CHAPTER 1

INTRODUCTION TO OXYGEN SAFETY

Pure oxygen is a colorless, odorless, and tasteless gas. It supports plant and animal life. The air we breathe contains approximately 21% of oxygen. The separation of oxygen from air led to its application in many fields of science, engineering and medicine. The introduction and subsequent increase in oxygen consumption in various fields like steel manufacturing, chemicals, pulp and paper, metal extraction, metal fabrication, glass manufacturing, aerospace, medical, waste management/environmental etc., have been instrumental in increasing the efficiencies of the processes. It is also used in hospitals to save lives.

Although, oxygen-rich environment has significantly enhanced the performance of several processes, unless properly designed and handled, it also carries along with it the risk of fire leading to possible loss of property and lives. Several incidents and accidents have occurred around the globe during the last one hundred years since oxygen debuted as a potential process-accelerator in the industrial scenario. Industrialists and researchers have realized long ago that the key to prevention of oxygen-related fire lay in proper insight into the physics and chemistry leading to ignition and combustion under oxygen-rich environment.

One of the key understandings is that of the ignitability and flammability of the constituent materials that compose the oxygen handling system. Oxygen systems can prove to be a serious fire hazard despite its innocent appearance. Though oxygen by itself is non-flammable being an oxidizing gas, it vigorously supports combustion. Many materials, which are otherwise non-combustible or not easily combustible in air-environment, become readily combustible and burn actively in an oxygen-rich environment, more so when they are subjected to higher temperatures, higher pressures and higher purity of oxygen. Analyses on accidents, if properly documented, publicized and discussed among stakeholders, can help one to devise ways to avoid its recurrence in future. Identifying all the potential ignition criteria, ranking the materials as per their suitability for particular applications and, designing the components accordingly can pave the path for safe systems. In the application of oxygen, be it in liquid and gaseous phase, the quest of avoiding incidents and accidents have led to the development of numerous codes, standards and testing systems.

1.1 Fires in oxygen system

Fire is the primary hazard associated with oxygen apart from cryogenic hazards associated with liquid oxygen, such as, pressurization and cold-burn. Oxygen is neither explosive nor flammable, but supports combustion of such materials that might otherwise be considered non-flammable in ordinary air. A system may become unsafe due to faulty system design, faulty choice of compatible materials (metal or non-metal) or letting operating parameters cross their allowable limits. Designs should consider system dynamics, component interactions, and operational constraints to prevent conditions leading to oxygen fires. While it is always safe to design a system with materials having good oxygen compatibility, they are usually highly expensive and often not available off-the-shelf in the market. It makes a great economic sense to use materials that are otherwise less compatible and yet make the system safe by appropriate design of components or system avoiding the ñsparkò or ñauto-ignition temperatureò, which is essential to initiate fire. An alarming feature about oxygen fire is that it can occur in a system any time, even after several decades of safe operation, with no apparent change of geometric or operating parameters.

