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Identification of ignition sources in high pressure enriched gaseous oxygen system incidents using flow chart road map diagram methodology

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ABSTRACT

High pressure enriched oxygen is used in a wide number of areas, including aircraft, medical breathing apparatus, and a number of industrial processes including combustion. Unwanted ignition in such systems can cause significant damage to property and danger to life. It is important to gain as much information, and record relevant data for every oxygen incident, enabling both immediate analysis, and post-event evaluations (especially where circumstances are repeated). The lack of clear concise guidance can result in data loss. This work successfully develops investigation 'road maps' as guidance documents for investigators to use, even under difficult & time pressured conditions. The work demonstrates their usefulness and importance for information collection and the down-selection' or elimination of possible ignition causes through their use with a 'real world' case study. The benefit of this work will be to enable faster and more effective investigation of oxygen incidents, ensuring key details are recorded (benefitting post-accident academic data & meta-study analysis). The roadmaps can also benefit designers of oxygen systems allowing them to test their designs and operating procedures against specific ignition scenarios.

1. Introduction

Oxygen is of course vital to sustain life and for this reason oxygen life support systems or breathing apparatuses are used in a wide number of areas, including civil and military aircraft, medical breathing apparatus and hyperbaric chambers, and diving and mountaineering systems. Oxygen is also used industrially to support combustion. Combustion is the rapid runaway oxidation of a fuel, generally following a specific energy input to a fuel/oxidiser mixture. In the case of combustion, the oxidation reaction rate passes a critical point, resulting in energy release and free radical formation that is great enough to bring about further oxidation. Thus a self-perpetuating reaction occurs, while there is both oxygen and fuel to sustain it.

As oxygen is used so extensively, it is often necessary to store and use it at pressures and concentrations well above that of atmospheric. Under these conditions, oxidation reactions occur more readily, and at a faster rate. Some adverse circumstances can result in ignition incidents that can, in turn, lead to catastrophic system failure, destruction of property and endangerment of life.

A large number of oxygen incidents have been described in the literature, showing both the seriousness and scale of this problem. Between 1982 and 1985, Dicker and Wharton (1988) reported 28 high pressure oxygen incidents, while Fowler and Baxter (2000) detailed several incidents in the UK involving pressurized oxygen in the period 1996–1998. Gregson (2008) (of the UK HSE) recorded 158 reported oxygen incidents between 1996 and 2002, including 59 minor injuries, 25 major injuries and 5 fatalities. The NASA Oxygen-Enriched Fire Incidents reporting site (2013) records 119 documents for the period 1984 and 2009. A few of these relate to proposed possible incidents, but the majority detail actual oxygen incidents, with a number containing details of more than

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1 event. These primarily occurred in the USA armed forces, hospitals or similar commercial establishments. The site also lists 30 further incidents in Boeing establishments prior to 1992. This is a voluntary recording system and is not therefore indicative of the total number of incidents in the USA, but does show there is in continuing problem. Ahrens (2008) detailed a series of oxygen incidents between 2002 and 2005. These incidents all occurred in the USA, and had been attended and recorder by the US Fire Service attended. He reported an average of 182 fire incidents per year where medical oxygen had been the cause of the fire, resulting in an average of 46 deaths per year. Ahrens also reported there were an average of 1190 thermal burns per year for the period between 2003 and 2006 involving oxygen use, primarily in the home. The NFPA (2014a) medical oxygen incident document recoded a selected 40 serious incidents, primarily in the home, involving significant death, injury or financial damage, where medical oxygen was involved. This included 2 fatal fires from 2014. The EIGA Safety Advisory group (2009), the industry group on European compressed gas safety, listed examples of oxygen incidents stating there have been many more similar incidents.

After an incident has occurred a there is clearly a need to investigate what happened, to learn what went wrong and inform future guidance and safety research. In the case of oxygen systems There are a number of interested parties concerned with oxygen incidents. The process can be confined to one organisation, for example an insurance company consultant, or collaborative. The more serious the incident, the more institutions may have to be involved e.g. an injury or death will result in the involvement of police and, in the UK Health and Safety Executive (HSE) or in the USA the Occupational Safety and Health Administration (OSHA) or one of the organisations they oversee.

