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MISHAPS WITH OXYGEN IN NASA OPERATIONS

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INTRODUCTION

The successful design and operation of oxygen systems in aerospace applications have been based on the technologies developed by both industrial organizations, involved in the production and use of oxygen, and the government agencies, primarily concerned with its use. NASA has used over 8.5 million pounds of oxygen in a single operation and the storage, supply, and flow systems have been designed with safety as a major consideration.

Accidents/incidents with oxygen in our aerospace operations have occurred and some have been extremely costly in life and materials. In order to increase the safety of handling oxygen the Aerospace Safety Research and Data Institute at the NASA - Lewis Research Center is conducting a number of safety-related research projects which include a review of oxygen systems safety practices. The oxygen safety programs include a review of the hazards, the available data concerning the failure of components and systems in oxygen use, and the oxygen handling procedures followed by NASA and its contractors. These studies are expected to provide information for the development of design and operational criteria and standards to increase the reliability of oxygen systems and minimize the probability of the occurrence of future mishaps. A study of the scope and magnitude of mishaps also provides needed information on the selection of alternative components and/or systems.

The propulsion, power and life-support systems presently under development for use in earth orbit manned missions use large quantities of oxygen. The systems specifications include requirements for extended life and reuse capabilities which could result in an increase in the number of accidents unless continuing efforts are applied to the safety of the oxygen systems.

NASA SAFETY GOAL

A single safety goal has been imposed by NASA, as a basic ground rule, on the Space Station Phase B study contractors. This is: "As a goal, no single malfunction or credible combination of malfunctions and/or accidents shall result in serious injury to personnel or to crew abandonment of the space station." Credible accidents with oxygen could best be established from past experience. A review of accident/incident information to define the accident, its cause, and to recommend modifications, contributes to a better understanding of the hazards of oxygen which include fire, explosion, leakage and loss of pressurization.

This paper presents information from a substantial number of oxygen mishaps obtained primarily from NASA and contractor records. Information from several Air Force records, concerning oxygen accidents involving aircraft operations, are also included. The description of the mishaps and their causes, with both liquid (LOX) and gaseous oxygen (GOX) in ground test facilities and space vehicle systems are included in Appendix A. The mishaps are listed under the general heading of Accidents/Incidents and not identified as to the type of mishap according to NASA standards. The NASA Safety Manual (ref. 1) defines the various types of mishaps according to the degree of severity; Type A Accident, Type B Accident, Incident, Mission Contingency and Aviation Flight Accident (Appendix B).

This paper also includes a number of safety regulations aimed at reducing the accident probability. The problems related to material compatibility and materials testing are discussed, indicating the limited information on factors affecting the ignition of materials in oxygen. In addition, details are given of several of the accidents/incidents listed in Appendix A to define the combination of conditions causing the mishap. The need for further research is also indicated.

The principal source of the oxygen accident information was a compilation of mishaps covering several years of manned space flight activity by NASA (ref. 2).

About 500 accidents/incidents were selected from approximately 10,000 documents reviewed and are published in the reference report. The selections were based on mishaps which reflected significant lessons and on occurrences which involved equipment and facilities providing direct support to the space program and on occurrences resulting in personnel fatalities and/or injuries. The description of the mishaps, possible causes, and recommended corrective actions are included. In addition to propellant system mishaps, the reference report includes accident/incidents which have occurred to space and ground system structures, electrical systems, ground support facilities, ordnance and related operations. The mishaps pertaining to oxygen were selected from the reference report and are included in this paper. In addition, oxygen mishaps which have occurred in programs not specifically identified with the Manned Space Program are included.

Although many of the mishap reports did not contain completely satisfactory information as to the technical coverage of the causes and corrective actions, the available information was used to establish categories of events causing the mishap. The causes have been categorized in an effort to obtain additional lessons from the mishap reports. The categories include the following:

A. Materials Incompatibility Deficiency

This basic cause of oxygen mishaps includes incompatible materials brought together because of errors in design, installation, fabrication and operational procedures.

B. Materials Failure

Includes failure of materials or components due to stresses within the design limits. These include failures of pipes, tubing, valves, pump, etc. during operation or during development tests under conditions within their design specifications.

C. Design Deficiency

Includes inadequate component or system design specifications which contributed to the occurrence of the mishap.

D. Cleaning Deficiency

This factor has been identified as a separate cause which contributed or was responsible for the mishap.

E. Procedural Deficiencies

This cause factor includes inadequate operating procedures, planning, training, quality control, and management supervision.

The distribution of the accidents/incidents according to these basic deficiencies for LOX is shown in Figure 1 and for GOX in Figure 2. A total of 55 mishaps for liquid oxygen and 47 for gaseous oxygen are listed in Appendix A and were used to establish the distribution shown in the figures. In most cases, more than one cause factor was considered as being responsible for the mishap. For both liquid and gas, procedural deficiencies caused the largest number of mishaps, closely followed by design deficiencies.

Figure 3 shows the comparison of the number of mishap causes for the liquid and gaseous oxygen. Note the substantial increase in gaseous oxygen mishaps due to material incompatibility. With respect to possible reactions between the materials and oxygen, we should expect a greater number of mishaps with gaseous oxygen since a small volume of gas is generally a prerequisite to the ignition of the material. The thermal mechanism of ignition assumes hot spots could not occur without the presence of the gaseous phase at the spot. The large heat sink provided by LOX contact precludes hot spots on immersed materials unless the heat source is strong and is abetted by concurrent chemical reactions between LOX and the material being heated. The liquid, therefore, would have a reduced effect on initiating any reaction of the materials with oxygen until sufficient heat was transferred to form the gaseous state. Adiabatic compression as a means of producing high temperature for ignition of the materials also becomes inefficient at cryogenic temperatures. The theoretical temperature due to adiabatic compression can be calculated from the values of final and initial pressure and the ratio of specific heats (1.4 for oxygen). A pressure ratio of about 47, capable of producing a temperature ratio of 3, would heat oxygen, initially at 300°K to 900°K whereas the same pressure ratio applied to oxygen at 90.1°K would heat a gas bubble to 270°K. Temperatures of 900°K could be obtained in a cold gas bubble but the pressure required would be about 3100 atm. if the initial pressure was 1 atmosphere.

Material failures account for more mishaps in liquid than gaseous oxygen and are probably due to the change in mechanical properties of the materials used at the low temperatures. The change in toughness for both ductile and brittle materials at low temperatures are usually taken into account in the design of equipment but this information is probably the least understood of the low temperature mechanical properties. Toughness measurement techniques include impact tests, notch tensile tests and tensile elongation tests but the behavior of the materials under stress, especially in the presence of flaws, at the low temperatures are not sufficiently understood to avoid mishaps.

The distribution of the mishaps according to the deficiencies listed show many outstanding examples of failures to heed safety procedures as well as many areas for improvement. The preparation of detailed procedures for the handling of oxygen and the enforcement of such procedures would reduce the number of mishaps. These procedures should include not only details for the safe operation of oxygen systems but also the presentation of the planning, training, quality control and management supervision methods to enforce the recommended procedures. Improvements in both component and systems design would also have a major effect in reducing the number of mishaps.

Fires and explosions have been responsible for the major losses in equipment and for most of the fatalities that have occurred. The materials react with the gaseous oxygen but the source of ignition responsible for the initiation of the fire and explosion mishaps is difficult to isolate.

The accident/incident studies have indicated that impact, friction, chemical reactivity, static electricity, electrical sparks, and heat due to gas compression have all been responsible for the ignition of some materials in oxygen.

A number of practical safety regulations could be introduced to reduce accidents caused by procedural and design deficiencies, but material compatibility and ignition problems are more difficult to resolve. What materials to use for a specific environment of gas or liquid oxygen, high or low pressure, etc. for positive safe performance cannot be answered. Methods of evaluating and rating materials for oxygen use have been developed (ref. 3, 4, 5) and these studies are being continued. These evaluation tests include determinations of flash and fire point and impact sensitivity of materials. The flash and fire point tests were developed to determine relative reactivity of materials when subjected to an electrical discharge. The flash point is the lowest temperature at which a material will give off flammable vapors that, when mixed with the test atmosphere and exposed to the spark energy, will provide a non-self-sustaining flash or flame. The fire point is similar except the material gives off flammable vapors which continue to burn after ignition. Although many of the mishap causes indicate the use of non-compatible materials, mishaps have taken place under conditions for which compatible materials, based upon evaluation tests, were used. The conditions under which the materials will or will not ignite in oxygen are difficult to prescribe. The ease of ignition depends upon the state of subdivision of the material, presence of foreign materials and many other circumstances. Structural metals generally burn in oxygen only after heating to relatively high temperatures. However, iron, lead, nickel and many other metals ignite spontaneously in air if sufficiently finely divided. The foreign material in an oxygen system frequently exerts a major effect on the rate of oxidation reactions, hence the need to design an oxygen system in a way that facilitates rigorous cleaning. The effects of velocity, mass and shape of a particle striking a component in the oxygen system are not sufficiently clear. Ignition of materials in lines, pumps, and valves have been attributed to particle impacts. Methods for preventing ignition by abrasion or friction, a cause estimated to have been responsible for a number of mishaps, cannot be adequately defined.

Polymeric materials have been recommended for use in oxygen systems based on oxygen sensitivity tests, but these materials may still present a safety hazard in aerospace applications. The polytetrafluoroethylene insulations as well as many of the metals used are potential fuels and all that is required is an ignition source of sufficient energy. Teflon and other polymeric materials may be particularly efficient sources of ignition for aluminum and other metals because the decomposition products of the fluorides tend to remove the protective oxide from these metals. In addition, the recommended materials, when tested in oxygen-rich environments, may be non-igniting or self-extinguishing or slow burning, but the decomposition products may be toxic and present hazards to personnel. Toxic gases and vapors given off include carbonyl fluoride (COF_2), carbon monoxide (CO), formaldehyde (H_2CO), phosgene (F_2CO), hydrogen fluoride (HF), chloroform ($HCCl_3$), hydrogen cyanide (HCH) and carbonyl chloride (Cl_2CO). Results of thermal-decomposition toxicity evaluations as a function of temperature for many of the polymeric materials have been compiled by the Aerospace Corporation and are shown in Figure 4 (ref. 6).

The thermal-decomposition toxicity index I, a direct measure of the hazard due to toxic product production, is defined as:

$$k \sum_i P_i / LC_{50}^i$$

where k is the rate constant for decomposition of the polymer (hr^{-1}) and is a function of the decomposition temperature T; P_i is the mol percent of decomposition product i in the product gases; and LC_{50}^i is the toxicity of the product i in ppm.

The order of relative toxicity for the polymeric materials when heated from 500°F to 700°F shows Teflon TFE to be least toxic followed by Teflon FEP, polyimide film, Viton, perfluoropropylene polymer and carboxy nitroso rubber. At lower temperatures the order of merit is slightly altered, also, at higher temperatures, there may be rearrangements of the decomposition products so that substantial changes may occur in the toxicity indexes. The fact that all materials will produce toxic decomposition products when heated, points out the need for accident and fire protection to restrict burning of the material for the safety of the NASA manned missions.

SAFETY RECOMMENDATIONS

Although the solution to many of the problems which caused the oxygen mishaps cannot be specifically prescribed without further research and development efforts, several practical safety regulations are recommended to increase the operational safety. These recommendations based on specific mishaps in Appendix A include the following:

(a) Prevent the cross connecting of fuel, oxygen and purge lines by means of designs and permit no subsequent uncontrolled revisions by maintenance personnel.

(b) Suitably restrain all flexible lines at specific intervals.

(c) Prevent the venting and disposal of oxygen near electrical systems or other ignition sources capable of initiating and promoting fires.

(d) Provide controlled valve operation of oxygen valves to limit generation of heat due to gas compression.

(e) Label pressure lines with values of operational, proof, and design burst pressure.

(f) Conduct pre-operational hazard analyses on liquid and gaseous pressure systems before checkout, operation or maintenance.

(g) Insure verification of pressure relief before liquid and gas lines are disconnected.

(h) Emphasize hazards of operations in oxygen systems through training. Many operating personnel are not fully aware of the hazards associated with oxygen systems.

(i) Maintain records of any rework on tanks, lines and related equipment. The operations performed should be available to evaluate continued use of equipment.

(j) Fluids used should be identified and environmental chamber operations include a verification of the composition of the gas mixtures employed.

(k) Liquid oxygen loading rates should be established commensurate with duct and equipment fatigue capacities. Material failures have been induced by low stress, high frequency vibrations caused by excessive fill rates. Instrumentation should be installed to measure and monitor induced vibrations.

(l) Standards should be established interfacing the electrical systems to the oxygen systems. Problems of electrical arcing of interior lights and fixtures should be resolved.

(m) Insure availability of recent information on results of testing and of field experiences on the compatibility of materials with oxygen.