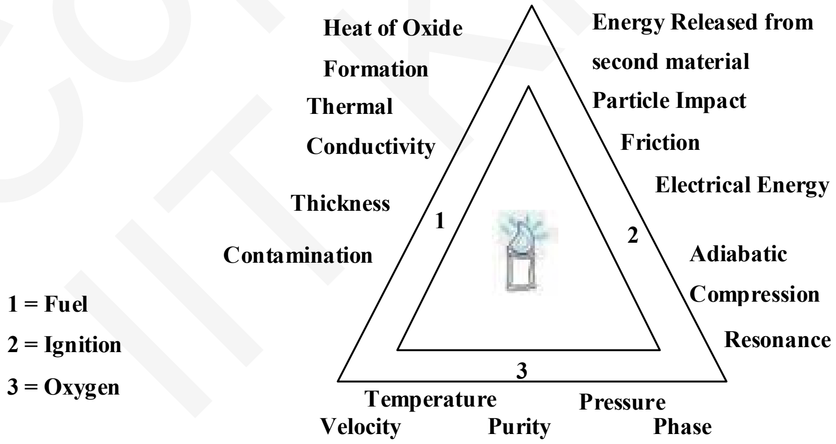

FIG. 1.1˙ *Slüsser-Miller fire triangle with modification*

Fire is possible only in the presence of a fuel, an oxidizer, and an ignition source. In an oxygen system, the fluid is the oxidizer, the system is the fuel, and possible ignition sources are ever-present in varied forms. The typical fire prevention practice is to remove one of the legs of the fire triangle. In case of an oxygen system, oxygen (the fluid) and fuel (the materials comprising the system) cannot be removed. Thus, eliminating the ignition sources is the only way out. However, since possible ignition sources are ever present in varied forms, the typical fire prevention practice of removing one leg of the fire triangle is difficult, though not impossible, in the industrial practice. In the extended fire triangle, as shown in Figure 1.1, Slüsser and Miller [1] pointed out that the system must be compatible to accommodate a specific oxygen environment, temperature, pressure, velocity and quantity.

The ignition chain begins when a very small amount of energy is released inside an oxygen system and ignites a material with low ignition temperature or a particle that is small in mass with a larger surface area. Once a small item is ignited, heat generated from that source ignites materials with higher ignition temperatures, which in turn generates more heat until the fire itself becomes self-sustaining. It is practically not possible to eliminate all sources of ignition.

Materials that do not burn at all or burn slothfully in air burn rapidly in oxygen. For example, stainless steel, PTFE, and silicones, which are generally regarded as fireproof or fire resistant, can burn easily in oxygen under certain conditions. This makes the selection of appropriate materials and designs of the system very important for reducing the probability of ignition and damage.

1.2 Oxygen system accidents and observations

Though an accident usually result from a combination of many criteria, material, design and operating, occurring simultaneously, it may also sometimes take place without any apparent or deliberate cause behind it. While an accident, by definition, is not predictable, it is, however preventable only if the root causes and circumstances leading to the accident are well-recognized and acted upon, prior to its occurrences. It is quite clear from the accident reports that a wide gap still exists in the understanding of the mechanism of ignition in oxygen environment in a comprehensive manner.

Beeson et al. [2] reviewed and analyzed the causes of four fire incidents in different oxygen production units that occurred due to failure of valves. From their analyses it was recommended that burn-resistant materials like Monel and brass be used for the valve-seat and also in places where metal to metal friction is a possibility. Hardeveld et al. [3] investigated and analyzed the causes of a serious explosion in an air separation unit. They believed that the hydrocarbon buildup in the reboiler of an oxygen column led to the explosion and destroyed the column. Hydrocarbon combustion triggered the aluminum combustion.

Liquid oxygen (LOX) reciprocating pump, tank, valve and hose failures reviewed by McMahon et al. [4] highlighted the possible mechanism of initiation and the propagation of fire. They believed that the contaminant buildup provided the kindling chain and caused fire hazard in the system. They discussed some fire accidents. Relevant to the present work is the information that soft seat cylinder valve was the location of fire and adiabatic compression at the dead-end created exactly at the seat was thought to be the cause of fire. The study and analysis conducted by Newton et al. [5] on two air-separation unit (ASU) fire incidents concluded that:

- The fire originated in valves (ball and butterfly)
- The valves were only slightly opened when fire occurred
- Particle and hydrocarbon contamination were present.

Waller et al. [6] made the following observations based on the investigations and analyses of eight different fire incidents of medical oxygen cylinders:

- Incidents involved cylinders and valves.
- Cylinder material was aluminum and valve seat material was polychlorotrifluoroethylene (PCTFE).
- Ignition occurred after the valve was opened for the first time after filling of the cylinder.
- Regulator was attached to the cylinder in all the incidents.

- Increase in the level of contamination accelerated the dynamics of initiation of ignition.
- Coining and deformation of valve seat under load led to the formation of thin lip of extruded material causing a change in oxygen flow path, hence, may have resulted in localized heating.

