)

EMS systems are normally installed in aircraft as modifications, under the auspices of CAR 35. An important part of any such modification is the provision of the necessary amendments or supplement to the aircraft flight manual. The CAR 35 authorised person who approves the modification should be ensure that such data are available and included in the modification package. This requirement will be reinforced in the CAAP.

Response classification: CLOSED - ACCEPTED

[Appendix]

DEPARTMENT OF DEFENCE

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

EXAMINATION OF OXYGEN SYSTEM COMPONENTS

from Bell 206-L3
VH-CKP

DSTO-DDP-0203

S. A. Barter

Contents

Executive summary

On 2 May 1997, during a medivac operation by a Sunshine Coast Helicopter Rescue (Bell 206-L3 VH-CKP) at Tartrus station (approx. 100 km NE Rockhampton Qld), the helicopter 'exploded and caught fire'. This event took place with the aircraft on the ground and occurred just after the onboard oxygen supply had been turned on at the cylinder regulator.

An examination of the wreckage and discussions with witnesses by the Bureau of Air Safety Investigation (BASI) implied that the fire initiated in a flexible oxygen hose which connected a cabin-mounted pressure gauge to the regulator fitted to an oxygen cylinder which was located in the rear baggage compartment. As the fire appeared to have started in the oxygen system, and Aeronautical and Maritime Research Laboratory (AMRL) has experience of investigations into oxygen fires in aircraft, BASI requested AMRL to examine and comment on the probable cause of the fire and the design of the oxygen system used in this aircraft.

As a result of this examination, several conclusions were reached about the fire:

1. The oxygen fire initiated in the high-pressure flexible oxygen hose situated between the fixed oxygen system regulator (in the rear baggage compartment) and the pressure gauge (in the helicopter cabin).
2. Although the exact cause of the ignition remains unknown, it is postulated that particle impact or near-adiabatic compression are likely factors, with the particle impact being the most likely in this case.
3. The design of the oxygen system (in particular the use of a long polymer-lined flexible hose running to a dead end—the cabin-mounted gauge) and the selection of a polyester lined hose, rather than the more usual selection of a polytetrafluorethylene (PTFE)-lined hose, were not consistent with best high-pressure oxygen system design practice.
4. The male-to-male adaptor used to connect the flexible hose to the regulator of the fixed system appeared to be of poor quality, and this may have contributed to the ignition of the hose. The fissures in the inner surface of the adaptor would have made thorough cleaning of this part difficult.
5. All other parts of the fixed oxygen system appeared to be suitably oxygen-compatible and there was no evidence that they contributed to the ignition.

From the above conclusions and base on the considerable AMRL experience with oxygen systems and fires in these systems, the following main recommendations (others are listed at the end of this report) are proposed for inclusion in the relevant regulations/advice:

1. High-pressure oxygen systems for aircraft use should be designed such that polymeric materials are kept to a minimum and, in particular, only oxygen-compatible PTFE-lined flexible hoses should be specified.
2. Where polymer flexible hoses are used in high-pressure oxygen applications, they should be kept to a minimum length and volume and fitted with distance pieces (tubing), (which are at least 150 mm long (copper) or 250 mm long (stainless steel) with the same internal diameter (ID) as the hose), at the downstream end before any restriction such as a valve, sharp bend, dead end, or reduction in ID.
3. Reference in regulations/advice to design and construction of aircraft oxygen systems should be made to an appropriate standard such as one or several of those set out at the end of this report.

Introduction

On 2 May 1997, during a medivac operation at Tartrus station (approx. 100 km NE Rockhampton, Qld) a Capricorn Rescue Bell 206-L3 helicopter, VH-CKP 'exploded and caught fire'. The resultant fire destroyed the helicopter (fig. 1). This event took place with the aircraft on the ground. The pilot indicated that the initial 'explosion' occurred just after the onboard oxygen system had been turned on at the cylinder valve. The area from which the explosion appeared to occur was in the region of a flexible high-pressure oxygen hose which runs to the oxygen contents gauge in the cockpit of the aircraft. Another oxygen system (portable) was also situated in the rear compartment near the fixed system. These main components are shown in the wreckage in fig. 2.

Figure 1: The wreckage of VH-CKP.

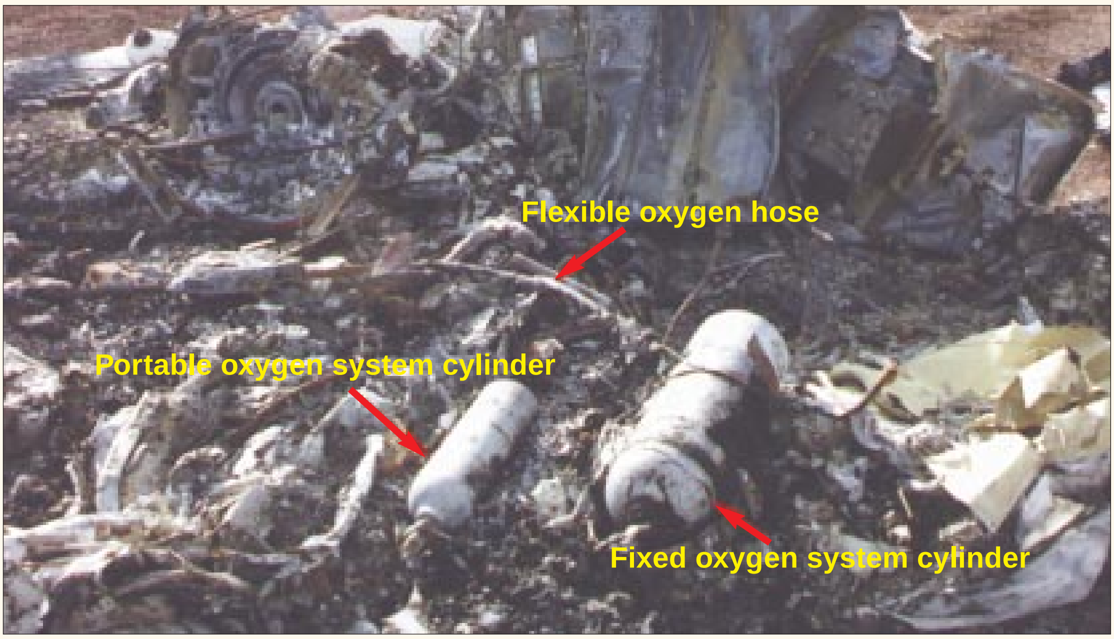

Figure 2: The two oxygen system cylinders and the remains of the flexible oxygen hose.

An examination of the wreckage by the Bureau of Air Safety Investigation (BASI) found evidence of a very high temperature fire in the flexible oxygen hose, and led, combined with the witness evidence, to the initial conclusion that the fire had initiated in the oxygen system. As the oxygen system was implicated, and AMRL has previously had considerable experience in the investigation of oxygen fires and incidents in aircraft oxygen systems [1], BASI requested that AMRL examine the system with a view to identifying the factors contributing to the fire, and to comment on the design of this oxygen system with regards to its safety.

To aid in this investigation, the remains of the fixed and portable oxygen systems were supplied along with two aircraft Federal Aviation Administration Advisory Circulars AC 26-1-C3 and AC 43.13-2A, chapter 6 (revised 1977), which refer to the design of civil aircraft oxygen systems.

1. EXAMINATION

1.1 General

The fixed oxygen system cylinder and regulator were fitted in the rear baggage compartment as shown in fig. 3. This system, as far as could be ascertained, consisted of a single high-pressure (2,700 lb/in^2) aluminium alloy cylinder fitted with a Comweld Group Medical Products Series-O regulator directly into the cylinder valve. Fitted to this regulator were an exit fitting and a pressure relief valve (both on the low-pressure side of the regulator) and a flexible hose (at cylinder pressure). The flexible hose was attached by three in-line fittings. From the regulator to the hose: a brass 1/4-in BSP male to 3/8-in BSP female adaptor (gauge port outlet fitting), a 3/8-in BSP male-to-male adaptor and a fabricated stainless steel 90° elbow (the exit end of the elbow fitting comprised part of the end of the flexible hose). The fittings had internal diameters of about 7.8 mm, 11.1 mm and 7.1 mm respectively. The flexible hose led from the regulator to a cabin mounted cylinder-pressure gauge. This hose was reported to have been about 1.5 m long. A schematic of the regulator, showing cross-sections taken at 90˚ is shown, along with the attached fittings, in fig. 4. It will be noted from this diagram that the body of the regulator and the inlet fitting (bull-nose connector) are manufactured from a 'free machining' brass (either UNS37700 or UNS38500) with a lead content of between 1.5% and 3.8% (depending on the alloy).