DISCUSSION OF SELECTED MISHAPS

The review of the reports indicates the mishaps are caused by a number of interacting factors. An effort was made in this paper to identify the cause as one of several basic deficiencies. In order to illustrate the interaction of deficiencies responsible for each mishap, a more detailed description, than is presented in the Appendix A, is given for the failure of an oxygen regulator, the motor vehicle fire at the launch pad and the Apollo 13 flight mishap.

1. Failure of Oxygen Resuscitator

During checkout of a 100% oxygen type resuscitator, a flash fire occurred in the high pressure side of the resuscitator. The unit was charged with 2200 psig oxygen and was being readied as emergency equipment for launch facility operations. The probable source of the fire was the regulator primary seat made of nylon. Ignition was most likely promoted by small metal particles which were found in the system. A schematic diagram of the resuscitator regulator is shown in Figure 5 and a photograph of the ruptured safety valve in Figure 6. A view into the regulator body illustrating the burned portions is shown in Figure 7.

The mishap was caused by procedural deficiencies which did not provide sufficient quality control; by the use of incompatible materials and by system design limitations resulting in galling between the stainless steel inlet valve camshaft and aluminum housing. The galling of the metals was most likely responsible for the metal particles found in the system. Redesign of the inlet valve camshaft assembly and the installation of a filter screen in the regulator are minimum changes required. The various rubber and plastic soft goods used in the regulator are listed in Table 1. With the exception of the TFE Teflon on the regulator inlet valve seat, all the materials are considered incompatible with high pressure oxygen systems.

Although the accident occurred with a particular make resuscitator, an inspection of oxygen resuscitators and pure breathing apparatus manufactured by other firms was conducted. Resuscitators manufactured by 5 firms were examined and on the basis of acceptability or non-acceptability of each item primarily determined on data contained in NASA publication, Materials Compatibility for Gaseous Oxygen Systems (ref. 7), approximately 50 to 90% of the materials analyzed in each resuscitator were unacceptable. Acceptable substitutes have been recommended.

2. Motor Vehicles Fire at Launch Pad

During launch pad clearing operations, three security cars were driven into an oxygen enriched area, the guards parked their cars, shut the engines, and got out for an inspection of the area. The LOX which was being dumped as part of normal operations vaporized and created an oxygen cloud which drifted into the path of the cars causing severe fire damage to the three vehicles. Prior to and during LOX pump operations for loading the Apollo Saturn vehicle, the LOX used in the storage area piping chilldown is normally drained into a ditch beyond a perimeter fence. Location of the LOX storage tank, three parked cars and drainage ditch is shown schematically in Figure 8. The drainage ditch approximately 40 ft. wide and 5 ft. deep is located about 227 ft. from the liquid oxygen storage tank.

A schematic showing the LOX chilldown outlets to the ditch is shown in Figure 9. Outlet number 1 used to chilldown the 1000 gpm pump was opened for 40 minutes and dumped 8000 gallons into the ditch. Outlet number 2 used to chilldown the 18" tee at the suction inlet of the 10,000 gpm, dumped a total flow of 2250 gals. Outlet number 3, used to chilldown the 10,000 gpm, and outlet number 4, opened after the three minute drain of outlet 3, passed a total of 860 gallons into the drainage ditch. The quantity of LOX dumped into the ditch was about

11,000 gallons and would be sufficient for a gaseous oxygen volume to cover areas of roughly 5, 10 and 20 acres to a depth of 4 ft. at concentrations in 100, 60 and 40% oxygen.

Results of the investigation indicated that two of the three vehicles caught fire in the engine compartment by autoignition resulting from engine heat, combustibles and enriched oxygen atmosphere. The other vehicle apparently ignited as the driver attempted to start the engine. This vehicle was also in the oxygen enriched environment.

A photograph showing the burned cars and their positions with respect to the fence and oxygen tank is shown in Figure 10. Detail comments from the official report on the accident (ref. 8) concerning results of the examination of each of the cars included the following:

Car No. 1 - Close-up Photograph Shown in Figure 11

(a) The fire was first observed by the operator in the engine compartment which upon examination indicated the most intense heat. It is believed that the point of ignition occurred in the engine compartment.

(b) The driver stated that vehicle had been operated for a sufficient time to be at normal operating temperature and that the vehicle ignition had been off for approximately five minutes when fire was first noticed.

(c) Normally, engine metal under the above conditions would attain an exhaust manifold temperature of above 600°F or above. Underhood temperatures increase after engine shutdown due to stoppage of the entire cooling system. It is believed that the increased, or high, temperatures caused vaporization of gasoline from the carburetor float level into the engine compartment and when augmented by an oxygen saturated atmosphere created an environment in which autoignition of combustibles occurred. Hydrogen gas vented from the battery could have attributed to the combustible underhood environment.

Car No. 2 - Close-up Photograph Shown in Figure 12

(a) Examination revealed that the most intense heat was in the engine compartment. The operator stated that the fire was first noticed after a "pop" in the engine compartment when he turned the ignition switch to the start position. It is believed that some underhood combustible material ignited in the oxygen saturated atmosphere when the ignition switch was turned. Sparks capable of igniting a combustible atmosphere could have been generated by any of the electrical components involved in the ignition sequences. There is no evidence that a fire occurred inside the engine crankcase.

(b) The driver stated that the vehicle had been operated only a few minutes and for a short distance. Based on this the engine would have not attained normal operating temperatures. However, it was considered that the underhood environment contained sufficient combustible vapors to ignite by an electrical spark.

Car No. 3 - Close-up Photograph Shown in Figure 13

(a) Examination revealed that the most intense heat was in the engine compartment. The evidence available indicates that the fire was first noticed in the engine compartment. The point of ignition is believed to have occurred in the engine compartment.

(b) Driver stated that the vehicle was not operating when the fire was first noticed, but had been operating for a sufficient time to reach normal operating temperatures.

(c) The underhood environment is considered similar to that in Car No. 1. That is, high temperatures and a relatively concentrated vaporization of gasoline from the carburetor augmented by an oxygen saturated atmosphere, created an environment in which ignition could have occurred either by autoignition or electrical spark.

Working or operating vehicles in oxygen clouds or oxygen enriched environments is hazardous since it provides an increased potential for ignition. The minimum spark energy required for ignition, the flash point and the autoignition temperature are all decreased. The deficiencies responsible for the accident included a combination of system design, procedural and training limitations. The overall loading and dumping systems should include methods of verifying, tracking and control of oxygen clouds. Procedures for alternate routes for emergency vehicles and fire control of personnel entry into oxygen clouds should be prescribed.

The safety training courses should include additional information to insure recognition and safe practices concerning LOX vapor hazards. Safe operations in and around areas suspected of having LOX vapors should be outlined in the safety courses.

Present operational practices include venting and dumping of relatively large quantities of both oxygen and nitrogen, with the resulting formation of vapor clouds. These clouds which may accumulate and persist for appreciable periods of time, depending on atmosphere conditions, constitute a significant hazard to personnel and equipment with which they come in contact. Additional studies should be performed to permit assessment of the occurrence and properties of such clouds, the hazards associated with them and methods for preventing or safely operating in the presence of such clouds.

3. Apollo 13 Flight Mishaps

The Apollo 13 mishap was initiated primarily by the rupture of the oxygen tanks which supplied the fuel cells and the breathing oxygen for the command module. The loss of oxygen resulted in the loss of the fuel cell power. The contingencies designed into the space vehicle, however, were sufficient for the lunar mission crew to overcome the emergency situation and use the available life support systems to return to a safe recovery. The detailed investigations provided reasonable explanations for the causes of the mishap and details of the interacting events leading to the final loss of power. Design limitations, materials incompatibilities, quality control (which includes inspection) and procedural deficiencies all contributed to the mishap.

A schematic showing the various major systems of the Apollo/Saturn V launch vehicle is given in Figure 14.

The oxygen and hydrogen tanks and fuel cells are located within the service module of the spacecraft. The arrangements of the equipment are shown in Figure 15. The internal components in the oxygen tank are shown in Figure 16. Two heaters in each tank supply the heat necessary to maintain the design pressure in the oxygen tank. Fans circulate the oxygen over the heating elements to reduce any stratification present in the supercritical oxygen.

The data obtained during the flight indicated that a problem arose in the oxygen tank (No. 2) when the electrical fan circuits were activated. Several short circuits were detected which were isolated to the fan circuits of the tank. The short circuit could have contained as much as 160 joules of energy and tests have shown that this is sufficient energy to ignite the polytetrafluoroethylene (Teflon) insulation on the fan circuit wires submerged in the oxygen.

The wiring conduit which contained the power leads for the fan motors and heaters and the instrument leads are fed through the vacuum shell in a hermetic seal which are then passed into the oxygen vessel through about 1/2 inch diameter tubing. Figures 17 and 18 show the oxygen tank wiring and lines. The 1/2 inch diameter tubing containing the wiring was formed into a 10 inch coil with about 3 turns. The interior of the conduit is open to the pressurized oxygen to the point of the hermetic seals.

The insulation on the power wires may have become abraded due to vibration of the conduit and the rubbing of the wires against each other. The method of assembling leads into the conduit may have introduced strains into the wires causing increased insulation wear. These conditions could then lead to situations where sufficient energy, produced by shorting power leads, could ignite the surrounding Teflon. Most probably, the Teflon insulation fire progressed into the electrical conduit tubing at the top of the tank, opening the tank to the service bay. With the burn-through of the conduit, the pressure increased in the bay resulting in separation of the panel which enclosed the bay. The panel separation from the bay probably caused sufficient shock to close the oxygen supply valves. In all likelihood, the oxygen system (in tank 1) developed a leak either as a result of the shock when the panel separated or from the dynamics of the events associated with the failure of the tank 2 electrical conduit. A photograph of the oxygen tank in the service module bay is shown in Figure 19.

Investigations of the operating and testing procedures conducted on the oxygen tank indicated that during the countdown demonstration tests, an oxygen detanking problem arose which had a part in the anomaly. The normal procedure for detanking of the oxygen, after the loading demonstration, could not be accomplished and the method employed was to boil the fluid through the use of the tank heaters and fans. It was thought that no damage would be sustained by the tank or its components because internal thermal switches provided protection. Thermal sensitive interlock devices were connected in series with each of the heating elements to avoid excessive temperatures. The heater circuit would be automatically opened when the internal heater tube wall temperature reached 90°F and closed at 70°F. The use of the heaters to assist in detanking required a manual mode of operation which resulted in the switches opening under a load at twice the normal operating conditions for each heater. Tests showed that opening the switches under these conditions would fuse the contacts closed at the instant of power interruption. Tests have verified that with the heater on, for the duration experienced during prelaunch operations, fan motor wire insulation would be severely degraded. A photograph of the fan motor wire damage from simulated heater tests is shown in Figure 20. A fused thermal switch control obtained under simulated tests is shown in Figure 21.

Studies of such mishaps (and especially using simulations of actual occurrences) provide not only the positive corrective actions, which reduce the possibility of such mishaps in similar launch vehicle systems but also indicate areas for improved safety designs and operations for systems using the same propellants. Problems requiring additional studies, research and development are also identified.

Examples of the actions taken by NASA resulting from this mishap included not only a review and analysis of all oxygen systems in Apollo but a renewed awareness of the criticality of metals and materials combined with heat/ignition sources in oxygen systems. A number of specific design changes and contingency operations initiated included the following (refs. 9, 10):

(a) Redesign and replacement of O_2 tanks, and supply systems in the service module.

(b) Provision of additional battery power for backup operation of the command service module.

(c) Review and refinement of Apollo systems for contingency operation and contingency plans.

(d) Review and analysis of all liquid oxygen systems in Apollo and other systems.

(e) Review and analysis by all NASA agencies for hazards and unidentified deficiencies in all ground based as well as flight systems using LOX and other oxidizer.

(f) Renewed awareness of the criticality of metals and materials combined with heat/ignition sources in oxygen systems.

(g) Increased review of anomalies when they occur.

(h) Closer quality control contacts to be maintained with vendors, subcontractors and suppliers.

CONCLUDING REMARKS

The NASA recognizes that some of the reports prepared do not contain sufficiently detailed technical descriptions of the mishaps or are not specific as to the hardware and/or operating procedures involved with causes of the mishaps. Efforts are presently under way to investigate methods of modifying the reporting procedures to include such information. The reporting requirements will also include more detailed explanations of the corrective actions that are recommended for the continued use of the system. The inclusion of detailed cost estimates of the mishaps would be of considerable assistance in providing management with needed information for establishing risk management prevention programs.

The compilation and review of mishaps with oxygen presented in the Appendix A and the brief descriptions of the interacting effects responsible for several of the mishaps emphasize some of the problems to be solved and provide basic inputs toward establishing adequate flight safety systems. Such studies are necessary to determine the potential hazards associated with oxygen, assist in the evaluation of the effects of such potential hazards, and finally help in establishing preventive and remedial measures.