Gallus et al. [7] observed that the occurrence of fire in whole component body in an oxygen system could only be possible if the fire in polymer particles ignited the metal contaminants which in turn released enough energy for fire-engulfment of the metal body. They also pointed out that the worn-out non-metal parts, hydrocarbon and dust particle contaminations, sudden opening of valves etc. are the possible causes of fire in an oxygen system. The three fire incidents discussed, namely, in a commercial airliner, Royal Australian Air Force P-3 Orion Spacecraft and WSTF test system brought out the following important observations:

- Three fires were caused under different operating conditions, different materials and geometries.
- All three systems were at high oxygen pressure.
- In all probabilities, the fire in the three systems originated in the polymers.
- Systems that ran for decades without any problem suddenly caught fire even in absence of any apparent or abrupt change of operating parameters or handling procedure.

Dicker et al. [8] reviewed incidents occurring in the compressed gas industry in Great Britain in the early years of 1980-decade and highlighted the following:

- A large number of fires occurred in regulators, cylinder valves, manifold check valves and stop valves.
- Incidents are caused when contaminating materials are present and are exposed to high-pressure oxygen.
- These contaminating materials include hydrocarbon and silicone oils or grease, fragments of polymers, deposits of rust and sealing tape.

Grubb [9] briefed that the root causes of the fires in RAAF have been identified as:

- The location of fire was a poppet valve in an aluminum manifold check valve assembly.
- Contamination was present in the system in sufficient quantity and consisted primarily of iron oxide.
- Deterioration of silicone rubber seal was believed to be the cause of failure.

Gusky [10] remarked that the combination of a contaminant accumulation on the seat and ignition mechanism like adiabatic compression makes the regulators the most vulnerable component for system failure. He also reviewed that in most failures in oxygen systems, the components ignited were valve seat, valve biasing spring, diaphragm, and pressure adjusting spring.

Newton et al. [11] observed that the accumulation of contaminants occur in valves and regulators. They conducted experiments with contamination on valves and regulators and observed that the regions in the proximity of valve/regulator seat, non-metallic diaphragms and the stem region are the most ignition-prone.

The failure analyses of regulators and the fire events in compressed gaseous oxygen done by Barthelemy et al. [12] also suggested that it requires a careful selection process while choosing materials of construction for the valves and regulators, particularly the type and grade of plastics and the elastomeric materials. However, the most critical element linking these incidents was the contaminant built up in the systems, particularly in the valves and the regulators.

1.3 Potential ignition sources and material compatibility in oxygen systems

The study and analyses of an oxygen incident typically begins after the event has concluded. For example, a major explosion at an air separation unit at Bintulu, Malayasia in 1997 [13, 3] raised the doubt about the suitability of use of aluminum in oxygen enriched systems. The subsequent tanker fire involving extensive aluminum combustion led to many test campaigns and reviews for several years by various research organizations concerning incidents and experimental results related to oxygen supply and storage system explosions, taking into account the mechanisms of ignition with aluminum in LOX/GOX environment [3]. The Apollo 1 fire at the Kennedy Space Center in 1967 accelerated the concerted efforts for developing testing methods for materials more compatible in oxygen enriched environment. As a result, committees like European Industrial Gas Association (EIGA), British Compressed Gas Association, International Fire Protection Association, National Fire Protection Association (NFPA) of the USA, Bundesanstalt für Materialforschung und- Prüfung (BAM), Deutsches Institut für Normung (DIN), National Aeronautics and Space Administration (NASA) and Compressed Gas Association (CGA) were instituted where the development of component testing capabilities were evaluated. American Society for Testing and Materials (ASTM) committee was created out of the need of oxygen-handling organizations to have an umbrella organization that focused solely on research on the compatibility of materials, components, and systems used in oxygen-enriched application and their systematic documentation. Thus, the ASTM G-4 committee, the International Organization for Standardization (ISO), the European Committee for Standardization (CEN), BAM and DIN and the British Standards Institution (BSI), contributed actively in the testing and evaluating materials for oxygen service, and setting of standards.

Material selection for fabricating oxygen systems is vital for its safe operation. A system is oxygen compatible if the material is unlikely to burn in the event of outburst of fire or can even tolerate and isolate the effect of potential fire. Compatibility involves both ease of ignition and combustibility. Materials, that burn in air, would burn violently in pure or enriched oxygen at normal pressure and explosively in pressurized oxygen environment. The ignitibility of structural material in oxygen-enriched systems and their ability to propagate fire after ignition should be compared to their flammability properties. Vigorous efforts of several researchers and investigators from organizations mentioned above over decades highlighted several potential mechanisms leading to ignition and ultimately fire in oxygen systems.

