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Hazards of Hospital Bulk Oxygen Delivery Systems

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Numerous problems can occur with liquid oxygen delivery systems, in part because of the complexities of such systems. These systems must comply with guidelines of the Joint Commission on Accreditation of Hospitals. During the past year, 18 major problems with the liquid oxygen delivery system have occurred at the authors' hospital. Five times, false alarms have resulted from calibration drift in line pressure sensors. Thrice, excessive depletion of the reserve supply has occurred because of pressure imbalance between the main and reserve systems. Twice, excessive depletion of the reserve supply occurred owing to failure of the vacuum seal on the reserve supply vessel. Eight other potentially serious mishaps have also been reported. These problems, which are inherent in liquid oxygen delivery systems, are for the most part preventable. (Key words: Equipment, oxygen delivery systems.)

LIQUID OXYGEN DELIVERY SYSTEMS are in common use at hospitals throughout the United States. Often these systems are owned and maintained by the company that supplies the liquid oxygen to the hospital, and as a result hospital personnel have little or no involvement with the actual mechanisms responsible for the supply of this vital drug. Numerous problems have resulted from this approach.[1,2] We have reviewed our existing system and the numerous regulations and codes that cover its construction and operation. We have documented numerous incidents, many of which could have resulted in patient injury. We have also found several potentially serious problems that are not addressed by the standards regulating this area.

Components of the Liquid Oxygen Delivery System

In many ways the installation at the Beth Israel Hospital may be considered typical for a 500-bed general hospital, and the following description of its components and their function illustrates the complex nature of bulk oxygen supply from a liquid reservoir.

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The liquid oxygen delivery system is composed of two reservoirs, five vaporizers, seven regulators, and eight pressure-relief valves or frangible discs (fig. 1). The main supply reservoir has a capacity of 6,000 liquid gallons (22,712 l), and when completely filled weighs approximately 98,800 pounds (48,815 kg). The reserve supply reservoir also contains liquid oxygen, and has a capacity of 350 gallons (1,325 l). It is located in the same enclosure as the main supply. Liquid oxygen at a temperature of −297 F (−197 C) is pumped from the supply truck into the main storage vessel, and then the reserve is filled from the main supply. The connection between the supply truck and the main cylinder is specific for liquid oxygen in order to avoid inadvertent connection with a vehicle carrying another type of cryogenic liquid.[3] During the filling procedure liquid oxygen is introduced into both the bottom and the top of the vessel. The liquid pumped in the top is sprayed into the vessel to lower the temperature and consequently decreases the pressure exerted by gas within the cylinder, thus compensating for the volume of liquid introduced through the lower fill line.

The two storage vessels are of similar construction. The internal pressure vessel is made of stainless steel (others may be made of aluminum), and is designed to withstand a pressure of 250 psig (1,723 kPa). The external shell is made of steel and is separated from the internal container by approximately 4 inches. This annular space is filled with an expanded silicone-base insulation called Pearlite®. The external vessel is also sealed, and a vacuum of 50–100 μ is created in the annular space, further decreasing heat transfer from the atmosphere to the liquid oxygen. Both vessels are fitted with pressure relief devices to prevent internal gas pressure from exceeding the safety point to which the vessel has been tested, in accordance with American Society of Mechanical Engineers (ASME) standards.[4,5]

Some of the liquid oxygen is vaporizing all of the time, and it is this process that maintains gas pressure within the entire system. This gas is introduced into the piping system via the "economizer" circuit. In order to regulate the supply pressure at a constant level, gas or liquid is channeled through a small vaporizer