APPENDIX A

LOX CRYOGENIC SYSTEMS

Liquid Oxygen Accidents/Incidents

Accident/Incident Description	Causes
1. A fire occurred at a liquid oxygen pigtail vent valve when it was ignited by instrumentation wiring. Extensive damage to the system resulted.	A valve design deficiency resulting in a leaking LOX valve and inadequate installation of instrumentation circuits.
2. When the valve was opened, a liquid oxygen container exploded due to use of improper lubricant on the LOX fittings.	Materials incompatibility and inadequate procedures and training to prevent use of unauthorized lubricants on LOX fittings.
3. A major explosion and fire occurred at a test facility during qualification testing of a booster engine fuel injector system. Major damage to the test set-up and the facility resulted.	Material failure in that the LOX splitter plate failed from fatigue, allowing LOX to be dumped into the test area. Contributing cause to the damage was inadequate cleanliness and housekeeping in the test area.
4. During qualification test of a LOX turbopump for a booster engine, the pump exploded on the 33rd start.	A pump design deficiency in that there was inadequate clearances between the LOX seal and the slinger and between the impeller and the backplate resulting in excessive rubbing.
5. Low stress/high frequency vibration during LOX fill operation of a stage, resulted in leakage of the GSE fill ducts and shutdown of the operation.	Material failure induced by low stress/high frequency vibrations caused by excessive fill rates. A fast flow rate of 10,000 gpm was completed and the slow flow rate was nearing completion. Engineering had not performed a fatigue analysis to determine an optimum fill rate.
6. A 63,000 gal. LOX spill occurred at a test stand when the LOX transfer valve was inadvertently left open after transfer operations were completed.	The transfer procedure was signed off as "valve closed" but it actually was open. The bleed valve was open, as it should be, to allow bleed off of residual and caused the tank to drain through the transfer valve.
7. During an engine sequence to check start tank, a LOX flowmeter spin occurred when the engine valves were opened. Spin lasted for 106 seconds at 700 RPM. No damage.	A pressure differential caused by pressure build up in the LOX system while tank vents had been closed for 110 minutes. The deficiencies included both design and procedural since evaluations had not been made for the tank vent closure time limits.

Accident/Incident Description	Causes
8. An explosion of a LOX container occurred when the valve was opened.	Noncompatible lubricants used and inadequate work control procedures to perform inspection of LOX installations.
9. An explosion occurred in a LOX system when it was inadvertently over-pressurized due to installation of improper bleed plugs in a pressure regulator.	Deficiency in work control procedures and inadequate identification of bleed plugs. Contributing was inadequate inspection of test installation.
10. During transfer of LOX from tanker to tanker, the main valve malfunctioned resulting in dumping of 3200 gallons of LOX on the ramp.	The liquid control valve design for the pressure build-up coil was deficient. It was jammed by a piece of aluminum which apparently came from one of the baffles in the tank. Tank and system design deficiencies contributed to the accident.
11. During de-fueling operations after a test, a fire occurred at the vent when LOX was ignited by an electrical short during venting.	A design deficiency in the test installation in that the LOX vent was located in a manner in which vapors were emitted in the area of electrical wiring.
12. A major LOX spill (26,000 gal.) occurred at a test stand during securing operations following a test. The tank valve was left open during a lunch period after the piping system drain was opened.	System was maintained in operational mode after the test due to planned test of the turbopumps. Subsequently, a decision was made to secure. The technician went through normal draining operations that would be done with the tank valve closed and did not close the tank valve. There was no verification procedure in effect for valves.
13. During a human factors analysis of a stage fuel system, a potential for cross-connecting the fuel test line flex hose and the LOX sensing flex hose was discovered. Corrective action prevented such an event, however the potential for a major explosion existed.	Lines had been designed in assemblies of flex lines of the same length and size which included both fuel and LOX lines. The lines were not color coded and were of the same length, permitting cross-connection.
14. Apollo SC 204 fire. Fire in Apollo command module on launch pad resulted in fatalities and extensive damage. Atmosphere - 100% O_2 at approximately 16 psia. Fire was propagated thru spacecraft by materials which were very flammable in 100% O_2 as compared to air.	The probable source of ignition was associated with the spacecraft wiring. The results of the investigation concluded the deficiencies which led to the disaster included inadequate work procedures, use ofnoncompatible materials and inadequate system designs. These conditions included (a) a pressurized oxygen atmosphere in the sealed cabin; (b) large quantities of combustible materials in the cabin; (c) wiring and plumbing located in hazardous locations; (d) inadequate escape and rescue provisions for the crew.

Accident/Incident Description	Causes
15. During operational testing of a stage, the gas generator LOX injector purge flex line was cross-connected with the thrust chamber injector purge flex line on an engine. This resulted in contamination of the flex lines and the LOX dome. No injury to personnel.	A design deficiency in that adjacent flex lines were not properly coded and were of similar size and design. This contributed to the error on the part of the maintenance personnel who cross-connected the flex lines. Contributing causes were workman was in an uncomfortable posture when connecting the lines, with lighting that is not optimum, and cramped for space to use tools.
16. During initial activation test of an Altitude Simulation Facility, a LOX fire occurred when LOX was turned on after normal purge operation and resulted in damage to a facility pump and piping. LOX pressure 500-600 psi, pump driven by 250 HP motor.	Ignition apparently occurred as a result of contamination in the line and LOX impact. Piece of impeller between housing and impeller. Shock of impact damaged impeller. Inboard thrust bearing failed which may have generated sufficient energy for ignition. The pump design was not adequate to prevent failure and the installation and maintenance procedures were not adequate to prevent contamination. Also purge and inspection procedures were not satisfactory.
17. During altitude simulation test of a booster stage, a piece of Buna rubber broke off the LOX feed valve and caused impact ignition when it struck the pump impeller, destroying the pump. LOX pressure 980 psig, driven by 250 HP motor.	A design deficiency in using noncompatible materials (Buna rubber) in a LOX system. Contributing cause was failure to transmit information from a previous incident, when a piece of Buna rubber was found in a LOX discharge screen. Valve material noncompatible with LOX.
18. During a demonstration test involving nine pressure and temperature countdowns to demonstrate certain capabilities of foam insulation, a LOX tank dome ruptured and scattered throughout the test area. Occurred on seventh countdown when pressure reached 77 psig in a scheduled 79 psig test. No personnel were injured.	Failure to proof test the tank after a weld rework. Contributing causes were poor workmanship in the welding and inadequate inspection of welds. Complete history of repairs or modifications was not available.
19. During pneumatic control subsystem checkout, a LOX chilldown pump housing was inadvertently overpressurized and had to be replaced when two adjacent lines were cross-connected.	Installation error caused by identical pipes and joints located together in a manner that permitted cross-connection. The purge line to the chilldown pump was connected to the shutoff valve piping. A contributing cause to the accident was a design deficiency in not locating pipes so they could not be cross-connected or sizing or keying to prevent cross-connection.

Accident/Incident Description	Causes
20. During unloading of LOX from rail car to sphere, a LOX spill occurred when fill hose was disconnected. Two men were exposed to LOX.	Failure to allow sufficient boil off time prior to disconnecting fill line. Contributing cause was lack of specific instructions for boil off times of different types of cars.
21. During countdown for static firing, a leak occurred at 12th level in the LOX fill and drain lines. The topping operation was discontinued for assessment but a dangerous condition resulted when an excessive number of people were allowed in the area during this emergency.	Material failure of the LOX hoses, causing cracks. Contributing to the potentially hazardous condition was inadequate control over entry of personnel to the area during an emergency.
22. A LOX system exploded during a static firing due to cleaning fluid corrosion in the system.	Noncompatible cleaning fluids were used and periodic inspection for corrosion was not accomplished.
23. A LOX system caught fire and exploded due to the use of hydro-carbon lubricants on connections.	Failure to specify compatible lubricants for use on oxygen system.
24. A titanium sphere used in a LOX system exploded and burned causing serious system damage.	Design deficiency in using a titanium sphere in a LOX system. Titanium is not compatible with LOX.
25. A LOX system was contaminated by use of incompatible ink used for internal stamping during manufacture of components, causing complete analysis of system and cleaning of components to be performed.	A cleaning procedural deficiency in manufacturing. Action had not been taken to determine compatibility of the ink with LOX prior to specifying its use.
26. Electrical wiring and plumbing were damaged in a test set up when electrical wiring near an oxygen pig tail vent shorted and ignited the oxygen.	A design deficiency in the test installation. The pigtail vent was located in such a manner that it vented directly to adjacent wire bundles. Contributing was a procedural error in continuing the test with a leaking LOX valve which resulted in the venting and the fire.

Accident/Incident Description	Causes
27. A malfunction occurred during a propellant laoding operation. The oxygen alarm (over 25%) and abort sequence were initiated. The emergency check list required opening of the boil-off valve but was purposely omitted because of the high oxygen concentration that had been indicated. The pressure increased reaching a value of 29.5 psi at which time the valve opened. Oxygen was observed coming out of the enclosure area. Two explosions occurred after about 30 minutes after the tank pressure indicated about 7 psi.	There was an excessive loss of oxygen after the pressure was allowed to build-up and suddenly released. The boil-off valve should not have been allowed to remain closed for that long a period. Ignition could have been due to a number of the electrical systems existing in the area just outside the enclosure section. System design deficiencies did not provide satisfactory venting systems or limit maximum valve closure times.
28. After a propellant loading exercise, the liquid oxygen was being removed from a vehicle located within enclosed area. A major fire and explosion occurred destroying both the vehicle and enclosure. The fire initiated in the 40 micron stainless steel filter which was located within the filter housing .	Ignition of the primary fire was due to organic contaminants inside the filter case. The most probable source of organic contaminants was (a) wicking of hydrocarbon contaminants through flange to gasket, (b) contamination of the filter vent plugs and (c) accumulation of material present in LOX supply and LOX replenishment.
29. An explosion occurred during flow through a LOX ground-supply line filter. The facility used a stainless steel filter cartridge maintained against an aluminum support plate.	Explosion was probably initiated by abrasion of aluminum by small hard particles present on filter. Chattering of steel cartridge against aluminum plate was noticed. Materials incompatibility, design deficiencies and inadequate cleanliness all contributed to the accident.
30. During pressurization of LOX system, the flexible hose assembly failed. The inner line was 321 SS with a seamless tubing bellows and a wire braided outer covering. Tubing was rated at 2500 psig min. Examination of the failure indicated corrosion of the wire braid, and pitting of first and second convolutes.	Failure of the flexible hose was probably caused by movement of the wire braid destroying the protective or passive layer on SS. Water entered resulting in corrosion. A design deficiency and limited inspection to ensure protection of the system against the environment were responsible for the accident.

Accident/Incident Description	Causes
31. During a LOX manual loading test, the corrugated flex-hose assembly located between the manual and remote operated pump suction valve ruptured immediately after the valve was opened. Wire mesh braid failed which allowed the pressure in the line to extend the flex hose until the weld at the end of the corrugations failed. Twisting moments exerted on the line and valve caused separation and movement of the system and pulled loose a pipe support. 800,000 gallons of LOX was spilled and the tank was partially collapsed from vacuum. The seal bellows which connected the inner sphere relief valve standoff to the outer shell collapsed. The carbon steel pump baseplate was cracked.	A design deficiency in the main pump suction valve and input lines permitted trapped air in the line to escape when the valve opened causing a rapid acceleration in the flow of liquid. The liquid reached the valve prior to achieving its fully open position. The liquid hammer effect forced the valve to a closed position causing excessive tension on the hose. The use of a flex hose upstream of the valve is indicative of an unacceptable design. The inner sphere collapsed due to the negative pressure since the liquid flow could not be terminated. The relative location of the valving was not designed to permit termination of the flow. Design changes should include supports on either side of the remote operating valves and a remotely operated system to feed LOX into line upstream of valve. The system design was also deficient in not providing vacuum relief devices to prevent ullage pressure of inner sphere to reach below atmospheric pressure.
32. A LOX-RP-4 test vehicle was destroyed by fire and explosion. Initial testing indicated some difficulty with LOX feed system and the LOX pump inlet flange and inlet assembly showed erosion and metallic deposits.	Ignition of oxygen and pump parts was probably caused by heat due to friction produced by rubbing between impeller and wear ring diverter lip. Excessive pitting was evidenced on inner surface of volute. The pits contained foreign material like sand and chromic acid. Droplets of aluminum alloy found on wear ring. Design deficiencies and contamination in the line and pump parts contributed to the accident.
33. During preparation for a stage engine LOX dome flush procedure, the high pressure GN_2 facility valve was opened to pressurize the tank with regulated 500 psig and simultaneously regulated 500 psig GN_2 was introduced as back-pressure on a spring loaded vent valve on the tank. The vent valve blew out when the regulator supplying back-pressure stabilized at 2100 psig instead of 500 psig. No personnel injuries, however the vent valve was destroyed.	System design studies and a hazards analysis of the facility installation and flush procedure, which would have detected the need for relief capability in the system, were not performed. Contributing was the failure of facility inspection to detect the absence of relief capability as specified in construction/installation drawings.