In the absence of specific guidance such parties are likely to apply their own procedures for the investigation of such incidents, leading to significant variations with what is recorded and how. Of the incidents listed on the NASA Oxygen-Enriched Fire Incidents reporting site (2013) 12% mention incorrect material use as the cause, 5% are attributed to contamination (usually of oil), 4% to adiabatic compression/pressure shock and 3% to particle ignition. 54% do not state a cause, or identify, multiple possible ignition sources due to burn damage and insufficient evidence. Gregson (2008) attributes incidents to and list of four common causes (contamination, fast opening of valves, oxygen enrichment from leaks, incompatible materials). Dicker and Wharton (1988) report 28 incidents, not by cause, but by system location with 39% occurring in pressure regulators, 21% during cylinder filling operations, 18% in pipelines/manifold and the rest in other equipment such as cylinder valves. Indeed past incident investigation reports carried out by qualified investigators (Benson, 2015) show a dramatic lack of standardisation or thoroughness in the information collected. This has resulted in limited and inadequate information to academically assess/review incidents or conduct further analysis in relation to specific pathways to ignition.

This is in stark comparison to other areas of incident investigation such as house appliance fires where the collection of detailed data has led to databases for academics & fire professionals to draw on and identify un-safe activities and products (Campbell, 2017; Holborn et al., 2003) and encourage recalls.

There are currently standards & guidance that can be used to identify hazards in an oxygen system, or the likelihood of material ignition (BCGA, CGA, EIGA, HSE indg459, BS 5N100-5, ASTM standards G63, G88, and G124) but they exist in different jurisdictions, 'sit' in different industries, and serve different purposes. Only one standard, ASTM G145-08 (2016), specifically advises on oxygen incident investigation but while this also advises on likely hazards, and contributory factors, it does not offer a detailed framework or process guidance that any investigator, especially those relatively unfamiliar with high-pressure enriched oxygen systems, might use. This has contributed to the lack of consistency of approach, and a dramatic shortage of data to enable academics and engineers to identify safety problems (Benson, 2015). Therefore a standardised methodology for narrowing the field of, or down selecting, likely ignition sources, would be useful.

The principles of accident investigation, in general, are well documented. Although investigation of the most serious events will have substantial resources available to it, the philosophy behind having a safety culture, regulations and regulatory organisations is to identify problems before they happen, or before they cause serious harm (HSE "Investigating accidents and incidents" guide, 2004). In investigating an oxygen incident, it is essential to ensure as much key information as possible can be gleaned from the debris to help identify inappropriate materials, aid in the design of oxygen system components, and most importantly, to prevent similar incidents occurring in the future. It is also essential to record the scientific information for even minor incidents/near misses, since this could give insight into potential root causes of problems in a major incident (of similar root cause) where escalation might make identification of the ignition source difficult or impossible.

Frameworks such as a checklist or flow diagram can aid in making sure key information is identified, and recorded, benefiting the wider investigation process and industry safety information (Mansi, 2012). They can also enable the fast and accurate causes of incidents, as well as ensure that useful data was collected for post incident investigation and academic scrutiny. Such a system could readily be applied to the investigation of incidents involving oxygen systems, providing a means of combining the known data on oxygen systems fires/hazards with the principles of incident investigation.

This work details the development and application of incident investigation roadmaps for oxygen systems. These will enable faster and more effective investigation of oxygen incidents, while ensuring key details are recorded and thus benefit post-accident academic analysis. The roadmaps can also benefit designers of oxygen systems allowing them to test their designs and operating procedures against specific ignition scenarios.

2. Theoretical oxygen incident investigation

2.1. *Oxygen incident causes*

Although the root cause of an incident may be any number of different things including a range of management failures involved in equipment checks and maintenance, staff training etc. the actual sources of ignition for the vast majority of incidents in high pressure enriched oxygen systems are limited to a few events (BS 5N 100-5, 2006; ASTM G88-13). These are identified as:

- Pressure shock and rapid adiabatic compression (accumulated oil/grease often facilitates this method of ignition).
- Impact by contaminant particles
- Mechanical impact
- Friction in valves
- Cavity resonance
- Electric arcing (e.g. short circuit arcing through sheath)

Electrostatic ignition is also identified in G88-13 as a hazard. Although Fresh Metal Exposure (FME) is another listed cause in that standard, particularly for materials like aluminium with a high combustion enthalpy, the mechanism will likely be through some form of impact or rubbing and thus is included under those umbrella terms in this work. ASTM G128/G128M - 15, a guide to controlling hazards and risks in oxygen systems, deals only directly with the first four sources listed for ignition prevention, stating these are the most common.

The accumulation of dust in a system, the contamination by grease not suitable for high pressure oxygen service, poor design or inappropriate component material selection resulting in shearing and particle generation can all contribute to the ignition. For example, some dusts and liquids, particularly organic materials, can self-heat (HSE Offshore