Table 1.1 highlights the commonly recognized ignition sources (or their combination) that can raise the thermal energy within the system above its ignition threshold.

TABLE 1.1ˈ *Ignition mechanisms in oxygen-enriched environment*

Ignition Source	**Principle**	**Example** [15]
Friction	Heat and interaction of the two rubbing parts, along with the resulting destruction of protective oxide surfaces or coatings cause the parts to ignite.	Rub of a centrifugal compressor rotor against its casing causes galling and friction.
Heat of compression	Heat is generated from the conversion of mechanical work when a gas is compressed from a low to a high pressure. Pneumatic impact is an effective ignition mechanism with polymers but not with metals.	High-pressure oxygen released into a dead-end tube or pipe compresses the residual oxygen in the tube ahead and causes pneumatic impact.
Heat from mass impact	Heat is generated from the transfer of kinetic energy when an object having a relatively large mass or momentum strikes a component.	Poppet of a solenoid-operated valve striking the seat can cause mechanical impact ignition.
Heat from particle impact	Heat is generated from the transfer of kinetic, thermal, or chemical energy when small particles moving at high velocity strike a component.	High velocity particles from assembly-generated contaminants striking a valve body just downstream of the control element of the valve can cause particle impact ignition.
Static electric discharge	Discharge of accumulated static charge with enough energy to ignite the material receiving the charge.	Static discharge accumulation of dry oxygen flow through polymer hoses can lead to static discharge.
Electric arc	Electrical arcing can occur from motor brushes, electrical power supplies, lighting, etc.	Insulated electrical heater element can experience short circuit and arc through its sheath to the oxygen gas, causing an ignition.
Fresh metal exposure	Fresh metal might initiate reaction with oxygen releasing heat marking the initiation of chain reaction of oxide formation and heat release until ignition and a potential fire occur.	Fire in multi-gas compressors or in compressors that are initially purged by inert gases before oxygen use.
Resonance	Acoustic oscillations within resonant cavities cause a rapid temperature rise. This rise is more rapid and reaches higher values if particles are present or gas velocities are high.	Gas flow into a tee and out of a branch port can form a resonant chamber at the remaining closed port.
Promoted Ignition	A source of heat input occurs (perhaps caused by a kindling chain) that acts to start ignition in the nearby materials.	Ignition of contaminants (oil or debris) and combusts, releasing heat that ignites adjacent components, thus causing promoted ignition. Or a polymer valve seat can ignite and combust, igniting the valve stem.
Others	Thermal runaway, personnel smoking or open flames, shockwaves from tank rupture or ordnance, fragments from bursting vessels, lightning, exhaust streams.	Potential sources of heat include lightning, explosive charges, personnel smoking and open flames, fragments from bursting vessels, welding, and exhaust from thermal combustion engines.

The selection of oxygen compatible materials for oxygen system components is done after ascertaining that the material is not susceptible to any of these ignition sources. While some of the potential ignition sources can be eliminated through a proper system design, the use of appropriate operational and maintenance controls to limit the contamination and selection of proper materials are always important for preventing ignition.

Proper selection of metals for oxygen system coupled with good design practice (geometry, configuration, thickness etc.) and appropriate non-metal component can minimize the hazards of ignition and combustion of metals. The resistance to ignition is also caused by protective oxide film. However, iron and nickel oxides allow high diffusion through vacancies and interstitials. Chromium oxide, silicone oxide and aluminum oxides are better as passivating films, though Cr_2O_3 cannot be used for temperatures above 800^O C, because it volatilizes. SiO_2 cannot sustain thermal cycling. Al_2O_3 is good but it also may skin off with thermal cycling and thermal shock [14].

New alloys are continually being developed for better oxygen compatibility, and some that resist ignition and do not support self-sustained combustion in high-pressure oxygen systems are designed. The newly developed metals also have to be tested for compatibility with respect to all the ignition sources.

Nickel, Nickel-Iron alloys such as Inconel 718 and Inconel MA754, Nickel-Copper alloys such as Monel 400 and Monel K-500 and other Nickel-based alloys such as Hastelloy C-22 and C-276 are used extensively for oxygen use. Monel® and other nickel alloys are flammable in finely divided configurations, such as wire mesh and sintered powder.