Accident/Incident Description	Causes
34. A flex hose from the pressure checkout and calibration panel of a booster manufacturing tower was used to activate a stage LOX prevalve to a closed position so that installation of a LOX low pressure duct could be performed. Second shift manufacturing personnel unaware of the flex hose installation, pressurized the panel to 100 psi for engine purge operations on another vehicle and consequently the prevalve actuator was subjected to approximately twice its operating pressure.	Installation of the flex hose without formal documentation or procedural authorization and failure to pass information from one shift to another as to the panel configuration were the causes of the accident.
35. During leak check tests on a LOX valve, following maintenance and cleaning, laboratory pressure of approximately 2000 psi was applied through an unsecured flex line causing it to snap and in so doing, forcing the valve in an unmounted vise off the table. No personnel injuries.	The flex hose used was of excessive length and was not restrained. The test article was not properly secured prior to test, test procedures were not adequate and there was no inspection verification of the test setup.
36. During cleaning of a 5000 gal. oxygen tank using trichloroethylene, a flash fire occurred in the tank when a piece of plastic fell into the tank and onto the heater element rod. One man received minor injury.	Procedural deficiency in not exercising adequate control of the area during hazardous cleaning operations, to prevent contamination. "Housekeeping" was marginal and area inspection lax.
37. During fuel cell pressurization of a flight vehicle the O_2 system was overpressurized to 25% above design burst, when a new "K" bottle pressure source was added. Although no damage occurred, the system could have been damaged.	Failure to close regulator valve. The regulator valve on the "K" bottle source had been opened as the supply was depleted. When the new "K" bottle was added, the regulator valve was not reclosed, allowing a maximum of 2200 psig to be applied to a 350 psig system.
38. During third acceptance test of a booster engine, a turbopump fire occurred as a result of LOX leakage into the pump gear box. There was extensive damage to the engine and minor damage to the facility.	A design deficiency in that there was shaft-to-seal movements which impacted the seal against the mating ring and caused LOX leakage into the gear box.

Accident/Incident Description	Causes
39. During a laboratory test for qualification of a LOX prevalve for engine shutdown of a booster engine, the test system exploded ten seconds after initiation, destroying the valve, and damaging the test facility and the test engine.	A design deficiency in that the pump developed an uneven two-phase flow and cavitation after closing of the LOX prevalve. This flow condition caused uneven loads on the impeller and ultimate failure.
40. During static firing test, a fuel leak occurred and resulted in a fire which burned through measurement wires causing test shutdown. Configuration of the LOX system following shutdown caused rupture of a LOX interconnect line and approximately 50,000 gals. flowed into the stage thrust structure and on engines. Fire damaged engine harnesses and hardware.	A polyethylene shipping disc had not been removed from a fuel connection and caused the fuel leak. Contributing causes were design deficiencies in the shipping disc such that it was not properly color coded or identified as a shipping disc and was not sized or configured to prevent inadvertent installation on the operating system. Test termination resulted in the closing of the oxygen prevalves. With the closing of the prevalves, the LOX interconnecting valves opened automatically allowing "hot LOX" to escape into the suction lines. This resulted in geysering in the LOX feed system.
41. During LOX tank repair, an electric heater blanket was installed on the LOX filter unit to provide heat inside the tank. The blanket overheated and the stage LOX tank caught fire, causing extensive damage.	A modification had been made to install the heater blanket without a formal engineering work order, without a hazard analysis and without safety approval. The installation of the 220V AC blanket was made to a 440V AC line. No temperature control devices were provided on the blanket.
42. A thrust chamber purge was inadvertently applied to a stage without the LOX dome purge being "on" resulting in contamination of the LOX system and blowing off of engine exit covers.	An erroneous verification to the operator that the RP-1 fuel simulator had been installed. Contributing cause was an engineering deficiency in not preparing an engineering order change requiring the installation of the simulator.
43. The main stage exploded during final countdown phase of static firing, destroying the stage and causing major damage to the facility. Explosion caused by rupture of stage LOX tank.	Two redundant LOX vent valves failed to release due to presence of solid oxygen. Solids formed due to the use of cold helium gas for pressurization from tanks located within the liquid hydrogen fuel tank. Normally the helium passes through heater before entering LOX tank. Contributing causes were failure to follow approved procedures and an unsatisfactory helium shut-off valve during cold conditions. Test preparation was inadequate in that a number of valves were overlooked during pretest checks and were not in the proper position.

Accident/Incident Description	Causes
44. During inspection of a stage LOX tank, a plastic container and cleaning pads were found in the screens and bottom of the tank.	The cleaning and inspection operations were inadequate. Procedures for work control during the installation were deficient.
45. During removal of the oxygen shelf from a spacecraft, the shelf was damaged when a weld failure occurred on an installation adapter.	The cause of accident was due to both procedural and design deficiencies. The proof loading requirements was authorized without following the prescribed procedures. In addition, the handling equipment was designed for a shelf weight approximately 90 lbs. less than the actual shelf weight.
46. During development tests of LH_2-LO_2 stage an explosion destroyed the booster stage after being loaded with propellants. The explosion took place just prior to the static firing.	There was an excessive level of oxygen in the LH_2 tank vent line and a flash back from the burn stack at the end of the tank vent line initiated the explosion. The procedures for inerting the LH_2 tank were inadequate permitting a dangerous oxygen concentration to be present. The system design was deficient in not providing measurements of the oxygen concentrations.
47. During development testing of a LOX-RP fuel stage engine an explosion occurred in the open air at the test facility. The explosion caused extensive damage to the test stand.	An inproperly designed gaseous oxygen igniter installation and nitrogen purge system prevented the flow of oxygen and ignition of the fuel in the chamber during the start sequence. A large amount of fuel flowed out of the engine and ignited outside the chamber. The plumbing installation was not designed properly nor were procedures set up to check the system operation.
48. During testing of LOX-LH_2 engine, a leak in the oxygen system and fire caused extensive damage to the test stand, liquid oxygen system, thrust chamber propellant valves and other flight hardware. Accident occurred during initial testing of systems.	At the time of ignition, the chamber pressure increase produced an increase in system back pressure and was propagated into the oxidizer manifold. This was followed by a second pressure surge. The vibrational modes and high "g" loads resulted in actuator lipseal failure. During rapid valve closure severe vibrations caused metal-to-metal contact and rubbing of the aluminum against the Inconel-X. The heat developed due to friction is believed to have caused the fire. Hydrocarbon contaminants found in turnbuckle cavities in valves may have also been the source of ignition. A satisfactory level of cleanliness was not maintained. Iron oxide, aluminum oxide, phosphate lubricant, fluorolube, aliphates hydrocarbon and paraffine hydrocarbon were found in the systems. Increased quality control surveillance required. Valve design changes suggested.

Accident/Incident Description	Causes
49. A liquid nitrogen supply was contaminated with oxygen and although no injuries or serious incidents resulted, the potential was great. Liquid nitrogen was supplied by a vendor in a truck that was used for the transportation of both liquid oxygen and liquid nitrogen. Apparently the truck was filled with liquid oxygen remaining in the vessel. The error was discovered when a technician noticed a bluish hue to the liquid.	Requirements for vendor practices were not sufficiently detailed. Purging requirement specifications were not properly adhered to. The tank truck contents should be analyzed prior to transfer and specific gravity measurements taken of the tank contents. Further procedural actions should include consideration of one truck only for LN_2 and to fill dewars from plant storage tank rather than vendor's local storage tank.
50. During preparations for static testing, LOX was being pumped from two adjacent LOX barges. An explosion and fire occurred on the one barge and a fire on the second barge. The barge pump thrust bearing or LOX mechanical seals failed. The seal leaked and the radial bearing temperature dropped. The thrust bearing continued to fail allowing rubbing of the impeller and aluminum pump housing.	The rubbing of the impeller against the aluminum housing caused ignition inside the pump. Catastrophic failure of pump occurred due to excessive pressures. A leak on the second barge was caused by loss of several studs on pump discharge flange due to excessive vibrations of the LOX pump. The recommended procedures in reporting out-of-limits temperature indications on the radial bearing of the LOX pump prior to the pump's failure was not followed. A design deficiency existed in that inadequate observation and instrumentation were provided to fully detect incipient problems. Pump design, although considered adequate was not capable of limiting deformation of the mechanical seals to pressures in excess of the 50 psig specification which could occur due to the vaporization of LOX.
51. During stage static firing test with LOX and LH_2 propellants, an explosion occurred destroying substantial equipment. The stage exploded before scheduled ignition of the propellants. Damage resulted to structures about 800 ft away. Also damage to metal door on facility shop about 1600 ft distant. Damage report heard 12 miles away probably due to heavy cloud cover (reflection and focusing of sound waves).	The explosion was due to a catastrophic failure of a high pressure titanium sphere. The tank contained helium gas for propellant pressurization. A human error resulted in use of commercially pure titanium filler wire for welding the spheres which were made of Ti-6Al-4V. The use of pure titanium for welding in place of the filler having the same composition as the sphere resulted in a 30 to 40% reduction in strength. The tank that initially failed was held to a support structure and during failure forced in the LOX bulkhead. The yield of H_2+O_2 was estimated to be 1% TNT equivalent. Attention was not given to production check or vendor control. Control and procedure check for welding not satisfactory.

Accident/Incident Description	Causes
52. During launch pad clearing operation, three cars driven into an oxygen enriched area ignited. LOX was discharged into a drainage ditch and cars driven into oxygen fog. All three vehicles were parked with engines off. Center vehicle engine key was turned on and fire started under the hood; other two cars started on fire immediately after. All three cars were destroyed.	The dumping of large quantities of LOX and the resulting formation of vapor clouds constitute a significant hazard to personnel and equipment with which they come in contact. The vehicles were driven into and parked in the oxygen cloud. A flammable mixture of oxygen and hydrocarbons accumulated under the hood of the three cars while they were parked with the engines off. The mixture in the second car was probably ignited by a spark from turning on the ignition key. For the other two cars, ignition probably took place when the flammable mixtures contacted the hot surfaces of the exhaust manifold. The quantity of LOX dumped into drainage ditch suggests a volume of 40% GOX covering about 20 acres to a depth of 4 feet. System design deficiencies and procedural deficiencies contributed to the accident.
53. During installation of equipment for engine testing, the purge lines to the fuel and oxygen systems were cross-connected and placing the LOX and fuel system in a common line. The oxygen lines were contaminated with hydrocarbons.	The procedures for connecting lines were not followed; in addition, the work was done without authorization. A design deficiency permitted such a line interconnecting.
54. During purging of a propellant loading assembly, a reducing fitting was installed in a LOX line and connected to a flex hose. When the valve downstream of the fitting was opened, the workman was subjected to a stream of liquid oxygen.	The accident was caused by both design and procedural deficiencies. A leaking LOX valve permitted trapping of LOX in the line. The connections were inadequate as well as the procedures which did not detail the operations to be followed. The quality control inspection of the connection was deficient.

Accident/Incident Description	Cause
55. The Apollo 13 mission mishap involved failure of the liquid oxygen supply for the command and service module and consequently loss of H_2-O_2 fuel cell operation. Sufficient contingency actions were taken to ensure a safe return of the lunar mission crew. The liquid oxygen supply tank (Tank No. 2) failed at the electrical conduit tubing at the top of the tank. The release of oxygen into the bay 4 of the service module resulted in separation of the panel covering the bay 4 area. The panel separation caused the oxygen supply valves to close resulting in the eventual loss of pressure in the second oxygen tank (Tank No. 1).	The accident was caused by interacting effects due to design limitations, materials compatibility limitations, and inspection, quality control and procedure deficiencies. The evidence from the studies conducted indicated that the polytetrafluoroethylene insulation on the fan wiring was ignited by a short circuit. The fans in the oxygen tank are activated to reduce any stratification in the supercritical oxygen. The burning of the insulation caused the tank pressure to rise resulting in the opening of the relief valve but the burning had progressed so that all electrical circuits to the oxygen tank had shorted. The fire apparently progressed into the electrical conduit tubing at the top of the tank and opened the oxygen supply to the service module. One of the service module panels separated resulting in the loss of tank pressure in the adjacent oxygen tank due to closing of oxygen valve. The procedures in operations and fabrication did not provide for sufficient review of anomalies when they occur. Sufficient awareness of the criticality of metals and nonmetals combined with heat and ignition sources in oxygen system was not demonstrated.