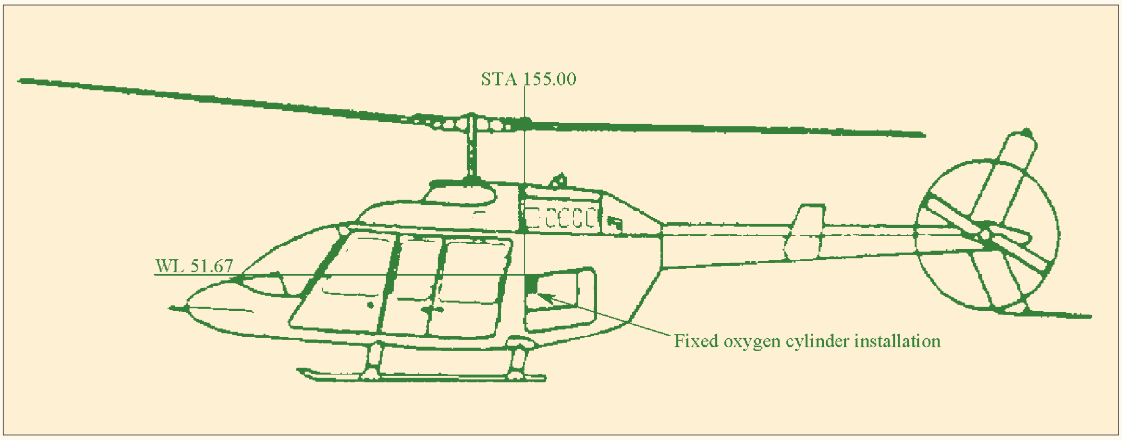

Figure 3: Schematic of the fixed oxygen cylinder position in the helicopter.

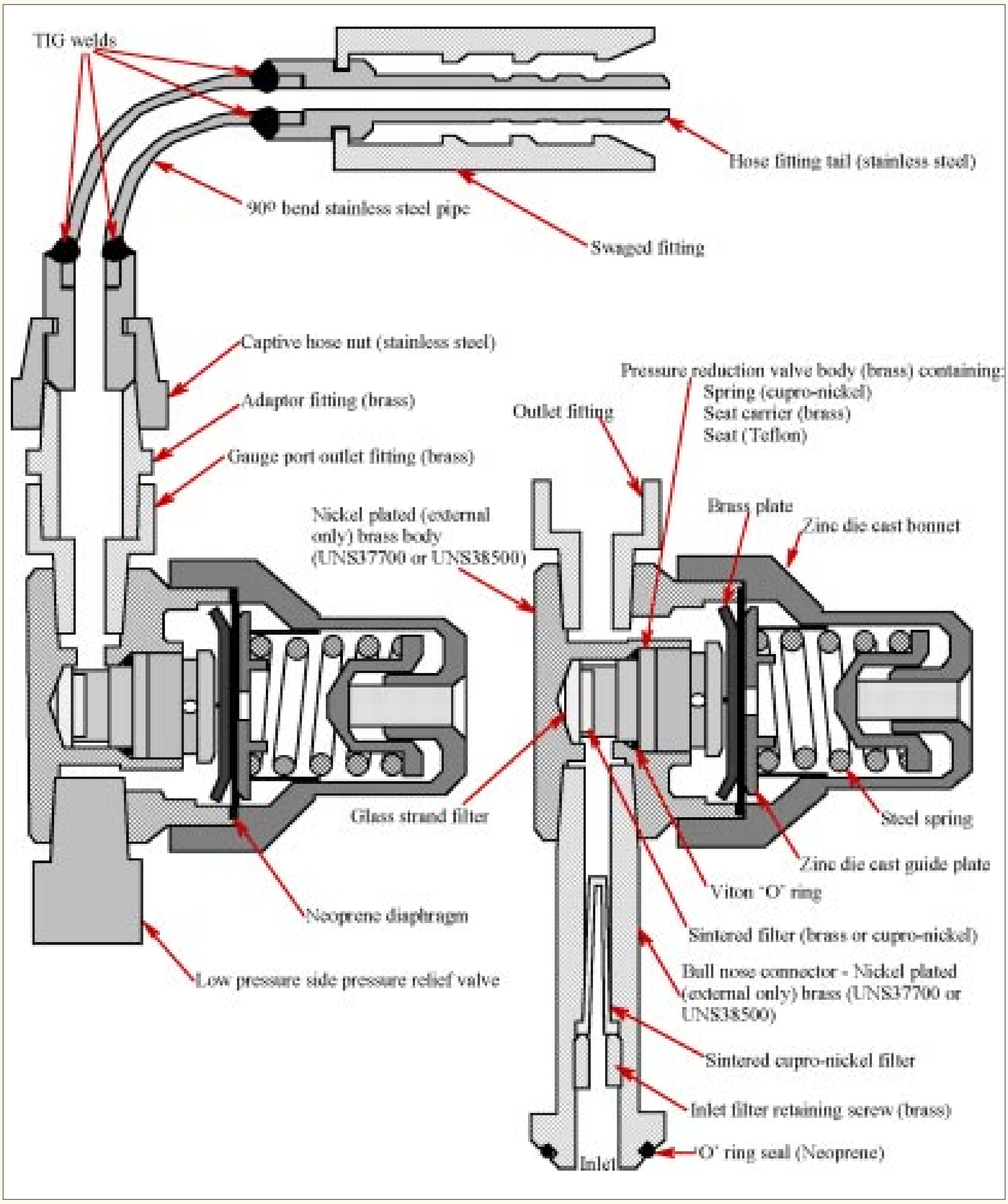

Figure 4: A schematic diagram of the fixed oxygen system regulator and the attached fittings. Note that the threads are not represented, and that the details of the relief valve and the pressure reduction valve are not shown. These two views are orientated 90° to one another.

A portable oxygen system was also situated in the rear baggage compartment at the time of the fire. This system consisted of a smaller aluminium alloy cylinder, an attached valve (marked O2, VM 16, 8 88), and a yoke-style oxygen regulator (integral with gauge). As found, the gauge had been broken from the yoke, and the cylinder valve showed signs of metal combustion due to oxygen impingement. Figure 2 shows the portable cylinder and valve as found in the wreckage.

1.2 Oxygen cylinders

Although two oxygen cylinders were in the aircraft, only one was connected to the fixed onboard system. This cylinder was manufactured from an aluminium alloy.

Examination of the cylinder after the accident revealed that it was more or less intact. No melting or distortion had occurred, although most of the paint had been burnt away. For typical wrought aluminium, alloy melting will occur at about 650°C. An internal examination did not reveal any evidence of contamination.

The smaller portable oxygen cylinder was also found to be intact, although the cylinder valve seal had been burnt away so that the cylinder was open to the atmosphere. Again, most of the external paint had been burnt and there was no evidence of melting. An internal inspection of the cylinder revealed an oily carbonaceous coating along with numerous droplets of water.

1.3 Cylinder valves

1.3.1 Fixed system valve

A chromium plated (outer surface only) copper alloy bodied (probably brass) 'CIG CV372' type valve was fitted to the fixed oxygen cylinder. Although this type of valve can be supplied with an integral pressure relief valve, it was not so fitted. Sealing the valve was accomplished by screwing a flat polymeric seal onto a raised land, which made up part of the valve body. The seal is normally contained in a nickel copper alloy carrier, flush with its lower face. The carrier has an external thread with a 1.4-mm thread pitch, which mates with a thread in the body of the valve. As found, the seal carrier lower surface was about 0.73 mm off the land, indicating that the seal was about half a turn off its seat.

The seal had been consumed by fire and a great deal of carbonaceous material, typical of the debris of polymer combustion in a fuel-rich and oxygen-depleted atmosphere, covered the internal surfaces of the valve body adjacent to where the seal had been. Although the carbonaceous material was distributed in both the inlet and exit ports, little or no evidence could be found in these deposits that would indicate significant gas flow (i.e. consistent with the flow rates expected for a cylinder venting its pressurised gas).

1.3.2 Portable system valve

The body of the valve was made from a copper alloy (probably a brass), plated with chromium. The valve seal carrier, when viewed through the outlet hole, appeared to be fully closed. As found, the regulator had been broken from its attachment point on the valve.