Stainless Steel (SS) is extensively used in high-pressure oxygen systems. SS particulates are less hazardous than aluminum particulates. SS have to be protected from frictional heating, particle impacts and promoters. Aluminum is used in aerospace systems because of its high strength-to-weight ratios. High-pressure systems, valves or filters should not be made out of aluminum. Aluminum alloys are more suitable for static components with low oxygen flow rates, such as storage tanks, and, usually, not suitable for components with internal movement such as valves and regulators. Anodizing the aluminum surface increases the resistance to ignition by particle impact. Brazed aluminum heat exchangers are extensively used in air separation plants. Hence, compatibility of aluminum and its alloys in oxygen-enriched environment is an extensive research field.

Iron alloys ignite easily and hence are not generally used for oxygen systems. However, iron alloys are used extensively in compressed gas cylinders. Alloy steels (Fe-Ni), which are suitable for use in oxygen systems include 5% Nickel (but not at temperatures below 129 K because of low temperature embrittlement), 9% Nickel and 36% Nickel (Invar).

In oxygen systems, uses of certain metals including titanium, cadmium, beryllium, magnesium, and mercury are restricted. Titanium alloys must be avoided because titanium is impact-sensitive in oxygen. Titanium may be completely consumed due to its reaction in LOX or GOX. Table 1.2 gives an idea of the preference to be given for selection of metals/alloys based on the ignition temperature, friction-induced ignition, promoted ignition and the threshold (minimum) pressure for self-sustained combustion.

TABLE 1.2—*Relative ranking of commonly used metals/alloys in oxygen system [14, 16]*

Material	**Ignition temp (K)**	**Heat of combustion (kJ/g)**	**Threshold Pressure (MPa)**	**Friction heating ranking**	**Promoted Ignition Ranking**
Nickel 200	1773	4.00	55.2	Nickel 200	Nickel 200
Inconel 600	1670	5.43	20.7	Monel 400	Monel 400
Monel 400	1520	3.64	68.9	Inconel 600	Inconel 600
Hastelloy X	1600	5.00	34.5	Hastelloy X	Hastelloy X
Brass 360	1273	3.60	68.9	316 SS	316 SS
Invar 36	1203	7.38	6.9	Brass 360	Invar 36
316 SS	1500 to 1550	7.95	6.9	Invar 36	Brass 360
Aluminum 6061-T6	2210	31.07	0.17	Aluminum 6061-T6	Aluminum 6061-T6
Ti-6Al-4V	1855	16.00	0.007	Ti-6Al-4V	Ti-6Al-4V

Non-metals generally are used in oxygen systems for components like filters, valves, gaskets, and for lubrication purposes. Ignition of nonmetallic material can promote ignition of stainless steel hardware ignition and lead to severe damage. The probability of this ignition depends on the nature of the material, impacting oxygen pressure, rate of pressurization and the configuration of the system.

- **Semi-crystalline plastics** like polytetrafluoroethylene (PTFE), fluorinated ethylene propylene (FEP), polychlorotrifluoroethylene (PCTFE), Kel-F® 81, and amorphous polymers like polyimides (Vespel® SP21) are used in oxygen systems. PTFE is commonly used in oxygen systems because of its resistance to ignition by mechanical impact, high AIT, high oxygen index, and low heat of combustion. PTFE has poor creep resistance, hence is normally replaced by more compatible non-metal with oxygen.
- **Thermosets** are less frequently used in oxygen and include epoxies and cross-linked polyamides, such as Polybon®.
- **Composites** include the above polymer groups with non-polymer reinforcement. But in general material reinforcement into a polymer, such as glass-filled PTFE, will lower the ignition resistance of the material. Lubricants and greases used in oxygen systems are mainly fluorinated (greases are typically derived from perfluoroalkyl ether fluids thickened with PTFE or FEP polymers or halogenated chlorotrifluoroethylene (CTFE) fluids thickened with SiO_2 or higher molecular weight CTFEôs). Ceramics and glasses are not often used in oxygen systems.