GOX SYSTEMS

GASEOUS OXYGEN ACCIDENTS/INCIDENTS

Accident/Incident Description	Cause
1. Explosion and fire occurred in 2 inch stainless steel piping containing oxygen. The piping contained 2200 psi oxygen and was fitted with a stainless steel ball valve. The stainless steel ball and pipe were ignited and the pipe burst in several places.	The pipe line containing the oxygen was considered to be contaminated with a halogenated hydrocarbon. Ignition occurred due to friction through the restricted opening of a ball valve as it was opened. (friction produced by operation of valve parts).
2. Fire occurred in Two Man Space Environment Simulator. Environmental conditions at time of fire were 100% O_2 at 380 mm Hg. The chamber was repressurized and opened within 30 seconds subsequent to the initiation of the fire. The accident resulted in fatalities.	Fire attributed to short circuit caused by accidentally kicking power plug located in a floor-lined receptacle. The chamber contained two small portable CO_2 fire extinguishers but one overheated and discharged through the pressure relief valve. System design and procedural deficiencies contributed to accident.
3. An oxygen high pressure gas system failed at valving. The GOX pressure was a maximum of 2250 psi. Accident resulted in 2nd and 3rd degree burns.	Accident attributed to either build-up of contamination on valve seat or sudden entrapment of contaminants between ball and seat of valve.
4. A GOX aircraft bottle failed causing fire and explosions. Bottle pressure was 1800 psi. Accident resulted in injuries.	Materials incompatibility and procedural deficiencies contributed to accident. A loose nylon poppet moving under 1800 psi or heat generated by compression ignited the poppet in the valve, causing fire and explosion.
5. Aircraft oxygen breathing equipment failed causing explosion and fire. Extensive damage to equipment and injuries. Oxygen pressure - 1800 psi.	Accident attributed to letharge-glycerol cement in oxygen cylinder ignition by heat generated by compression of gas when cylinder valve was opened.
6. In space-cabin experiment with 100% oxygen, hot resin from the base of the power tube in TV cabin monitor dropped on coolant lines passing beneath. Ruberoid insulation on coolant lines did not catch on fire but fumes from the hot resin alerted the crew.	The power tube in the TV cabin monitor failed causing ignition of the resin base and melting of the hot plastic. The molten resins and Ruberoid insulation did not burst into flame. Procedural and design deficiencies were responsible for the accident.Materials failure also contributed to the accident cause.
7. An explosion occurred when capacitor was discharged during experiment with Febetron Pulsed Electron-Beam X-Ray Equipment. The gas was 99% oxygen and was contained within flask designed for 2015 psi; working pressure was 240 psi.	The explosion was caused by the capacitor discharge in pure oxygen which was mislabeled "Compressed Air, 79% Nitrogen, 21% Oxygen".

Accident/Incident Description	Cause
8. An explosion and fire occurred in the filter of high pressure oxygen pump equipment. The equipment was used for charging self-contained breathing equipment oxygen cylinders.	The explosion believed to be caused by the burning of oxidizable material in bottom of filter. The material was believed to be glycerine which was used for lubricating the pump.
9. During test of a life support system oxygen source valve caught on fire and melted. The oxygen source consisted of two six (6) cylinder K-bottle assemblies hooked into a common manifold at 2200 psi. The fire occurred when the valve was turned on to maintain the manifold pressure. Personnel injury and system damage was sustained.	The fire apparently started in the valve seat which was made of a polyether material which had not been tested and approved for oxygen compatibility. Also, procedures for cleaning and inspecting of oxygen system components were not adequate. The system contained numerous contaminants consisting of aluminum chips, rust and organic materials. Additionally, there were no filters installed between the source and inlet valves and lines were of stainless steel with teflon parts.
10. During conduct of pneumatic tests on a stage, an 8' flex line failed at 2000 psi and subsequent whipping damaged adjacent GN_2 hard lines and propelled fragments for 75 ft.	Material failure of the flex hose. Contributing to the extensive damage that resulted was the lack of restraint of the flex hose.
11. In preparation for an O_2 subsystem checkout test of a flight vehicle, an incorrect hookup of a flex line to a water line instead of an O_2 line resulted in rupture of the potable water tank and damage to the waste water tank and water panel when 250 psig GN_2 was applied to the H_2O system. No personnel injury.	The flex lines of the vehicle system were incorrectly tagged and no procedural instructions or verification methods were used prior to application of GN_2 pressure.
12. While performing a leak check of a ground service equipment setup during a prelaunch systems checkout on a spacecraft emergency O_2 pressure system, a wrong flex line was disconnected and capped, allowing the O_2 pressure system to be inadvertently pressurized to 50% above the design burst level. No damage resulted but it constituted a potential accident.	Failure to follow test procedures which required the O_2 emergency system to be isolated from the GSE setup during leak checks of the GSE equipment. Contributing cause was inadequate. Quality control/supervision and surveillance during critical prelaunch checks.

Accident/Incident Description	Cause
13. During pressurization of a stage O_2 system, it was inadvertently overpressurized to 570 psig when the specified pressure was 350 psig. No damage occurred but potential damage to system was effected.	Deviation from normal procedures to save time. The GSE regulator was increased to 750 psig to save time and when pressure reached 350 psi, the regulator was not reset until the pressure reached 570 psig.
14. Electric sparks (static discharge) were observed during handling of O_2 conditioning cannisters under atmospheric conditions in a vehicle. Static electricity was not bled off causing electrical discharge - which could be a source of ignition in a 100% O_2 atmosphere. No personnel injuries.	A design deficiency in selection of insulating material in the storage boxes for the cannisters. The material generated a static charge when the stainless steel cannisters were removed, due to inadequate grounding of storage boxes.
15. During checkout of the fuel and propellant system in the high pressure test facility, the fuel and oxidizer orifices did not flow in accordance with specification. Complete analysis of the system revealed a plastic cover in the oxidizer line downstream of the orifice, reversal of the fuel and oxidizer orifices during installation and damaged lines, strainer and orifices.	Inadequate work control procedures during assembly, packaging, installation and cleaning. The plastic cover was identified as a type used to seal line ends during cleaning or packaging. The oxidizer orifice had been installed on the fuel line and vice versa during assembly and the strainer, lines, and orifice had received minor damage during installation. Contributing cause to this incident was inadequate inspection of critical work and failure to exercise positive control over materials used in assembly and packaging of critical flight systems.
16. During hydrostatic proof pressure test of pressure bottle for a spacecraft emergency oxygen system (13,250 psig) the bottle weld failed at 9000 psig due to a faulty weld. The pressure vessel was destroyed, however, no personnel injuries were sustained.	Inadequate manufacturing control and inspection procedures. The weld seam failed due to incomplete fusion of the bottle half, apparently caused by either improper centering of the high intensity fusion welding on the seam or being directed at an incorrect angle. X-ray inspection of the welded seam did not reveal the discrepancy.
17. After completing transfer of a CO_2/O_2 gas mixture from a "K" bottle to a small hoke-type cylinder, attempted closure of the cylinder needle valve resulted in the valve failing and the valve stem blew-out at a pressure of 1350 psig. No personnel injuries, however, a potentially hazardous condition existed.	Material failure of the valve stem and the apparent lack of an established procedure for periodic hydrostatic tests or other controlled maintenance as evidenced by no inspection or test record stamp on the cylinder.

Accident/Incident Description	Cause
18. A fire occurred during the operation of a high pressure oxygen service system. The nylon seats of ball valves were tested and found to decompose and burn under the high pressure conditions.	A design deficiency in specifying nylon seats for ball valves. Test results showed that nylon decomposed and burned due to heat of compression at high pressures. (Test pressures used were 1800 to 4000 psig.)
19. During checkout test in high Mach number tunnel in which oxygen enriched combustion air is made to burn with methane, a fire and explosion occurred downstream of the orifice used to measure the flow. The fire occurred when a switch was operated which would permit actuation of an air signal for the control of the oxygen control valve. High pressure was introduced into the system which resulted in the rupture of the pressure transducers and transmitter allowing damping fluid to be discharged into the main oxygen line. The oil reacted with the oxygen, promoting combustion of the stainless steel piping and valving.	A system design and operational performance deficiency permitted sufficient pressure from a previous run to remain in the line leading to the control system to operate the control valve without actuation of the air signal control systems. Opening of the control valve rapidly probably resulted in rapid compression with temperatures from 1900 to 2200°R. The high temperature and pressure caused rupture of the bellows in the flow measuring instruments, atomizing the damping fluid and causing fire and explosions at downstream connections. Material and R&QA requirements were not sufficiently detailed to preclude the use of noncompatible materials.
20. During proof testing of a spacecraft 0_2 control module on an environmental control system, a fire occurred which blew off a cap boss when an 0_2 ring seal failed permitting a subsequent 1400 psig pressure surge.	The 0_2 ring seals were being reused on subsequent tests in lieu of installing new seals. Also, a thread lubrication which was not compatible with oxygen was used and thereby caused ignition when the pressure surge occurred.
21. During oxidation/humidity qualification tests on spacecraft components in a test tank, (ambient pressure of 7 psia, 95 ± .5% 0_2, 95 ± 5% humidity and 90°F), an explosion occurred within the tank when polyurethane foam used under the water pan swelled, causing a suspended electrical immersion heater to touch the bottom of the tank. Sufficient localized heating was generated to ignite the 0_2 saturated foam. No personnel injuries, however laboratory equipment sustained damage and test units required replacement.	A design deficiency in the test setup for conducting tests in high 0_2 and humidity environments. The highly saturable polyurethane foam was not compatible with the test environment due to its proximity with the heater and susceptibility to ignition from heat generated by the heater. Also, there was lack of adequate safety analysis and QC verification prior to tests.

Accident/Incident Description	Cause
22. GN_2 and O_2 facility lines at a test facility were inadvertently cross-connected on the roof at a junction header when the lines were disconnected to correct a leak. Test setups were contaminated and systems/lines required purging.	Procedural due to the lack of detailed maintenance/repair procedures and checklists. Also, there was an installation design deficiency due to lack of identification of lines, i.e., no color coding or connector sizing, and lack of adequate work inspection.
23. One person was fatally burned and one seriously injured in a space chamber under 100% oxygen when a flash fire occurred during routine maintenance from an electrical spark. The chamber was destroyed.	Inadequate maintenance procedures for 100% oxygen environments. Contributing was failure to ensure that non-flammable materials were used and failure to specifically rate equipment for use in oxygen environment.
24. During an unmanned 500 hour life cycle test of a space vehicle in a chamber with 100% oxygen, a fire broke out at 480 hours from a spark from an electrical tape. Severe damage to the chamber and vehicle resulted.	A design deficiency in the test installation. The heat tape had been installed as part of the test setup and had not been specifically rated for a 100% oxygen environment. The wires in the tape shorted, igniting the flammable material in the environment.
25. Two flight crew members were seriously injured in a space chamber under 100% oxygen when an electrical spark caused a fire on the thirteenth day of a simulated 14 day space mission.	A design deficiency in the installation which permitted an overloaded electrical circuit under the instrument panel to overheat and cause ignition. Contributing was lack of adequate planning and specification for equipment used in 100% oxygen environment.
26. During a pressure test using a bio-satellite bleed and fill line to pressurize an O_2 system vessel to 3500 psig and bleed down to 500 psig, a fire occurred in the fill line when bleed down was initiated. Accident resulted in damage to the system and personnel injury.	Primary cause was inadequate cleaning procedures and specifications for O_2 components. The test article had received only standard cleaning at the manufacturer, and it was certified for use in O_2 systems; however, aluminum chips and rust were found in the system. Neoprene was used for the regulator diaphragm, which was found unsafe for O_2 systems and there was no filter on the inlet side of the regulator. Ignition was apparently caused by impingement of contaminants against the walls of the lines.

Accident/Incident Description	Cause
27. During preparation for a reliability test on a GOX duct assembly of a booster stage, a six inch "hot" line ruptured under pressure of 3200 psig at 610 degrees F. and damaged adjacent piping. Uneven heating of the pipe caused it to overstress locally. The system was being pressurized with gaseous nitrogen.	A design deficiency in the test setup. The heating element on the line permitted uneven heating and caused hot spots which weakened the line. The instrumentation provided "average" thermocouples readings and did not provide loca temperature of hot spots. Unauthorized substitutions were utilized and thermocouples were of a different size. Contributing causes were inadequate procedures for control of parts purchases and inadequate work control procedures.
28. During acceptance testing of emergency oxygen equipment, an incident occurred causing an out-of-specification pressure condition to exist because of a damaged "O" ring. The "O" ring was damaged during assembly. No damage to equipment but a leak occurred requiring re-run of test.	Incident was caused by improper installation procedures. The back-up ring had been damaged and the "O" ring was extruded into the damaged ring. The damage was not noticed by inspection.
29. During checkout of ground support oxygen resuscitator, a fire occurred in the high pressure side and burned through the regulator. The unit charged with 2200 psi oxygen was being readied as emergency equipment for the altitude chamber. The probable source of the fire was the primary seat in the regulator.	The primary cause of the accident was the use of incompatible materials. The seat was made of nylon, a material considered unsatisfactory for 100% oxygen use. Studies indicated that either a small particle or thread of the nylon seat left from the initial machining ignited the nylon seat. The inspection and procedural deficiencies permitting material not satisfactory for oxygen also contributed to the accident.
30. A regulator controlling an oxygen and breathing air system failed to shut off permitting gas to escape and causing a fire. Examination indicated heat and flame damage through the port area opening and charring of the regulator seat. The valve was melted and deformed.	A materials incompatibility and design deficiency were the cause of the failure. A metallic object was removed from the inlet port of the regulator. The metal ball originated upstream of the regulator and the impact was probably responsible for the ignition of the nylon seat.
31. During preparation for altitude chamber pumpdown for spacecraft purge and leak check, 100% O_2 was used for the purge instead of 65% O_2 and 35% N_2. Damage did not occur bu the environment presented a potential fire hazard.	The cause of this incident was human error since the pressure relief and panel configuration were specified in the test checkout procedures. Procedural and design changes should be added to require gas sample analysis before mixture enters spacecraft. Lack of QC verification and lack of inspection of valve settings contributed to accident.