The control wheel end of the valve showed evidence of having been burnt in a stream of oxygen (figs. 5 & 6). Marks on the surface between the regulator attachment and the burnt areas indicated that gas had been flowing from the base of the regulator attachment and impinging on the burnt area (fig. 6). Figure 5, which shows the cylinder and valve in the wreckage of the helicopter, also shows a pair of what appear to be forceps (identified later as a needle holder) which had been burnt by impinging oxygen (probably an austenitic stainless steel, which would begin to melt at about 1,400°C and burn in oxygen at in excess of 2,000°C [2]). These needle holders were adjacent to the area where the gas had been venting from the cylinder valve. The combustion products from the needle holders appear to have been impinging on the burnt area of the valve, which had led to the burning of the brass of the valve body [3]. As the position of the needle holder relative to the cylinder valve was correct for the apparent damage observed, it would appear that the damage to the needle holder and the end of the cylinder valve occurred after the helicopter had been substantially damaged. In other words little displacement from the as-found position of these items could have occurred—a relative position unlikely to have survived the main destruction of the helicopter had the oxygen fire damage occurred prior to this destruction.

Figure 5: The end of the portable oxygen cylinder and the valve. Note that the regulator is missing, and that a high-temperature fire has damaged the end of the valve.

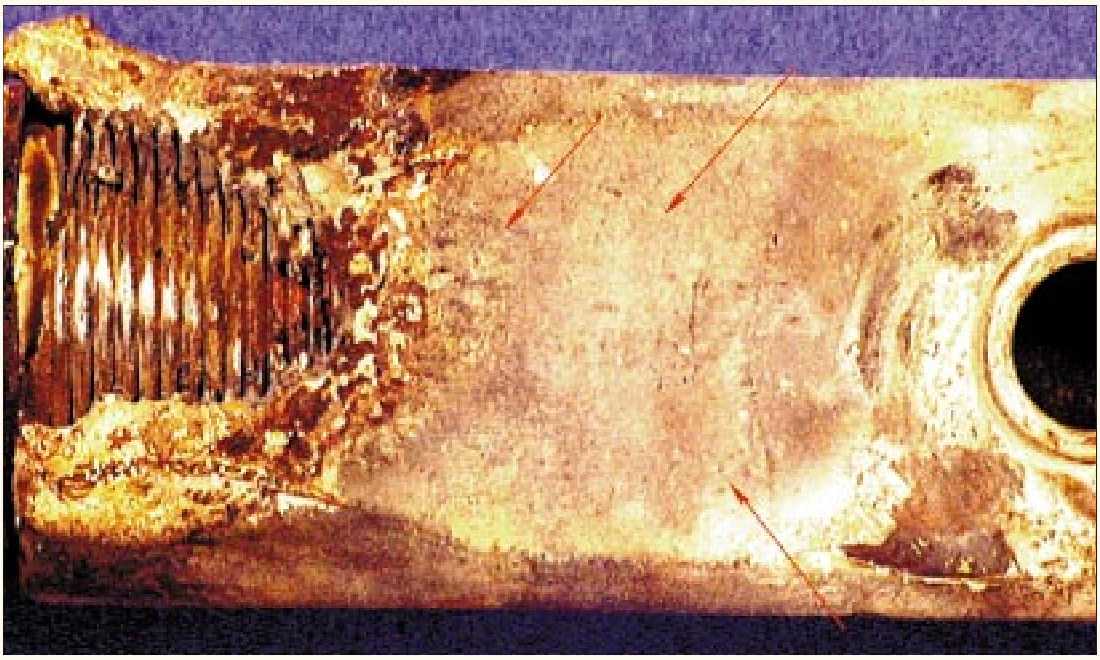

Figure 6: The faint indications of the gas flow as shown (some arrowed) on the portable oxygen system cylinder valve surface.

Dismantling the valve revealed that the seal material had been consumed during the fire. The seat area was considerably cleaner than the similar area of the fixed system valve seal, the seal probably having ignited after heating from the aircraft fire.

1.4 Regulators

1.4.1 Fixed system regulator

The regulator was found still attached to the cylinder valve, as shown in fig. 7. The bonnet (containing regulating pressure control spring) had melted (probably between 380°C and 420°C, the melting range for common zinc die cast alloys). All polymeric parts had burnt. A schematic of the regulator construction is shown in fig. 4.

Figure 7: The fixed oxygen system cylinder and regulator as found in the wreckage of the helicopter. Note the elbow and the end fitting of the flexible line are still attached to the regulator.

Internal examination of the regulator revealed that the glass-fibre filter and the Viton O-ring in the high-pressure cavity of the regulator were burnt, although some polymeric material (green/white) and carbonaceous material remained. The source of the polymer is unknown, although it was found to be intimately associated with the remains of the glass-fibre filter. The surfaces of the brass valve body in the high pressure chamber, inlet and gauge port were all coated with a dark crystalline material. There was little evidence of high-speed gas flow having disturbed this debris, indicating that the combustion of the polymer materials probably occurred after the cylinder had fully vented. Also coated with a dark crystalline material were the internal surfaces of the high-pressure chamber, inlet and outlet ports, the sintered cupro-nickel inlet filter and the fittings which lead to the flexible hose. The coating in each of these parts was analysed using energy dispersive x-ray analysis* (EDX). This analysis found relatively high levels of lead and chlorine in contrast to the low levels of lead found in the brass beneath these parts. These results are set out in table 1 and an example of spectra from the coating material and the underlying alloy, for one part, are shown in fig. 8. Several sections of this material were analysed, by both chemical spot analysis and EDX, which indicated that they consistently contained high levels of lead.

* EDX only gives an indication of the elements present and their approximate proportional amounts. It does not indicate if the elements are bound to each other in the form of compounds, although the information supplied from this type of analysis along with other observations and the experience of the investigator may lead to a reasonably accurate understanding of the compounds which are present.

Table 1: Results of a number of EDX analyses on the regulator fittings

Part	UNDERLYING MATERIAL		COATING	
	Main elements	**Minor elements**	**Main elements**	**Minor elements**
Bull nose connector	Cu, Zn,	Pb, Sn, Mn	Pb, Cl. Cu, Zn	–
Bull nose filter	–	–	Cu, Ni, Zn, Cl	Mn, Sn, Pb
Bull nose filter retaining screw	Cu, Zn	Pb, Sn, Ni	Zn, Pb, Cu, Cl	–
Gauge port adaptor	–	–	Zn, Pb, Cu, Cl	Al, Mn, Ni
Male-to-male gauge adaptor	Cu, Zn	Pb	Zn, Pb, Cu, Cl	–

Note that these analyses did not test for Fluorine

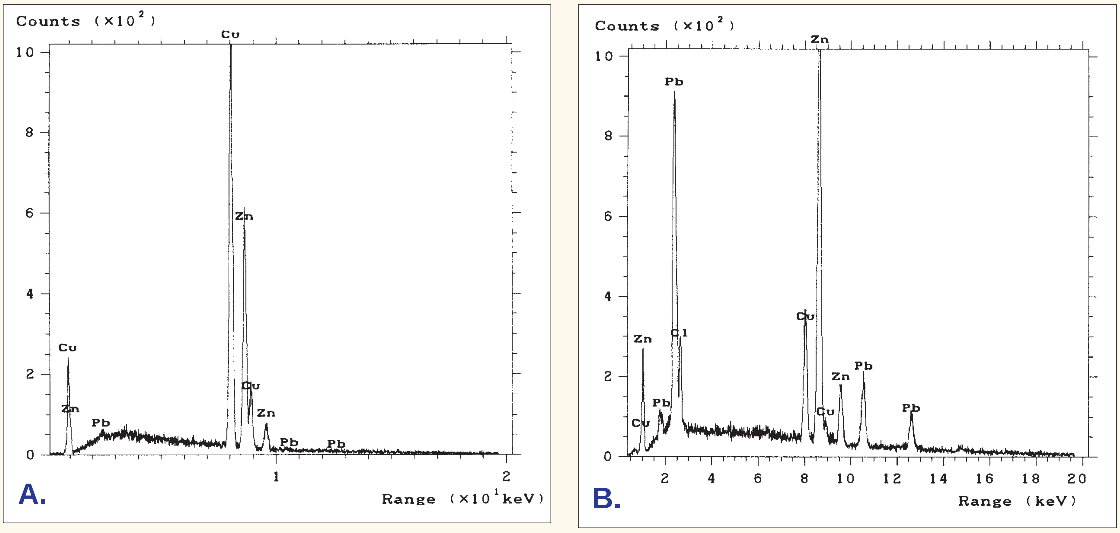

Figure 8: Two spectra taken from the fittings attached to the regulator. Spectrum A is of the alloy of the bull-nose connector which would appear to be a leaded brass and spectrum B the dark crystalline material coating the inner surface of this part.