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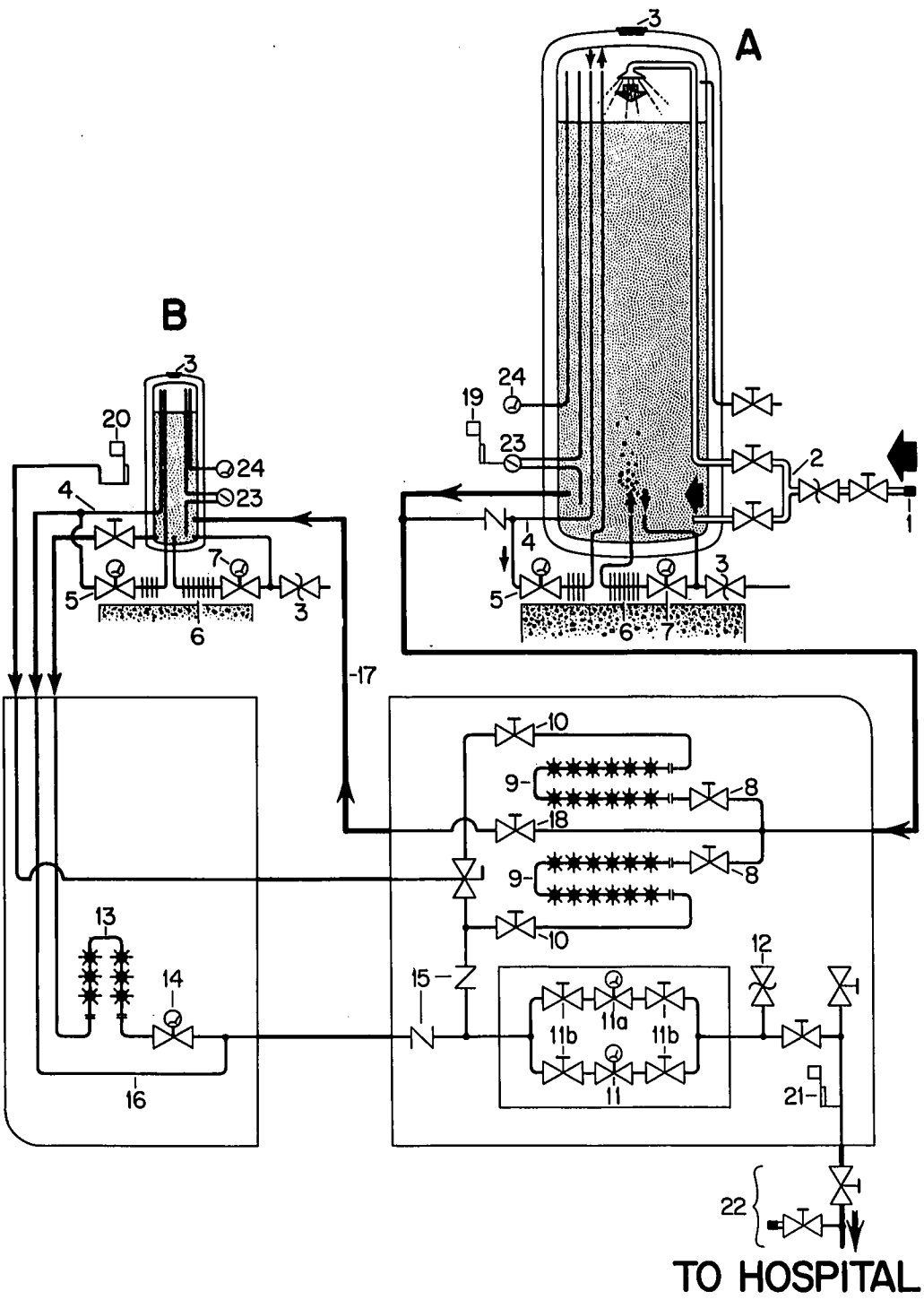


FIG. 1. *A*, Main liquid oxygen reservoir; *B*, reserve liquid oxygen reservoir. *1*, Connection to supply vehicle. *2*, Top and bottom fill lines. *3*, Reservoir pressure-relief valves. *4*, "Economizer" circuit. *5*, Gas regulator in pressure-building circuit. *6*, Pressure-building vaporizer. *7*, Liquid regulator in pressure-building circuit. *8*, Cryogenic liquid-control valves. *9*, Liquid vaporizers. *10*, Downstream valves for isolation of vaporizers. *11*, Primary line pressure regulator; *11a*, secondary line pressure regulator; *11b*, valves to isolate regulators for repair. *12*, Pressure-relief valve for main pipeline. *13*, Reserve system liquid vaporizer. *14*, Reserve system line pressure regulator. *15*, Gas-flow check valves. *16*, Reserve system "economizer" line. *17*, Reserve system fill line. *18*, Valve controlling flow to reserve system from main cylinder. *19*, "Low-liquid-level" alarm. *20*, "Reserve-in-use" alarm. *21*, Main line pressure alarm. *22*, Main shut-off valve and T fitting. *23*, Liquid level indicators. *24*, Vapor or "head" pressure guages.

beneath each of the storage vessels (fig. 1). If the vapor pressure in either liquid container drops below a set point (100–200 psig) (689–1,378 kPa), a regulator will open and allow some liquid oxygen to flow into the vaporizer. The gas or liquid absorbs heat from the atmosphere and is returned to the pressure vessel as gas, increasing the pressure of the "head" of gas vapor in the container.

Liquid oxygen leaves the storage vessel through a 2-inch pipe of copper alloy specifically formulated to withstand extreme cold[6] and passes through two valves (item *8*, fig. 1) leading to the main vaporizers. These valves are constructed of stainless steel and have Teflon® seats. The valve stem is elongated to protect the valve-stem packing material from exposure to the extreme cold of the cryogenic liquid.

The vaporizers are constructed of aluminum alloy and are finned to increase the surface area for absorption of heat energy from the atmosphere. Each unit has the capacity of vaporizing approximately 3,000 cubic feet (86,032 l) of oxygen per hour. As the liquid travels through the vaporizer it will expand to a gas volume 860 times the original liquid volume, and it is this factor that makes the storage and transport of oxygen as a liquid so efficient and convenient.