Accident/Incident Description	Cause
32. During fuel cell pressurization of vehicle oxygen system, the tank was overpressurized to about 25% above the design burst valve. No damage was done but a serious hazard was produced.	During the pressurization process, the "K" bottle source of gas was replaced but the regulating valve had not been adjusted for the higher tank pressure. Procedural and design limitations were the cause of the accident.
33. While performing leak check of spacecraft emergency oxygen systems, the wrong flex line was disconnected and capped allowing systems to be pressurized to 900 psig, 50% above design burst level.	A test/checkout procedure was used but human error was responsible for the accident. Q.C. surveillance was inadequate to catch mistake. System design was deficient in permitting making wrong connection.
34. Fire damage to parts of rocket engine used in lifting body research aircraft was noticed after return from flight. Fire damage was also sustained on the aircraft control surfaces adjacent to the engine. The fire was probably at a low level of intensity initially, yet sufficient to melt a section of aluminum GOX line. One of the lines appeared to have been softened, swelled by internal pressure and eventually ruptured. Fire must have intensified as GOX lines ruptured causing additional damage.	The fire probably started just after propellant jettisoning was initiated. Ignition source could have been the engine nozzle extensions. The system design deficiencies, materials limitations and procedural deficiencies contributed to the accident. Material specifications did not consider the use of less vulnerable flexible hydraulic lines, instrumentation wiring and other damping devices to the fire damage. Operational procedures were deficient in not permitting a safe minimum delay between shutdown and jettison of the propellants. Material failures and their relationships to engine damage when exposed to fire were not evaluated.
35. During the pressure testing of a tank to be used for the testing of a quick release manhole cover, the tank burst causing extensive damage. The tank burst at a pressure between 60 and 67 psig. The tank had withstood a pressure of 60 psig in a previous test.	Insufficient communication among those responsible for the test to provide the design information for the tank testing was the cause of the accident. A misunderstanding concerning the tank design pressure existed between the designers and operators. Blueprint interpretation indicated the tank had been designed for 150 psig when it actually had a limit of 50.7 psig.
36. During receiving inspection tests, convoluted flexible ducts of the "Y" GOX collector were damaged when a test fixture was improperly installed. No injury to personnel.	The primary cause was procedural in that the workman neglected to restrain the flexible ducts with available clamps. The bellows ruptured at 350 psi and quality control instructions did not provide warning note to ensure use of bellows retaining clamps.

Accident/Incident Description	Cause
37. An employee collapsed while wearing an air mask supplied with air from a cylinder tagged as having been checked for oxygen. He was revived.	The oxygen content of the air in the cylinder was less than 1%. The supplier usually mixed N_2 and O_2 in the cylinder but in this case failed to add oxygen. Procedural and system design deficiencies contributed to accident.
38. A LOX pre-valve actuation control valve was overpressurized when a connecting flex hose was used incorrectly. The hose was installed from a calibration panel by one shift and used incorrectly by the 2nd shift. Major damage resulted from the overpressurization.	The primary cause was procedural in that the flex hose was connected without documentation or procedures. The 2nd shift pressurized the system to 1000 psi which was 500 psi above the operating pressure.
39. During leak check operations on a LOX valve, pressures of approximately 2000 psi were applied through an unsecured flex line forcing the line to snap and break the line and valve. No personnel injuries.	A procedural deficiency indicating that a lack of test set-up and operational instructions was the cause of the accident. Proof test procedures were not available.
40. During pressurization of a stage test ground tank system to support a stage LOX dome test, a 500 psig spring loaded vent valve on the LOX tank failed. The regulator indicated pressure of 2100 psig instead of 500 psig.	The system did not have sufficient regulator relief capability indicating a design deficiency. A procedural deficiency was also evident in that a hazards analysis of the installation was not performed which would have detected the need for the regulator relief capability.
41. During proof test of a check valve in a test chamber, GN_2 at 4800 psi was admitted through an inlet port while the outlet port was capped. The valve was removed from chamber after which the valve ruptured. No injury to personnel.	The primary cause of the accident was a design deficiency. The trapped GN_2 in the check valve was at about -285°F in the test chamber and at room temperature, the gas expanded causing rupture of the valve. The design did not provide for the release of pressure when test article is in chamber.
42. During testing of a pressure vessel, a rupture of the flange to head weld caused damage and injury to nearby personnel.	The pressure exceeded operational limits due to an inoperative pressure regulator. The LOX sensor gave faulty readings on the pressure gage. Procedural and design limitations were responsible for the accident. Procedures were not sufficiently detailed to assure no initial pressurization with personnel nearby.

Accident/Incident Description	Cause
43. During pre-launch leak checks of instrument containers with GN_2 at a pressure supply of 1750 psig, a regulator failed. The flow was bypassed causing overpressurization of the container and damaging the bulkhead and tank.	The cause was procedural in conjunction with a design deficiency. A plastic dust cap was left in the quick disconnect for the instrument container pressure sensor causing erroneous pressure readings. In addition, a 900 psi pressure source was used on a low pressure system with the bypassing of the regulator. No relief valve was provided in the container.
44. During a proof pressure test of an oxygen panel, the low pressure side (210 psig) was inadvertently subjected to pressure from the high pressure side (1500 psig) when the high pressure shutoff on a common "T" connection was not closed.	Procedural error in failing to close the high pressure side of the "T" connection. Contributing was lack of adequate verification of test installation prior to tests and failure to include adequate warning notes in test procedures.
45. During a space simulation test, an explosion occurred in the oxygen system of a test chamber causing system damage.	A design deficiency in that noncompatible seals used in the ball valves were subject to impact ignition with oxygen. Subsequent impact tests confirmed this compatibility.
46. During checkout of a check valve under cryogenic temperatures in a test cell, an explosion occurred injuring one person and causing minor damage to equipment. System was being pressurized to 3000 psi and explosion occurred at 2900 psi.	The operator failed to shut off the power and close the solenoid valves after a previous run, as required by the test procedure. Contributing causes were a leaking hand valve, lack of a pressure relief device in the test set-up and failure to provide operator with the latest revision to the test procedure.
47. The oxygen supply system of a vehicle environmental control system was contaminated with mercury during replacement of a solenoid valve. Mercury was discovered in the cold trap of the leak detector during subsequent leak checks. Incident required complete analysis and cleaning of entire system.	Lack of adequate procedures for the control of instruments containing mercury in the manufacturing and test facilities. Mercury was apparently introduced through a solenoid bypass valve which had been replaced in the system.
48. During qualification testing of a spacecraft fuel cell power system, the test was prematurely terminated by an electrical failure caused by carbon deposits from cleaning fluid residuals left in the system.	The cleaning procedure being used was inadequate to ensure complete removal of all cleaning fluid residuals. Contributing was failure to establish by analysis and test, the compatibility of the cleaning agent with the carbon deposits and with the oxygen system electrodes.

Accident/Incident Description	Cause
49. During a manned crew training test in a vacuum chamber, electrical arcing of an interior overhead fluorescent light occurred. The chamber pressure was equivalent to 200,000 ft. altitude. No personnel injuries or hardware damage occurred.	Primary cause was due to chamber design deficiency. The failure of fluorescent lights was found to be common but was not taken into account in the chamber design. Sufficient heat is generated to melt portions of the electrical fixture and wiring, the metal end of the fluorescent tube and finally shatter the glass near the anode. Sodium in the glass acts as a cathode after extended usage making arcing possible between the anode and the glass.
50. During qualification test of an environmental control system in an altitude chamber, the commercial grade strip heater tape failed causing shorting of the wires and ignition of the flammable material. The altitude chamber was at 5 psi and 100% oxygen. The control system and test equipment were destroyed.	System design and procedural deficiencies were responsible for the accident. The test set up evolved from sketches and oral communication. Approved test hardware materials were not used. Adequate safety and emergency procedures were not established.

NON-NASA MISHAPS

During servicing of a T-33 aircraft with oxygen with operating pressures of 350 psi on cockpit gage and 400 psi on cart gage, a muffled explosion was heard. Flame was observed coming out of nose wheel well. The explosion and fire burned a hole in the aircraft skin. Fire started from within tubing and fitting system. Aluminum tubing wall was burned away (partially) in direction of oxygen flow.	The fire started within the tubing and fittings due to internal contamination of system with hydrocarbons or possible overtorquing of connections. Improper servicing procedures generating excessive heat in the system contributed to mishap.
During servicing of oxygen system on T-33 aircraft, an explosion and fire occurred at the oxygen cart being used for providing gaseous oxygen. A man at the oxygen cart was controlling the pressure regulator. The pressure at the regulator was being increased and the aircraft gage was being observed to increase slowly. The fire at the cart resulted in fatal injuries.	It was believed that the fire was caused by grease or oil contamination present on the purifier cylinder.
After an aircraft landed, an explosion occurred from within the cockpit area. The pilot noted some smoke from the cockpit area with subsequent flash fire.	A low pressure oxygen check valve failed. A small crack was noticed in the fitting which was probably caused by overtorquing. Leakage of oxygen into the area which contained a large amount of oil resulted in the fire and explosion.
Aircraft cockpit oxygen emergency bottle exploded during servicing (T-28) on preflight check. Intense fire in seat pan area. (Similar accident occurred 4 months later.)	Cause of failure believed to be due to contamination in oxygen system. Contamination considered to be introduced during servicing. Rapid charging resulted in excessive temperature and pressure due to oxidation of rubber plunger washer on valve cone.
During a preflight check which involved turning on the aircraft oxygen system, a fire started. The fire was accelerated due to the oxygen and attempts to put out the fire were unsuccessful.	An oxygen valve failed due to fatigue and the escaping oxygen impinged on the insulation and surrounding materials. System design deficiencies prevented shutting off the oxygen supply.

During an inerting operation of an aircraft fuel line with oxygen, a fire and explosion occurred destroying the aircraft and resulting in a number of fatalities.	The material being used for inerting was oxygen instead of nitrogen. The cylinders were stenciled oxygen. The high pressure oxygen reacted with the fuel remaining in the lines. System design and procedural deficiencies contributed to the cause of the mishap.
An explosion and fire erupted during servicing of rear cockpit (T-28 aircraft) high pressure gaseous oxygen bottle. The oxygen line was connected from the servicing cart and prior to pressurizing bailout bottle, the fire occurred.	Hydrocarbon contamination in the area of the servicing connection was suspected as causing the fire. The contamination was due to personnel not following safety precautions. Contamination came in contact with the hose fittings; lines and hoses not purged nor stored properly. The filter valve indicated damage due to dragging on hard ground (concrete).
Pilot, in aircraft, was preparing for test flight when flame shot out between his legs. The flame came from under the seat pan and was similar to a blow torch. The pilot released the leg straps and rolled clear of cockpit, receiving burns on both hand and legs.	The cause of the mishap was suspected to be failure of non-compatible nylon valve seat in the emergency oxygen bottle. Fire was fed by seat pad and other material.
Fire occurred in cockpit area of aircraft. Pilot experienced general failure, followed by smoke in cockpit and within seconds the oxygen was lost and flames erupted. Pilot received burns; ejected and rescued by helicopter. Aircraft exploded prior to impacting water.	Cause not known but considered to be due to material failure in oxygen system.
Aircraft was being prepared for servicing with oxygen. The oxygen cart had been positioned near the aircraft; the hose pressurized to 425 psi and while being connected to the aircraft receptacle an explosion and fire occurred.	Prior to explosion a small leak was heard in vicinity of purifier. The purifier and filter element were burned. The use of non-compatible materials and procedural deficiencies contributed to mishap.
Fire was initiated in cabin of aircraft located in hangar. Fire provided sufficient heat to melt aluminum fitting controlling oxygen. Fire spread to 5 other planes.	Fuel leaking from line supplying heater was ignited by short circuit in battery. Aluminum fitting melted off O_2 control allowing O_2 to be fed into fire. Material failures combined with system design and operational procedure deficiencies contributed to accident.

Fire initiated in passenger compartment of aircraft while men were removing linoleum with acetone and cleaning seats with other highly flammable solvents. Fire spread rapidly causing oxygen relief vent valves from 4 cylinders on board to open. Hangar's deluge system confined the fire.	Fire was believed to be initiated by a static spark or spark from an extension cord. Due to the high temperature developed, the oxygen relief valves opened, releasing O_2 and intensifying the fire. The system design and operational procedures employed contributed to the accident.