Inspection of the two brass fittings that connected the flexible hose to the regulator showed that, apart from the deposits noted above, the internal surface of the male-to-male adaptor had large fissures in it. Examination of these fissures and the microstructure of the fitting indicated that they had probably formed during a hot forming operation (hot-tears). The fitting appeared to have been produced by extrusion and/or near-net-shape forging, followed by machining. The fissures contained considerable amounts of relatively loose oxidised material, along with some evidence of corrosion product (figs. 9 & 10). This oxide was observed down to the internal tips of the fissures. In comparison, the external surface of the fitting was relatively un-oxidised.

Figure 9: Some of the large fissures in the inner surface of the male-to-male adaptor.

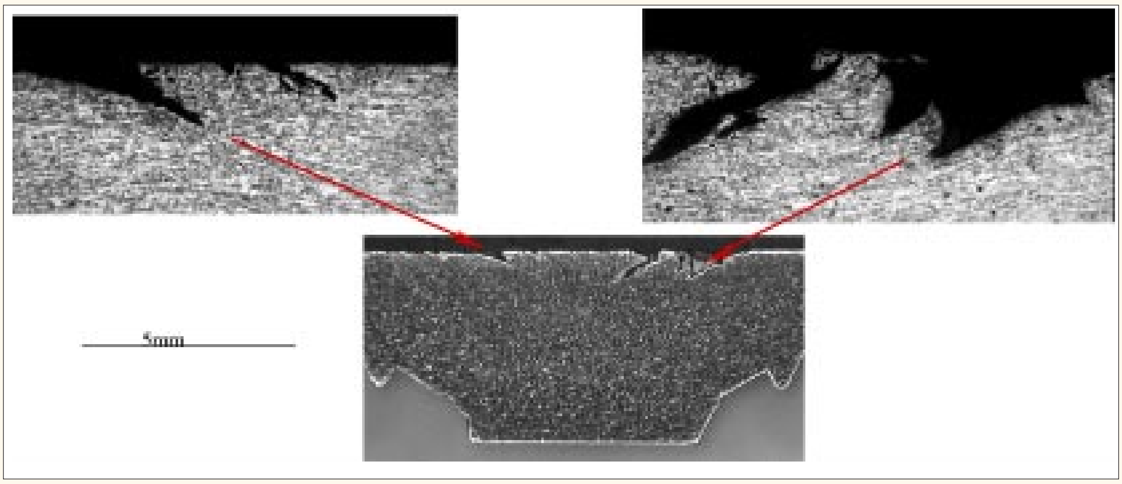

Figure 10: A cross-section through the male-to-male adaptor showing some of the large fissures in the inner surface.

1.4.2 Portable system regulator

The valve fitted to the portable oxygen cylinder was fitted with a ‘yoke’ style regulator which had been broken off at its attachment (this failure was typical of application of a single high load). This regulator did not have any damage consistent with an oxygen fire, although its internal polymeric materials had been consumed in the aircraft fire.

1.5 Flexible hose and fittings

1.5.1 Hose construction

The flexible hose was manufactured by ENZED and was designated by the manufacturer as being oxygen compatible. The hose consisted of stainless steel end fittings connected to a hose constructed of a thermoplastic inner liner covered by two layers of wire braiding, with an inner layer of a polymer material, and an outer protective cover of a polymeric material. Analysis of the inner liner material from a hose supplied by the manufacturer reported (by Scientific–Forensic & Technical Services Branch, Queensland Police) to be similar to the hose from the accident aircraft, indicated that it was made from a Polyester (Polyethylene terephthalate). The braiding was analysed by EDX and found to have an elemental content indicative of a carbon steel. A coating appeared to have been applied to the steel braiding thought to have been an electroplated bronze.

The ends of the hose were fitted with swaged-on stainless steel fittings. Swaging had been carried out with an eight-jaw, parallel sided chuck. The ferrules appeared to be zinc plated steel.

1.5.2 Hose condition as received for examination

The hose, as received, had been extensively burnt in the fire. All traces of the original polymer parts were missing. A large section of the hose could not be found in the wreckage, although some of the wire braiding was found in the overalls and neck of the person who had just (at the time of the reported explosion) turned on the oxygen cylinder. Of the 1.5-m hose length (estimated), approximately 850 mm was recovered (figs. 11 & 12). The recovered section ran from the gauge end of the hose and ended in a failure that showed clear evidence of melting and some combustion of the wire braiding. (The melting temperature of steel is approximately 1,500°C.) The regulator end of the hose, still attached to the regulator, consisted only of the swaged fitting and bend and a small amount of the braiding encased within the swaged ferrule. The area where the hose had exited the ferrule, exposing the 'hose tail', showed indications of melting and burning of the ends of the 'hose tail' (melting point for stainless steel is about 1,400°C), the braiding and the end of the ferrule (fig. 13). All of this damage was consistent with an oxygen fire having occurred within this hose.

Figure 11: The hose as found in the wreckage of the aircraft. Note that one of the oxygen cylinders is just visible at the bottom of the view. The gauge end of the hose is to the left in this view.

Figure 12: The end of the hose, which had damage consistent with a high-temperature fire (greater than 1,500°C). Note the secondary hole along with the melting steel braid.

Figure 13: Two views of the end of the hose fitting at the regulator end of the hose. Melting and burning of the hose tail, braiding, and the end of the ferrule can be seen.

One of the pieces of wire found in the neck of the person who had just turned on the oxygen system was examined. An end of this wire shown in fig. 14 appeared to be melted. The wire was found, when compared to a similar hose from the same manufacture, to be typical of the type of wire used to make the flexible oxygen hose braiding: this included the light-gold appearance of the surface of the wire.

Figure 14: The end of a piece of wire found in the neck of the person who had just turned on the fixed oxygen system at the time of the ignition. This end of the wire appears to show evidence of slight melting. The wire was found to be typical of the type of wire used to make the flexible oxygen hose braiding.

Sectioning the end fittings revealed that the 'hose tails' had been partially crushed as a result of the swaging process. At the regulator end of the hose, this crushing had resulted in the 7.1 mm ID 'hose tail' being reduced in ID to about 4 mm, in a smooth venturi-like manner (fig. 15). Discussions with the manufacturer indicated that this was not unexpected, the level of crush being an indicator of the effectiveness of the swaging process. Measurements of the final swaged diameter of the ferrules (20.5 mm for the regulator end and 20.8 mm for the gauge end) indicated that they were within the manufacturer's limits for the type of swaging machine used. An examination of an end fitting from the hose supplied for comparison purposes found that this hose tail was not notably crushed, although in this case the ferrule had been swaged on with a six-jaw chuck.

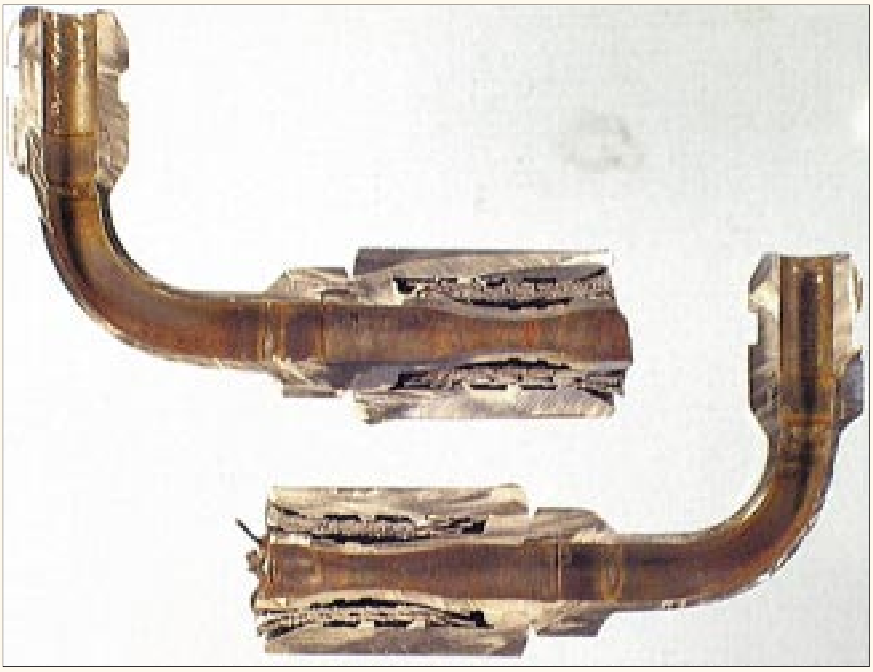

Figure 15: A section through the regulator end of the hose tail showing the reduction in the internal diameter caused by crushing the 'hose tail' during the swaging operation.