While the components in oxygen systems are built with most compatible materials, if not free of contaminants before initial assembling, pose a danger of being in fire.

1.4 Oxygen system cleanliness

A system, through which oxygen is flowing over a long time, would contain particle or particulates, however small the amount may be. While cleanliness alone may not make an ill-designed or poorly fabricated system safe, contamination can make the best systems and components a hazardous one. These dusts may be metallic, polymeric or ceramic in nature. They arise from the source of the fluid, from the abrasion of moving parts such as valves, from unclean components, and from generation of rust in steel pipes. These solid particles are carried by gas with some velocity which in turn generates electrostatic charges on impact or rubbing against the inner wall of pipes, valves and such other parts. Committees and organizations such as EIGA, NFPA, BAM, DIN, NASA, CGA [17-19] have set the cleanliness levels required in oxygen systems. Table 1.3 shows the maximum allowable particles for various cleaning levels in oxygen environment.

Table 1.3˙ *Typical maximum allowable particles for different cleaning levels [14]*

Cleaning Level	***Particle Size Range (µm)***	***Number of Particles per 0.1 m^2***
300	<100 100-200 >250-300 >300	Unlimited 93 3 0
100	<25 25-50 >50-100 >100	Unlimited 68 11 0
50	<10 15-25 >25-50 >50	Unlimited 17 8 0

It has been shown [20] that presences of bigger particles make the system more unsafe than that of the smaller particles, which is also clear from the requirement given in Table 1.3.

The nature of contaminant and acceptable level vary depending on the equipment and its function. Contaminants are generally categorized as particulates (fine dust) or non-volatile residue (NVR). The cleanliness level is defined as size distribution of particulates and mass of NVR per unit area [14].

The cleanliness levels have been fixed by performing several studies of contamination ignition in oxygen-rich systems by Research organizations like CGA, NASA, ASTM etc. Egoshi et al. [19] found that the accumulation of lubrication oil in an air separation plant is less than 1 mg/m^2, which is far below the threshold level. Pedley et al. [21] concluded that the threshold oil-contaminant level recommended by CGA (500 mg/m^2) is excessively generous, while that given by NASA (11 mg/m^2) appeared to be quite conservative. The fires observed in high-pressure oxygen systems resulted from the ignition of polymeric materials, which burnt with sufficient energy to ignite stainless steel or other metallic materials.

The existing dust particles in oxygen systems attain velocity and momentum from the flowing GOX/LOX. Particles with diameter smaller than 100 µm follow the gas turbulences, whereas larger particles would influence the gas turbulence due to their inertia. The standards recommend that presence of particles over 100 µm diameter is not safe owing to its ignition due to ignition mechanisms like particle impact, adiabatic compression etc. [22]

Fletcher et al. [23] investigated and analyzed the effect of joints and connections of a system in the particle generation. They observed the rise in particle count with the number of disconnections and reconnections of pipes in a system. Figure 1.2 shows the particle generation as a function of number of reconnections of the fittings and Figure 1.3 shows the particle generation as a function of material of pipe after five reconnections.