APPENDIX B

DEFINITION OF MISHAPS - NASA SAFETY MANUAL

TYPE A (Accident)	Any fatality, five or more persons seriously injured, $100,000 (or more) damage to NASA/NASA contractor equipment or property, or aircraft destruction.
TYPE B (Accident)	Serious injury to four (or fewer) persons; property damage over $10,000 but less than $100,000 to NASA/NASA contractor equipment or property.
INCIDENT	A mishap (less than accident severity) to persons or property, over $250 but less than $10,000, or a non-serious injury.
MISSION CONTINGENCY	Any event which jeopardizes a mission, prevents major mission objective, or premature mission termination.
AVIATION FLIGHT ACCIDENT	A NASA (type A or B) accident which involves NASA owned or operated aircraft or NASA flight crews, passengers or test personnel while on flight duty and which occurs after the engine(s) has been started with intent for flight.

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8. NASA, John F. Kennedy Space Center, Investigation of Circumstances Surrounding Incident Resulting in Destruction by Fire of Three Motor Vehicles in Vicinity of Perimeter Fence on Pad A of LC-39 on March 25, 1970.
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10. NASA, Report of Apollo 13 Review Board, With Appendices, December 1970.

TABLE I. - RUBBER AND SOFT GOODS USED IN RESUSCITATOR

Sample Description	Composition
Primary seat	Type 6/6 nylon
O-ring seal at jet base	Butadiene acrylonitrile rubber
Floating member diaphragm	Chloroprene (Neoprene) rubber
Floating diaphragm fiber reinforcement	Cotten
O-ring seal at end of inlet valve camshaft	Butadiene acrylonitrile rubber
Bellophragm grommet	Poly butadiene rubber
Secondary seat	Chloroprene (Neoprene) rubber
Inlet valve seat	Tetra-flouro-ethylene polymer (TFE Teflon)
Regulator core O-ring	Butadiene acrylonitrile rubber
Upper diaphragm	Butadiene acrylonitrile rubber
Upper diaphragm reinforced fibers	Nylon
Safety valve rubber	Natural rubber

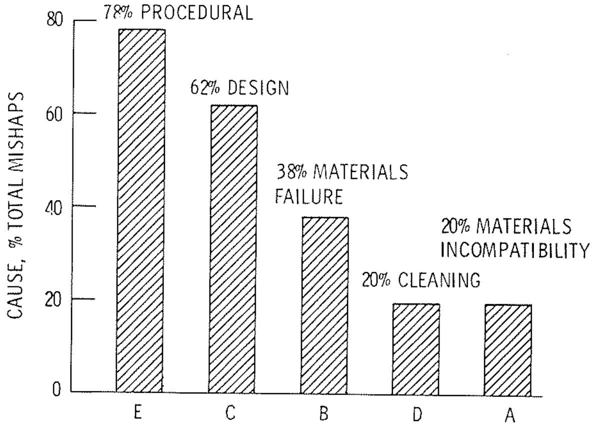

Figure 1. - Distribution of causes of mishaps with liquid oxygen (more than one cause factor is involved in most mishaps).

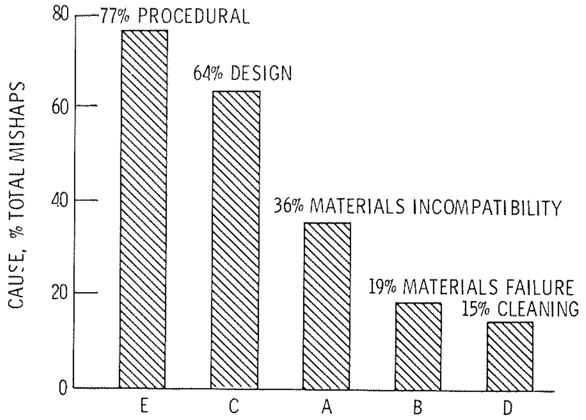

Figure 2. - Distribution of causes of mishaps with gaseous oxygen (more than one cause factor is involved in most mishaps).

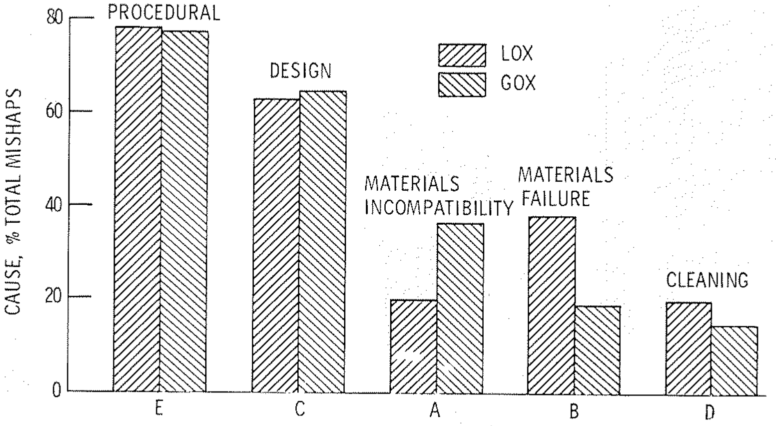

Figure 3. - Comparison of cause factors for liquid and gaseous oxygen.

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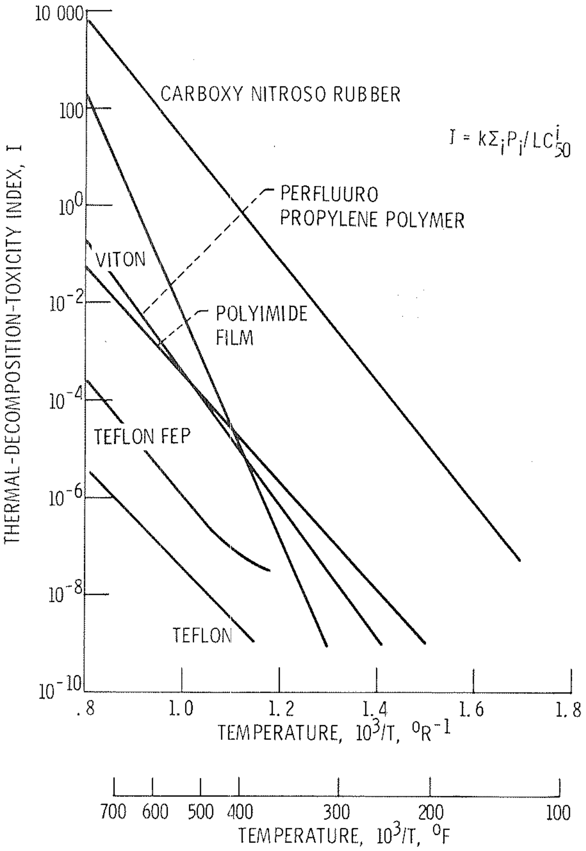

Figure 4. - Thermal-decomposition-toxicity index versus temperature.

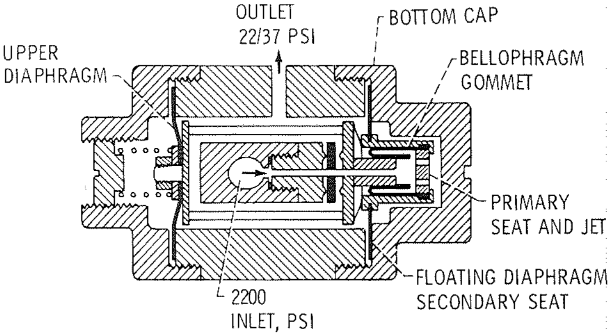

Figure 5. - Cutaway sketch of the resuscitator regulator illustrating the functioning position of various components

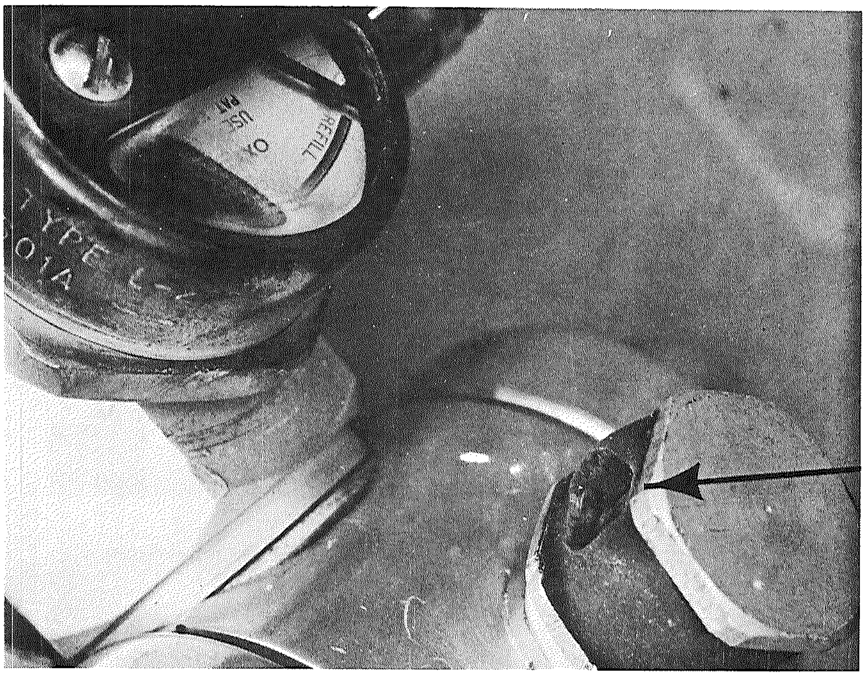

Figure 6. - External view of resuscitator regulator illustrating ruptured safety valve and flash damage to the pressure gauge.

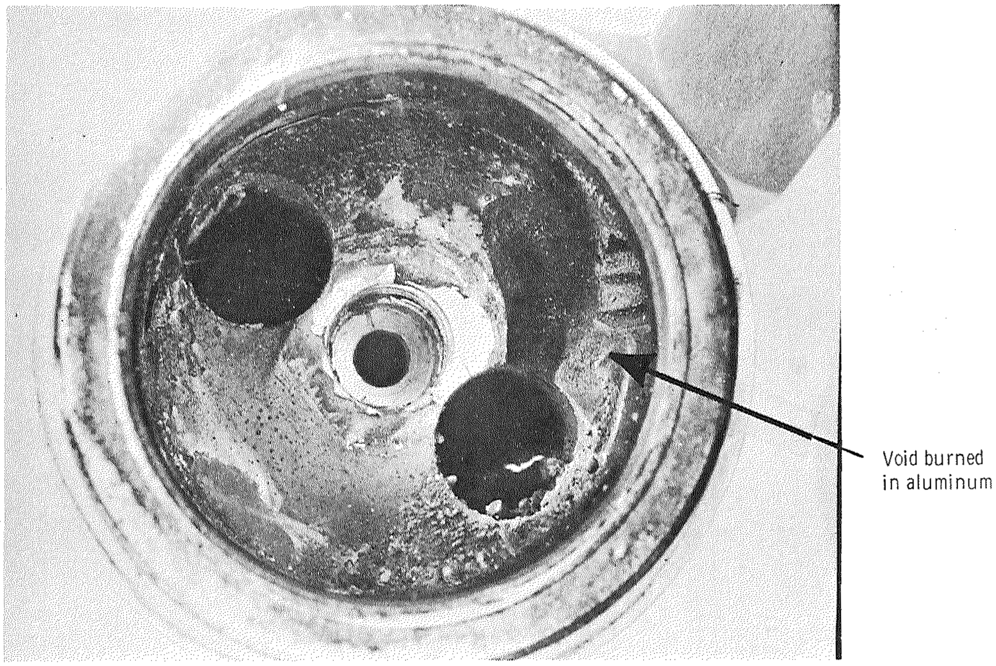

Figure 7. - View of inner surface of aluminum regulator body.

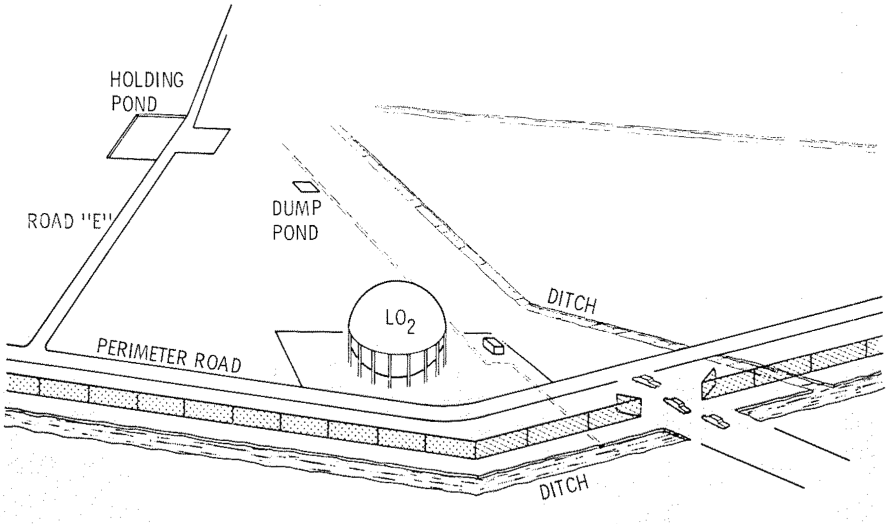

Figure 8. - Storage and drainage ditch area.