The internal surfaces of the hose end fitting, regulator end, and the elbow were coated with a thick layer of oxide. This oxide was considerably thicker on the inner surfaces of the welds that connected the elbow to its fittings. The thickness of the coating in these areas strongly suggested that they were oxidised prior to the fire as a result of a lack of gas shielding during the welding operation. Several chips (fig. 16) of the oxide from the welded regions had become dislodged, entering the gas stream. It is not known if these chips became dislodged before, during or after the fire.

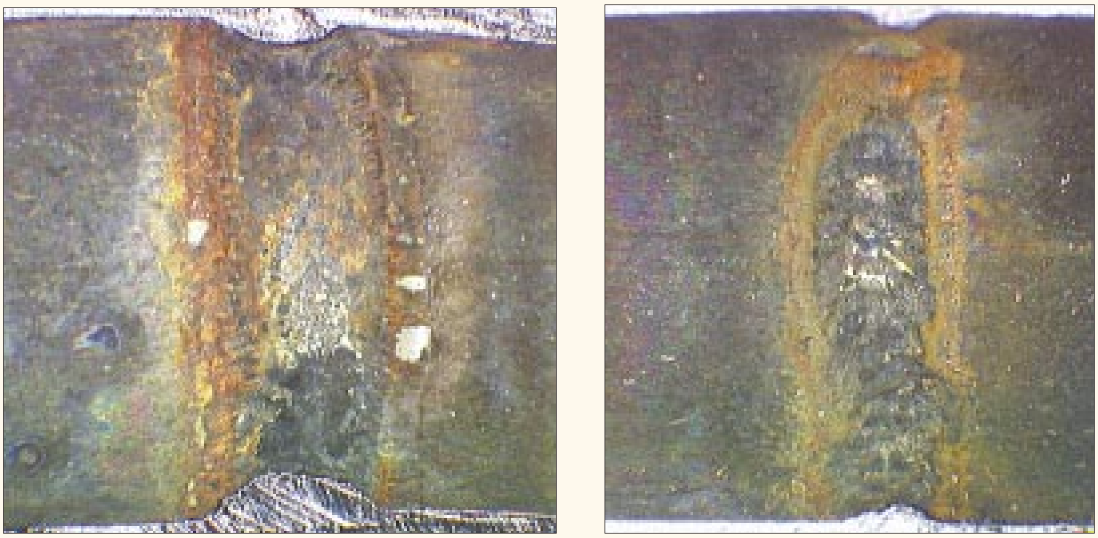

Figure 16: The inner weld surfaces of the elbow showing the thick oxide build-up in these regions. Note that several small regions of the oxide have become detached (cleaner areas).

The fitting at the gauge end of the hose was also examined. No evidence of melting or burning of any of the metals in this region of the hose could be found. The remains of the gauge were still attached to this fitting by a brass elbow. The bouillon tube, which was soldered in place, had become detached due to melting of the solder (temperature unknown, although it would be considerably lower than the melting point for the attached brass (about 900°C)). No damage consistent with an oxygen fire could be found.

Sectioning the gauge end of the hose in a similar manner to the sectioning of the regulator end revealed that the 'hose tail' had also been partially crushed, as a result of the swaging process, to a restricted internal diameter of about 4 mm from the normal 7.1 mm. The inner surface of the fitting was also covered with a thick oxide layer as with the regulator end fitting.

2. DISCUSSION

2.1 Fire in oxygen systems

Although both liquid and gaseous oxygen are themselves non-flammable, they will support the combustion of most materials if sufficient heat is present for an ignition to take place. The reactivity of oxygen increases with increases in pressure. At very high pressures it becomes extremely reactive. The successful design, development and operation of a high-pressure oxygen system requires special knowledge of materials, design practices, testing, manufacturing and operational techniques.

Fires involving excess levels of oxygen such as may be expected in an oxygen system allow the release of all the potential energy stored in a fuel, in a much shorter time frame than would normally be the case for an air-breathing fire. The result is a very rapid and highly intense fire that on ignition is often described as an explosion by the observer. Oxygen fires have little difficulty in reaching temperatures in excess of 2,000°C as compared to a natural draft air fire which may reach temperatures of 600°C and 800°C (naturally these figures depend on the flow and mixing characteristics of the oxidiser and fuel supply). While fuel and adequate oxygen remain to feed the fire, oxygen fires are extremely hard to control: normal aircraft fire fighting devices are useless in such situations. The most successful method of extinguishing an oxygen fire (as with most air-breathing fires) is to restrict the source of the oxygen.

Given the undesirability of an oxygen fire, the selection of materials for use in oxygen service, along with the detail of the design of the system, is of prime importance. Materials selection is a matter of understanding the factors that may cause oxygen to react with the material. Most materials in contact with oxygen will not ignite without a source of ignition energy. Two factors are important in this consideration: the temperature at which combustion of the material begins and the energy input rate of an ignition source. If the input rate is sufficiently high, a localised area of the material will reach its ignition temperature and the material will ignite. Conversely, if the dissipation rate of the energy from the heated area is higher than the input rate, the area will not reach its ignition temperature. Clearly, the intensity of the ignition source and the ability of the material to dissipate energy are key factors in oxygen compatibility. On both these counts, polymeric materials fare worse than metallic materials because of their low relative heat conductivity and ignition temperatures.

2.1.1 Ignition sources [4]

The potential ignition sources that could be present in even a simple component intended for high pressure oxygen service are numerous and varied. For example, small contamination particles, metallic and/or nonmetallic, can be accelerated to sonic velocities in high-flow regions of the component. These particles may then cause impact ignition of debris and/or any susceptible materials that they impact with. Alternately, contamination can collect in stagnant regions of a component and be heated to ignition by pneumatic shock (near-adiabatic compression), the result of heating during compression of gas in these areas. While the initial combustion might only involve contaminant (such as a normally flammable material) the additional heat evolved from the oxygen-accelerated combustion can cause adjacent metals to ignite and burn.

Actuation of valves can cause impact loading resulting in failure of the parts or mechanically induced ignition. Failure to consider metal-to-metal wear reactions between materials of similar composition can result in galling or rubbing surfaces and considerable frictional heating which can, in turn, cause both functional failure or ignition. Chatter and subsequent fretting can result from unbalanced gas loads and produce particulate contamination.

Cavity resonance ('organ pipe' effects) leading to ignition of trapped contamination can occur in blind passages upon system actuation. Flow-induced vibration leading to system failure can also occur in bellows and lines where system design of support structure is not adequate. Flow-induced cavitation in liquid oxygen (LOX) systems may result in the formation of ignition-susceptible fresh surfaces.

Burrs, wear debris, thin wall sections and sharp edges can present large surface area-to-volume ratios which can have a marked reduction in the energy input required to initiate fire and result in a considerable increase in the rate of fire propagation should ignition occur.

The above ignition possibilities should be considered during design/selection/modification of both components and systems. While this listing covers the most frequently observed ignition sources, it is not exhaustive. An analysis of the possible types of failures, and their effects on the system and/or aircraft, should be undertaken, which includes ignition as a failure mechanism. This analysis should be conducted as a part of each new design/selection/modification. Methods for carrying out such analyses are set out in several standards, which are listed at the end of this report.

2.1.2 Flexible hoses for use in oxygen

Coiled metal tubing connections (pigtail) used to connect high-pressure cylinders to fixed oxygen systems are frequently replaced by lined flexible hoses. The two most common reasons for this are: flexible hoses are easier and quicker to attach, and they eliminate the work hardening and fatigue problems associated with coiled pigtails.