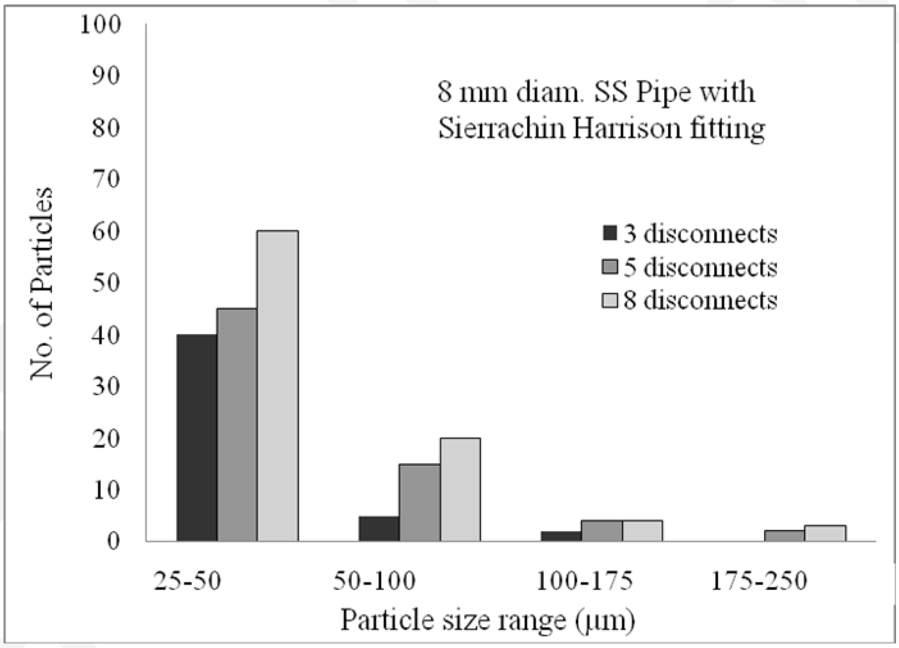

FIG. 1.2˙ *Particle generation as a function of number of reconnections of the fittings [23]*

Maintaining cleanliness is essential and critical for oxygen components and systems. Several researchers have reported the presence of contaminants as the key to the failure of components in oxygen-enriched systems.

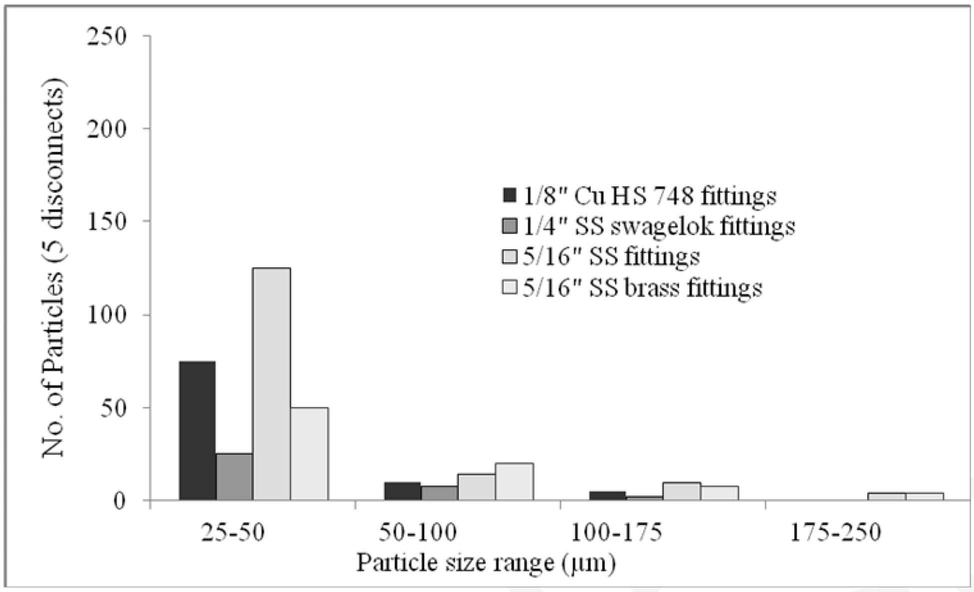

FIG. 1.3' *Particle generation for various pipe materials for five reconnections* [23]

1.5 Technological gap and motivation of the present work

While oxygen and fuel are ever present in an oxygen system, it is the ignition energy that is missing to complete the fire triangle for initiating fire. The reports on oxygen fire and accidents indicated the following:

- An oxygen system may run for several years or decades without any problem before suddenly catching fire one day.
- Valves of all categories are the prime suspect as the location of initiation of fire. Non-metal seat is the first to be ignited. Bends and the attached instruments are also possible locations. In regulators, the components ignited are valve seat, valve biasing spring, diaphragm, and pressure adjusting spring.
- Contamination of the system or presence of particles is responsible for ignition. Contamination by lubricating oil also aids the process of ignition.
- Particles consisting of a mixture of polymers or non-metals are generally responsible for ignition. However, polymer fire often cannot engulf valve body. Presence of metal particles is necessary to act as intermediary to provide the heat of ignition to the valve body.

- Fires seem to start at the high pressure side of the valve.
- Heating above the AIT is not enough for particle ignition. Spark (by friction or otherwise) is necessary.