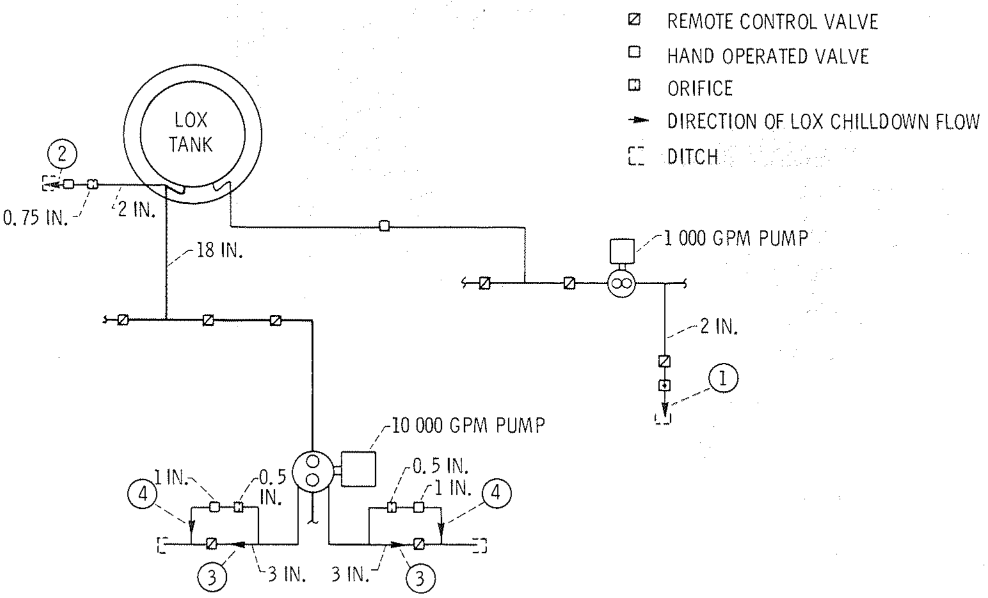

Figure 9. - LOX system schematic showing LOX chilldown outlets to ditch.

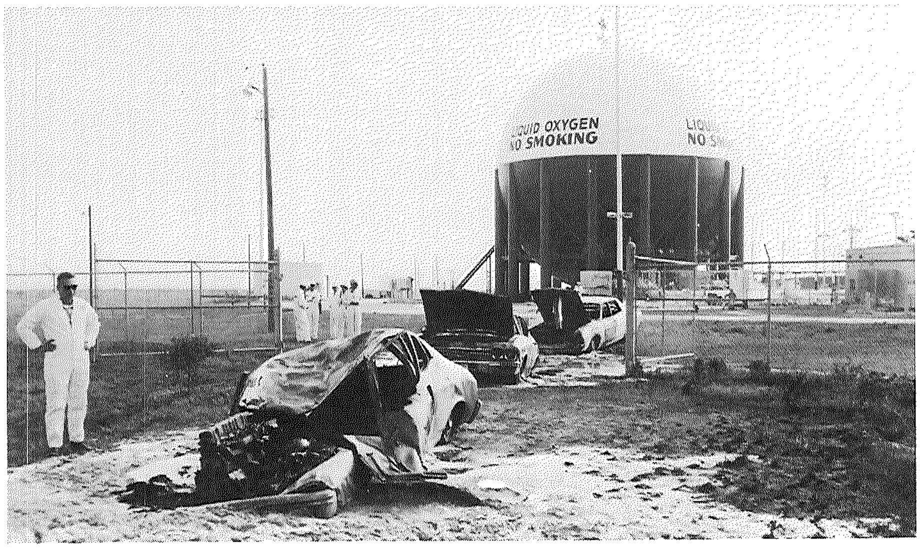

Figure 10. - Burned cars in relation to oxygen tank and fence.

Figure 11. - Damaged car number 1.

Figure 12. - Damaged car number 2.

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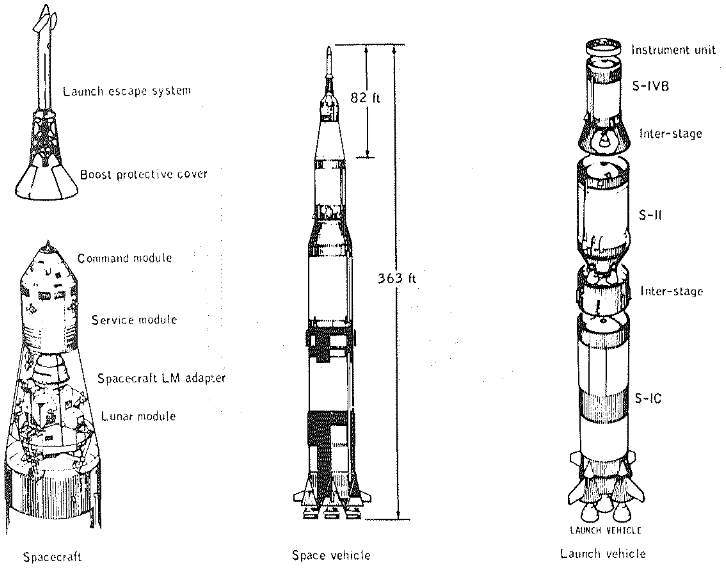
Figure 13. - Damaged car number 3.



Spacecraft

Space vehicle

Launch vehicle

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Figure 14. - Apollo/Saturn V space vehicle.

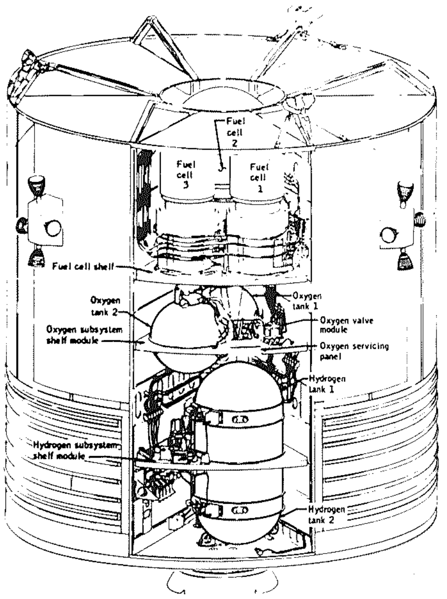

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Figure 15. - Arrangement of fuel cells and cryogenic systems in bay 4.

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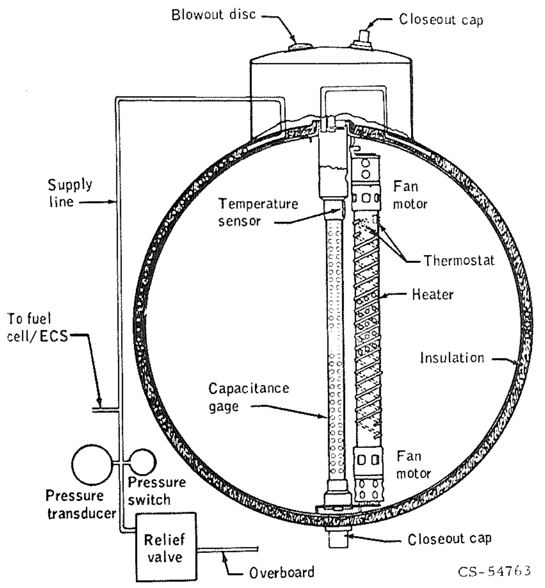

Figure 16. - Oxygen tank no. 2 internal components.

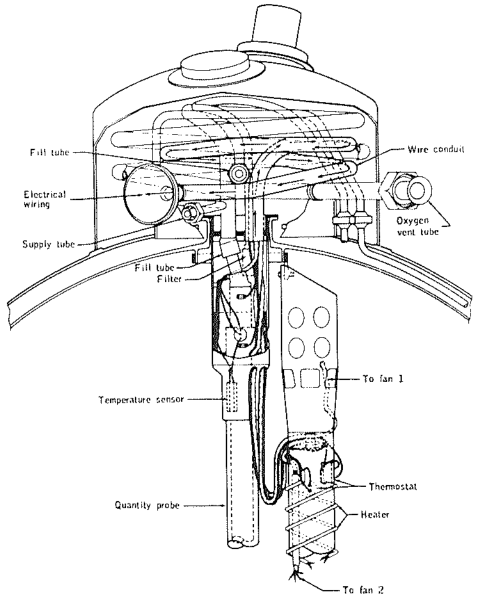

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Figure 17. - Oxygen tank wiring and lines.

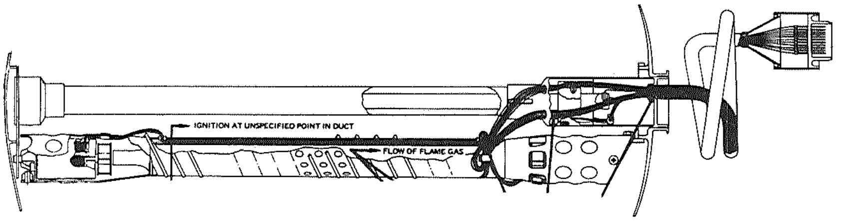

Figure 18. - Wiring in oxygen tank.

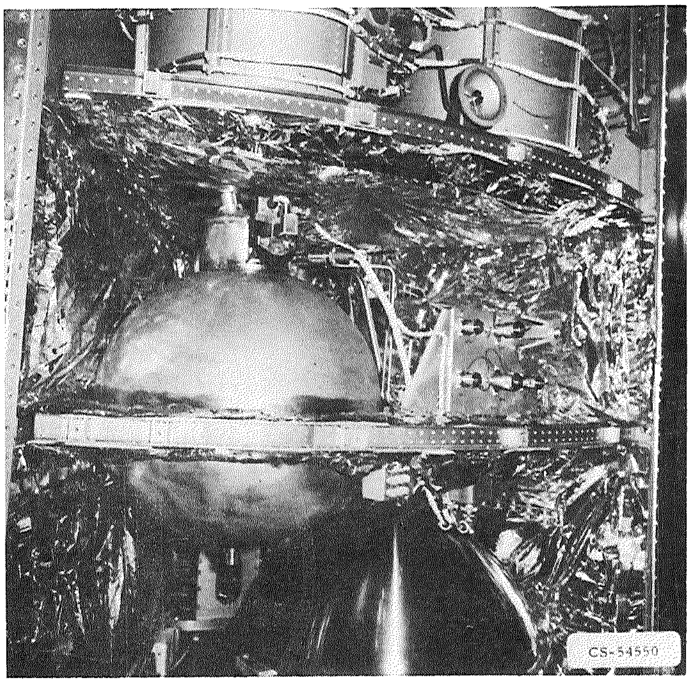

Figure 19. - Oxygen tank in service module bay.

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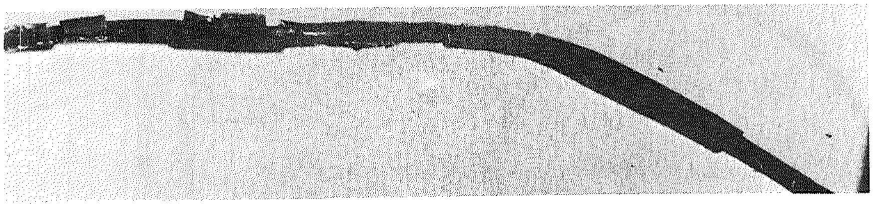

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Figure 20. - Damaged Teflon insulation.

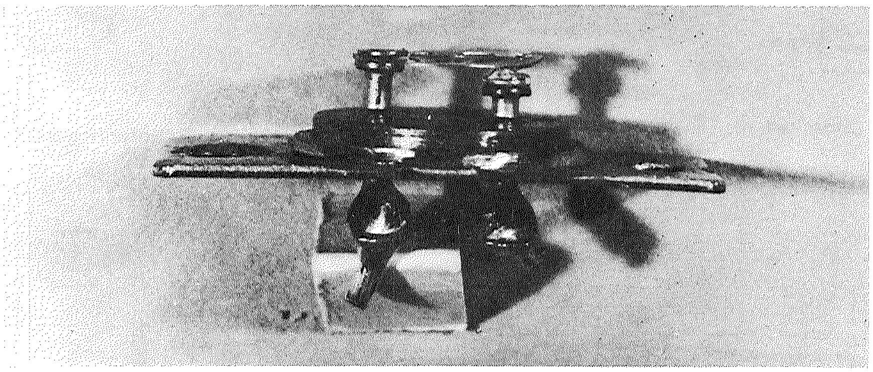

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Figure 21. - Fused thermal switch control.