All flexible hoses for high pressure service rely for their strength on a layer or layers of wire braiding or wrapping. The inner layer, which acts to contain the gas, is a tube of either a polymer or a corrugated metal. For corrugated metal lined hoses either stainless steel or copper alloys are preferred, although of these, the copper alloys are superior to stainless steels at resisting ignition and combustion. For polymer-lined high-pressure hoses, it is generally specified that PTFE (Teflon, TFE) should be used. None of the references or standards (see References and Standards listed at the end of this report) suggest any other type of liner for high-pressure oxygen use; indeed, Servicing Appraisal Executive (SAE) (in standard SAE AIR4918) suggest that, in general, 'flexible hoses are not recommended for use in high pressure oxygen equipment where pressure exceeds 500 psig' unless special precautions are taken, or the outcome of a fire will not be serious.

At lower pressures typically below 100 pounds per square inch—gauge (psig), polymers other than PTFE have been used with success. In these situations the volume of oxygen and the flow rate are so low as to render ignition highly unlikely, although these materials will burn readily in oxygen.

2.1.3 The overall design of oxygen equipment (adapted from [5])

Oxygen compatibility tests supply information on the performance of a material under specific conditions. However, assessing the performance of a component such as a valve, which is fabricated from many materials, requires a broader approach. The fire triangle helps analyse the broad situation and estimate the performance of a component in service. The fire triangle analysis is subjective, but provides a conceptual framework for the evaluation.

The fire triangle concept states that three components—fuel, ignition source, and oxygen (other oxidisers will not be considered here)—must be simultaneously present for a fire to occur. Each of the main components is affected by additional factors. These additional factors can be considered by using the extended fire triangle, as shown in fig. 17 and discussed below.

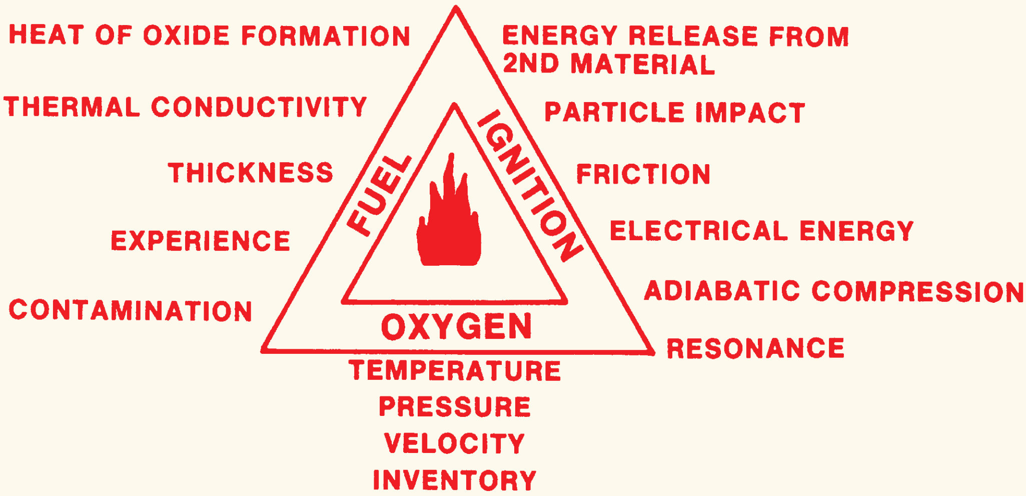

Figure 17: The extended fire triangle indicating some of the factors to be considered in a design.

2.1.3.1 Fuel leg

All metal and nonmetal components are potential fuels. The design of the system must ensure that the lower compatibility materials (such as nonmetals) do not ignite and initiate a 'kindling chain' reaction that causes a major failure. In this way the lowest compatibility material—probably a nonmetal—can ignite and lead to ignition of the major metal of construction of the component. Therefore, the design should limit the use of combustible nonmetals. If they must be used for valve seats, seals, etc., as is often the situation, the design should ensure that if ignited they do not propagate the chain.

As shown in the above figure, numerous properties of the metals used in the oxygen system (that is, the fuels) should be considered to estimate the potential for a fire. The following list is not comprehensive, but includes the properties most often considered:

- *Heat of oxide formation.* High heats of oxide formation provide energy to promote propagation.
- *Thermal conductivity.* Metals with good thermal conductivity, such as copper, should be more difficult to ignite because local hot spots can be dissipated before ignition occurs.
- *Thickness.* Sharp corners and thin sections promote easier ignition because they may be heated more quickly than thicker sections. As a rule of thumb, metal thickness of less than 0.8 mm should be avoided.
- *Experience.* Experience with the metal in the same or similar service provides a good basis for material selection. Successful use in more severe service is a strong indication that the material is acceptable for the intended service.
- *Contamination.* Areas of contamination left from manufacturing, such as oil or grease, or fine swarf from assembly, are often easy to ignite and can initiate the kindling chain. Contamination must be removed prior to startup, which implies that ease of contamination removal (design for cleaning), and contamination prevention and control (wear, assembly, filters etc.), should be a consideration of the design.

2.1.3.2 Ignition leg

Energy must be introduced to the fuel to start ignition. This is the least understood part of combustion. However, the following aspects should be considered:

- *Heat from combustion of lower compatibility materials (kindling chain).* Combustion of a polymer may release enough energy to ignite an adjacent metal component. Similarly, combustion of a less compatible metal such as carbon steel may cause the ignition of a more compatible metal such as brass.
- *Particle impact.* Impact from particles in the flowing oxygen stream can cause ignition of metals and nonmetals.
- *Friction.* The rubbing together of components generates heat that can cause ignition.
- *Electrical energy.* Electrical discharge from static electricity generated by gas flow in the presence of particles can cause ignition. Similarly, electrical discharge from shorts in associated electrical equipment such as heating elements and motors, can result in ignition.
- *Adiabatic compression.* When a valve is suddenly opened, the gas in the downstream system is compressed and the temperature of the trapped gas is instantaneously raised. Conduction and dilution effects tend to lower the resultant temperature. Polymers are susceptible to this type of ignition when they are situated at dead ends in the system. Procedural and the design control, such as avoiding, fast-opening valves and dead ends, and the use of energy absorbing, fire resistant piping sections at positions of an expected temperature rise, are usually effective in controlling this mechanism
- *Resonance.* Certain piping configurations provide possibilities for ‘organ pipe’ heating of gases.

2.1.3.3 Oxygen leg

Usually the oxygen side of the triangle cannot be modified. The system must be designed to accommodate a specific oxygen environment. However, it is important to understand how the oxygen conditions affect compatibility:

- *Temperature.* High oxygen temperatures increase the risk of ignition of polymers. This may lead to ignition of a metal component.
- *Pressure.* It has been shown that the rate of combustion of metals increases with pressure.
- *Velocity.* High velocities increase the risk of ignition from particle impact. The Compressed Gas Association Pamphlet G-4.4 gives allowable velocities for carbon steel and stainless steel oxygen piping. (Note that stainless steel is subject to the same limits as carbon steel. There is no stated maximum velocity for copper alloys and nickel alloys.)
- *Inventory.* The amount of oxygen in the system should be considered with regard to the potential damage if combustion occurs.

2.2 Review of the physical evidence

2.2.1 Cylinders

The cylinders were in reasonable condition and had no evidence of metal burns consistent with the ignition of an oxygen fire. The internal condition of the cylinders was reasonable and, although the small portable cylinder was found to be contaminated with an oily carbonaceous film and droplets of water, it is thought that cylinder contamination is unlikely to have contributed to this fire. The contamination observed in the portable cylinder probably gained entry during the post oxygen-enriched fire as a result of efforts by emergency services to extinguish the aircraft fire, in other words, it was probably sucked into the cylinder during cylinder cooling when it was sprayed with water as part of the fire-fighting process.

2.2.2 Fixed oxygen system valve

This valve had no evidence of metal burns that would indicate ignition within this component. The seat of the valve appears to have burnt in an atmosphere that was low in oxygen. This had resulted in the carbonaceous deposits around the seat area and within the inlet and exit passages—only possible after the cylinder had completely vented. Therefore, combustion of the polymeric materials in the valve was the result of external heating, probably from the well established aircraft fire.

2.2.3 Portable oxygen system valve

This valve had significant evidence consistent with burning metal. This fire damage was external to the valve and appears to be the result of oxygen venting from this valve impinging on a stainless steel needle holder which had ignited (ignition source was the external fire). The gas, deflected from the needle holder and containing the combustion products (burning iron from the holder), impinged on the end of the valve, resulting in burning of the brass in this region. For this sequence of events to have occurred along with the needle holder being in the correct position at the conclusion of the fire, it is most probable that the damage occurred late in the aircraft fire.