The laboratory experiments have mostly used external electrical energy as spark, while high velocity large particles or mechanical impact of large bodies have provided energy in some cases. However, scientific community has, so far, found it difficult to create and repeat fire incidents in a laboratory environment in spite of setting all parameters beyond the permissible values. It is known that movement of particles in a system results in the buildup of static charges in them. This static electricity, if supported by suitable geometric configuration and grounding of metal projections may lead to propagating brush discharge. It may thus provide the much-abhorred ignition energy needed for initiation of fire. Non-metal particles may help in initiating fire because of their low AIT while dispersed as dust particle cloud, while metal particles may help in propagation because of their high combustion energy.

Considering the valve seat as the location, particles (metal and non-metal) as the cause and lubricating oil as an extra aid for initiation and propagation of oxygen fire, there are three different hypotheses, which have so far been forwarded in the literature as the possible causes of initiation and subsequent propagation of fire:

- **Particle impact and adiabatic compression**: Newton et al. [5] reported the causes of failure of valves prominently as the combined effect of particle and pneumatic impact in the seat-plug region. They also emphasized on the accumulation of oil layer over the seat to contribute towards kindling, providing the thermal energy to the particles.
- **Mechanical Impact**: Spring loaded seats in valves and regulators react against fluid pressures. The impact of seat against the stem in case of transient flow causes sufficient heating of nonmetallic material in the seat region that is necessary for ignition [14]. The seat and plug impact is due to the rapid throttling caused by the imposed pressure and force variations owing to transient GOX flow.
- **Flow Friction**: As already mentioned, the phenomenon of flow friction is also thought to be a suitable candidate for ignition of non-metal valve-seat, though

experimentation reported so far have not been successful in establishing its contribution towards ignition [7]. However, it has been proved by experiment that the presence of contaminants, both metallic and nonmetallic, along with any ignition source should be there for initiation of the ignition process [7].

While the above three situations have been identified as the probable causes of ignition in oxygen systems, it has not yet been possible to create fire in laboratory environment each time, even if unsuitable material or adverse operating parameters one chooses to impose. Ignition in oxygen system has largely remained a probabilistic phenomenon. This has left the scientists always in doubt about the sufficiency or adequacy of the understanding of the phenomenon of initiation of oxygen fire. The present work hypothesizes yet another possible cause for initiation of fire in an oxygen system, particularly in the valves and regulators:

Propagating Brush Discharge: Flowing contamination particles in an engineering system get charged with static electricity due to their repeated impacts inside pipes, bends and valves. Valves, particularly the valve seat, constitute a potential location for accumulation of these charged particles, which create an electrostatic field around it. Operators are instructed to crack open the valves at the start of the operation of an oxygen system to avoid sudden on-rush of oxygen gas and consequent adiabatic heating. However, this brings the disk (or plug) very close to the non-metallic seat of the valve, which is the resting place of the charged particles. This configuration has the potential to create a high voltage between the grounded disk and the charged particles accumulated on the seat, which is backed by grounded conductor. This voltage may well exceed the breakdown voltage of the oxygen space and result in propagating brush discharge (PBD), which is proposed to be the source of energy needed to start ignition.

Estimation of concentration of particle contaminant and its behavior in oxygen systems is crucial for predicting the possibility of its ignition. A dust particle mixture with smaller particles would attain higher charge per unit mass than one with larger diameter particles. A settled dust layer without any dispersed dust particle may not be sufficient to cause ignition as the minimum ignition energy (MIE) of dust particle layer is high. On the other hand, a system with a high dispersed dust particle but without a dust particle layer is safe, as PBD can only result from the accumulation of charge in a settled layer. Only a charge dust particle layer can provide the condition of PBD. PBD has sufficient energy for igniting the dust particles under dispersed condition in an environment of enriched oxygen, when several coexisting factors, such as temperature rise due to adiabatic compression, low humidity, higher oxygen purity, higher oxygen pressure, etc., cause further lowering of MIE of particles. Investigation in this area may have the potential to redefine the existing international codes on the level of cleanliness required for a safe oxygen system by limiting the number of fine particles as well in a clean oxygen system.

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