2.2.4 Fixed oxygen system regulator and fittings

Although all the polymeric materials in this regulator had been consumed by fire, none appeared to have been burnt in a high-pressure oxygen stream, and no evidence of metal ignition was noted within the regulator or the fittings directly attached. Rather, it appears that the polymeric material had burnt due to external heating, after the cylinder had fully vented. The remains of carbonaceous and polymeric deposits and the lack of gas flow markings in these deposits support this conclusion.

The internal surfaces of the high-pressure region of the regulator, along with the inlet fitting (bull-nose fitting and filter) and the outlet fittings that attached the regulator to the flexible hose, were all coated with a deposit high in lead and chlorine. The probable source of this lead is thought to be from the lead content of the brass: it may have been concentrated at the surface by diffusion within the alloy and/or as a result of attack of the alloy surface by the combustion products of the halogenated polymers (chlorine and fluorine gas), which, in these conditions (high-temperature auto-ignition temperature for Viton is about 300°C) would have been very corrosive. Note: for the chlorine and fluorine gas to have caused the level of surface deposits noted, it would probably have been in contact with the inner surface of the valve etc. for some time—not possible if high pressure oxygen was still venting from the cylinder. This suggests that the halogenated polymers burnt due to external heating of the regulator, after the external fire was well established.

The remains of a polymer in the glass-fibre filter remain a mystery although there is no evidence that links this material with the ignition of the fire.

The examination of the fittings between the flexible hose and the regulator showed that the inner surface of the male-to-male adaptor had numerous fissures in it. These were produced during the manufacturing process. Comparison of these internal defects with the external surface indicated that the oxide and corrosion product, found in these fissures, was probably not associated with oxidation that may have occurred during the helicopter fire (also considering the effects of the halogenated gas probably present at some stage of the heating from the external fire); rather, it appeared to have formed (most likely) during the manufacturing process, or (only in part) during service. The main evidence to support this proposal is that considerable oxide could be observed at the internal (to the material) tips of the tears, where it was well protected by other debris during the fire. The presence of this material would have been a source of contamination within the oxygen system that existed prior to the fire. It is not known if this contamination was mobile prior to the ignition, or if some other (since burnt) contamination may have been present prior to the ignition. The condition of this part calls into question the cleaning process used by the constructor of this oxygen system. It would seem likely that had the part been properly cleaned (oxide removed) and inspected, the fissures would have been noticed.

Another possible source of contamination was from the weld surfaces in the stainless steel elbow of the flexible hose. Here there was some evidence that the coating on the inner surfaces of the welds had been spalling, although it is not clear at what time (before, during or after the ignition) this occurred.

Finally, contamination could have been present as a result of inadequate cleaning, or assembly generated swarf. Experience has shown that it is very difficult to assemble oxygen system parts without generating some swarf. This is usually the result of threads of metal being dislodged from the mating threads of the part, and, with a number of parts used to adapt the flexible hose to the regulator, it may be expected that at least some swarf was generated. Reducing the number of parts and the difficulty of cleaning those parts are important considerations in preventing contamination in oxygen systems.

2.2.5 Portable oxygen system regulator

The portable system regulator did not appear to have had any involvement in either the fire in the fixed system or the fire associated with the portable valve. All damage to this regulator was consistent with that which may be expected due to heating during the aircraft fire, and failure due to mechanical overload.

2.2.6 Flexible hose and gauge

The examination of the flexible hose indicated that this part was probably involved in the primary event, which started the aircraft fire. Such a conclusion can be reached based on:

- the witness evidence, which implied that the initial ‘explosion like’ event was associated with this hose;
- evidence of strands of the wire braiding found in the neck and overalls of the person who turned on the oxygen system;
- the extensive nature of the damage to the flexible hose (considerable part completely missing);
- the melting and burning of the hose braiding at the part that attached to the missing section; and
- the regulator end fitting of the hose, which had also suffered burning typical of an oxygen fire.

The lack of high-temperature fire damage (temperatures expected in an oxygen-fed fire) to other parts, which could not be explained by other possible scenarios, ruled them out as being involved in the ignition. The cause of the failure of this hose has not been established from the examination of the hose remains, although two possibilities are considered to be significant and are discussed fully in the next section (2.3).

The constriction of the hose-tails into the form of venturi may have considerably increased the velocity of the gas passing through them, and in turn imparted considerable kinetic energy to any particulate material that was entrained in the stream. This possibility is discussed in section 2.3.2.

2.3 Probable cause of ignition in the flexible hose

Ignition in an oxygen system usually begins as a small event and grows into a fire through the 'kindling chain', as discussed above (section 2.1.3.2). The source of the ignition energy is the primary concern in an oxygen system that contains low compatibility materials. The most common ignition energy sources are:

1. mechanical impact—where one relatively large object strikes another (unlikely to be the cause in this case);
2. particle impact—where small particles carried in the oxygen stream strike surfaces in the system resulting in ignition of the particle or the surface impacted (possible in this case);
3. friction—the rubbing together of two solid materials (unlikely); and
4. near adiabatic compression—where rapid compression of oxygen at dead ends or obstructions results in it being heated (possible).

The ignition of the flexible hose would appear to have been caused by either particle impact or near-adiabatic compression.

2.3.1 Near-adiabatic compression

Near-adiabatic compression can occur in a piping system when a valve is opened quickly and the high-velocity gas stream compresses the oxygen downstream against an obstruction—the seat of a valve or regulator, an elbow or T-fitting, or a burr protruding into the gas stream (in this case the valve was found to have been opened only about half a turn). At the obstruction, gas temperature may rise above 540°C, as noted in American Society for Testing and Materials, Guide G63. These temperatures can be above the auto ignition temperature (AIT) of polymeric materials (540°C is above the AIT for all commonly used carbon chain based polymers), organic contaminants, or small metal particles, whose combustion can add enough heat to ignite surrounding metal parts. Other dirt, scale and particles that will not burn can still become very hot, adding to the potential for ignition.

A notable feature of near-adiabatic compression ignition in polymer-lined flexible hoses is that the region of primary ignition usually corresponds with the region of initial failure of the hose. Although the entire lining of a flexible hose usually ignites shortly after a hose ignition occurs, the area around the initial ignition usually burns through first, resulting in combustion of the hose braiding, and therefore the most severe disruption, around this area. The other notable feature of flexible hose failures is that the restriction is usually at the far end of the hose. In this case it was at the end attached to the right-angle fitting that connected the pressure gauge to the hose. Although it would be expected that the most severe damage to the hose should be at the dead end (gauge end), this has not always been found to be the case. A study of a large number of PTFE-lined hoses subject to near-adiabatic compression ignition by Barthelemy &

Vagnard [6] which included particulate and oil contamination, found that although ignition nearly always starts at the dead end of the hose, the flame propagates much faster along the surface of the liner than through the liner (flame propagation rates for polyester would be expected to be considerably higher than for PTFE, as would the heat released), with the result that the point of first burn through may be considerably away from the dead end. They also found that oil contamination up to 83g/m^2 did not significantly alter the probability of ignition in the adiabatic compression tests when compared to cleaned hoses of a similar configuration: a good indication that flexible hoses, regardless of the materials of construction should be avoided in adiabatic compression sensitive areas.

Notwithstanding the work of Barthelemy & Vagnard, near-adiabatic compression ignition would seem to be less likely of the two possible causes in this incident as the most severely disrupted section of the hose was adjacent to the hose entry, and the hose was particularly long (1.5 m estimated). If a kink (no evidence to suggest this, although the area of the failure contained a region where the hose was probably bent through 90°) in the hose was present, this could have resulted in an effect similar to the dead end created by the gauge, which may account for the position of the hose failure. It should be noted that a hose of these dimensions made from a material with considerably less compatibility than PTFE and fitted with only minimal metallic fittings at the dead end, would probably ignite under any less-than-ideal pressurisation rate, and as the very large volume of the hose, relative to the system requirement (only supplying pressure to a contents gauge) allowed a large volume of oxygen and polymer to be in contact, a catastrophic event was guaranteed should ignition occur.

The reported slow opening of the cylinder valve and the observed narrow opening of the valve (approximately 1/2 a turn) would suggest that the pressure build-up in the flexible hose would have been reasonably slow, although this is only an subjective assessment.

2.3.2 Particle impact

When small particles carried by the flowing gas strike a surface, heat is generated proportional to the particles' change in kinetic energy. This heat may be sufficient to ignite the impacted material or the particle (if the particle is combustible). The probability of ignition depends on the velocity to which the particle is accelerated and the temperature of ignition of the materials involved: clearly the polymer lining of a flexible hose is potentially more easily ignited than an alternative copper or stainless steel tube.

In this case there are three factors that suggest that particle impact may be the cause of ignition:

- the hose liner was manufactured from a less than ideally oxygen compatible material;
- the 'hose tail' of the fitting at the entry point of the hose had been crushed to form a venturi which would have resulted in the acceleration of the gas stream at this point; and
- either some of the scale observed on the welds which were part of the bend attached to the fitting may have been dislodged (it must be remembered that this may have occurred during the subsequent fire and handling), debris from the male-to-male adapter may have become free, or construction-generated swarf could have been present (further discussed below).

Apart from the already considered sources of a particulate contaminant, there are two other possibilities, which, in the experience of the investigator, are commonly found in oxygen systems. The most common of these are metal fibres, removed from threads during the assembly/disassembly of components. In this case the use of two adaptor fittings prior to the hose fitting along with the mismatch in the hardnesses of the stainless steel fitting with the brass fittings would produce a strong possibility that metal particles would be present between the regulator and the venturi of the ‘hose tail’. The use of PTFE sealing tape has also been found to generate PTFE particles, particularly on disassembly and re-assembly, although these particles are low in mass and fairly resistant to ignition Auto Ignition Temperature (AIT) 427°C. While a particle of brass swath would have considerable potential to initiate an ignition of a low AIT material due to the high specific gravity (SG) of brass (should one be accelerated to high speed), the particles of PTFE are most likely less of a problem due to their low SG.

3. CONCLUSIONS

After consideration of the evidence highlighted during the investigation and the factors discussed above, the following conclusions are suggested:

1. The fire initiated in the high pressure flexible oxygen hose situated between the fixed oxygen system regulator (in the rear baggage compartment) and the pressure gauge (in the helicopter cabin).
2. Although the exact cause of the ignition remains unknown, it is postulated that particle impact or near-adiabatic compression are likely factors, with the particle impact being the more likely in this case.
3. The design of the oxygen system (in particular the use of a long polymer-lined flexible hose running to a dead end—the cabin mounted gauge) and the selection of a polyester-lined hose, rather than the more usual selection of a PTFE-lined hose, were not consistent with best high-pressure oxygen system design practice.
4. The male-to-male adaptor used to connect the flexible hose to the regulator of the fixed system appeared to be of poor quality, and this may have contributed to the ignition of the hose. The fissures in the inner surface of the adaptor would have made thorough cleaning of this part difficult.
5. All other parts of the fixed oxygen system appeared to be suitably oxygen-compatible and there was no evidence that they contributed to the ignition.

4. RECOMMENDATIONS

From the above examination along with considerable experience with oxygen systems and fires in these systems, the following recommendations are proposed for inclusion in the relevant regulations/advice:

1. Oxygen systems for aircraft use should be designed such that combustible (in oxygen) polymeric materials are kept to a minimum.
2. Copper pigtails are preferred to polymer lined flexible hoses where this is possible.
3. For aircraft use, only certified oxygen-compatible, PTFE-lined flexible hoses should be specified.
4. Where polymer flexible hoses are used, they should be kept to a minimum length and volume and fitted with distance pieces which are at least 150 mm long (made from copper) or 250 mm long (for stainless steel tubing (same ID as hose)), at the downstream end, before any restriction such as a valve, sharp bend, dead end, or reduction in ID.
5. Warnings about off-the-shelf parts used in oxygen systems should be included in guides to the design and construction of aircraft oxygen systems. In particular, the inspection of parts for detrimental defects and the possibility that internal surfaces will be difficult to clean should be highlighted. Notes should also include mention of the removal of burrs, sharp edges and thick oxide layers (excluding those deliberately formed as part of the corrosion protection scheme, for example, anodising).
6. Reference in regulations/advice to design and construction of aircraft oxygen systems should address an appropriate standard possibly selected from one of those set out at the end of this report.
7. Notwithstanding adherence to the regulations/advice, all high-pressure oxygen system designs should be reviewed by persons or organizations with significant experience in the design of high-pressure (above 100 psig) oxygen systems
8. Warnings about the danger posed by an oxygen fire should preface any discussion about the design and construction of oxygen systems

Relevant standards

1. British Standard 3N 100:1985.
2. ASTM standard G63 'Guide for Evaluating Nonmetallic Materials for Oxygen Service', American Society for Testing Materials, 1916 Race St. Philadelphia, PA 19103. ASTM Standards, vol. 14.02.
3. G72 Test Method for Autogenous Ignition Temperature of Liquids and Solids in High Pressure Oxygen-Enriched Environment, American Society for Testing Materials, 1916 Race St. Philadelphia, PA 19103. ASTM Standards, vol. 14.02.
4. G74 Test Method for Ignition Sensitivity of Materials to Gaseous Fluid Impact, American Society for Testing Materials, 1916 Race St. Philadelphia, PA 19103. ASTM Standards, vol. 14.02.
5. G86 Test Method for Determining Ignition Sensitivity of Materials to Mechanical Impact in Pressurized Oxygen Environments, American Society for Testing Materials, 1916 Race St. Philadelphia, PA 19103. ASTM Standards, vol. 14.02.
6. D2512 Test Method for Compatibility of Materials with Liquid Oxygen (Impact Sensitivity Threshold and Pass-Fail Technique). American Society for Testing Materials, 1916 Race St. Philadelphia, PA 19103. ASTM Standards, vol. 15.03.
7. D2863 Test Method for Measuring the minimum Oxygen Concentration to Support Candle-like Combustion of Plastics (Oxygen Index), American Society for Testing Materials, 1916 Race St. Philadelphia, PA 19103. ASTM Standards, vol. 08.02.

Additional reading

1. 'Design Guide for High Pressure Oxygen Systems', A. C. Bond, H. O. Poll, N. H. Chafe, W. W. Guy, C. S. Allot, R. L. Johnson, W. L. Caster and J. S. Straddling, NASA Reference Publication 1113, NASA Scientific and Technical Information Branch, 1983.
2. 'Guide to the Compatibility of Materials with Oxygen', Engineering Dept. Meggitt Oxygen Systems, Edinburgh Place, Edinburgh Way, Harrow, Essay CM20 2DJ. Prepared for the UK Ministry of Defence (PE) MAP 14. Specification No. 0.4081, Issue No. 4 (Al 3), June 1995.
3. 'Oxygen Compatibility Source Book', BOCL Group Technical Center, Murray Hill, NJ USA. May 1994. This document is commercial in confidence.
4. Compressed Gas Association Pamphlet Nos. G 4 'Oxygen' and G4.4 'Industrial Practices for Gaseous Oxygen Transmission and Distribution Piping Systems'. Compressed Gas Association Inc., 1725 Jefferson Davis Hwy., Arlington, VA, USA.

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2. J. W. Bransford, 'Ignition and Combustion Temperatures Determined by Laser Heating', Flammability and Sensitivity of Materials I Oxygen-Enriched Atmospheres: Second Volume, ASTM STP 910, M. A. Benning, Ed., American Society for Testing and Materials, Philadelphia, 1986, pp. 78-97.
3. F. J. Benz, R. C. Shaw & J. M. Homa, 'Burn Propagation Rates of Metals and Alloys in Gaseous Oxygen', Flammability and Sensitivity of Materials I Oxygen-Enriched Atmospheres: Second Volume, ASTM STP 910, M. A. Benning, Ed., American Society for Testing and Materials, Philadelphia, 1986, pp. 135-152.
4. ASTM G128-95 'Standard Guide for Control of Hazards and Risks in Oxygen Enriched Systems' American Society for Testing and Materials, Philadelphia, 1995
5. J. W. Slusser & K. A. Miller, 'Selection of Metals for Gaseous Oxygen Service', Flammability and Sensitivity of Materials I Oxygen-Enriched Atmospheres: Second Volume, ASTM STP 812, B. L. Werley, Ed., American Society for Testing and Materials, Philadelphia, 1983, pp. 167-191.
6. H. Barthelemy & G. Vagnard, 'Ignition of PTFE-Lined Hoses in High-pressure Oxygen Systems: Test Results and Considerations for Safe Design and Use', Flammability and Sensitivity of Materials I Oxygen-Enriched Atmospheres: Third Volume, ASTM STP 986, D. W. Schroll, Ed., American Society for Testing and Materials, Philadelphia, 1988, pp. 289-304.