In humid atmospheres ice will form on the vaporizers as the surrounding air temperature reaches the dew point. Extensive ice formation will impair heat transfer, and in severe instances may result in liquid oxygen's passing directly through the vaporizer into the piping system, resulting in damage to pressure regulators and high pipeline pressures. Valves are provided on the downstream side of the vaporizers so that either of the units may be isolated from the rest of the system for repair or replacement without disruption in service to the hospital.

Gaseous oxygen passes from the main vaporizers through piping to the main supply regulators (items *11* and *11a*, fig. 1), which control pressure to the hospital piping system. One regulator controls line pressure and the second provides a reserve capability should the first one fail. Each regulator is capable of handling 13,500 cubic feet (387,145 l) per hour at a supply pressure of 55 psig (379 kPa). Downstream from the main pressure regulators is a pressure-relief valve set to open if the line pressure reaches a level 50 per cent above normal, or approximately 80 psig (551 kPa).

The liquid reserve is simply a much smaller version of the main supply. Should it be necessary to use the reserve supply for all of the hospital's needs, gas would flow through the reserve vaporizer at a maximum rate of 1,200 cubic feet (34,412 l) per hour, at a pressure of approximately 115 psig (793 kPa). The pressure would be further decreased at the reserve supply pressure regulator (item *14*, fig. 1), and oxygen at 85 psig (586 kPa) would reach the main line pressure regulators, where the pressure would be further decreased to 55 psig (379 kPa). Check valves prevent the reversal of gas flow from either container. Liquid oxygen is continuously vaporizing out of the reserve supply, and this is added to the main piping system via the "economizer" circuit. Because of this natural depletion the reserve vessel must be filled periodically through the supply line from the main container.

Until recently, our hospital utilized a high-pressure (2,000 psig) (13,793 kPa) gas reserve. However, in order to comply with the requirements of the National Fire Protection Association (NFPA) standards of nonflammable medical gas systems,[7] the larger liquid reserve was installed. The NFPA standards require that the reserve supply be at least equivalent to an average day's consumption. The Beth Israel Hospital consumes approximately 25,000 cubic feet (717,000 l) of oxygen daily, and space was inadequate for the storage of this large a volume in high-pressure cylinders. Filling of the high-pressure gas reserve also necessitated a separate delivery to the hospital, and this was often neglected by the previous supplier. Although the use of a liquid reserve has simplified some aspects of the system, balancing of the pressures between the main supply and the reserve supply and the filling of the reserve require the regular attention of trained personnel.

Three separate alarm systems provide warning should a malfunction occur within the supply system. The main supply is provided with a low-liquid-level alarm that indicates when the level of liquid oxygen has fallen below 30 inches (76.2 cm). A reserve-in-use alarm serves much the same function, and is activated when supply pressures in the main supply line fall below 85 psig (586 kPa). A third alarm, which senses line pressure in the main supply line, is activated when a variation of more than 20 per cent either above or below normal occurs. All of these alarms provide an audible and visual signal in the maintenance area, and are now monitored 24 hours a day in the telephone operator's office.

A valve to shut off the main oxygen supply is located just inside the hospital. Downstream from this valve is another valve with a T fitting. In the event that the main supply were to be damaged, an emergency supply could be connected at this point.

Incidents Occurring during Normal Operation

Hazards arising in bulk oxygen delivery systems occur frequently and are due primarily to lack of awareness of design and function among hospital personnel.[1,2] Undetected equipment failures due to absent or faulty alarm systems,[8] and lack of communication between clinical and engineering departments and commercial suppliers relating to potential hazards, may also contribute to potentially harmful or life-threatening situations.[9–11] During the year 1978–79 the following problems were reported at least once at the Beth Israel Hospital:

1. Inappropriate and unilateral adjustment of the main line pressure regulators, resulting in a reduction in line pressure to the hospital.
2. Cessation of flow from the main supply vessel due to inappropriate manipulation of the main supply control valve.
3. Unsignaled activation and depletion of the reserve supply.
4. Excessive depletion of the reserve supply due to pressure imbalance in the system (three times).

5. Excessive depletion of the reserve supply due to failure of the vacuum seal on the reserve supply vessel (twice).
6. Leaking of oxygen from ruptured piping connecting the reserve supply to the main system.
7. Leakage of oxygen from the reserve supply through a loose packing gland on a valve.
8. Leaking seat in the main line pressure regulator.
9. False alarms resulting from calibration drift in line pressure sensors (five times).
10. Failure of a line pressure sensor due to occlusion of the pressure fitting with foreign material (welding flux).
11. Failure of monitoring personnel to notify the appropriate clinical service.

Clinical Considerations and Recommendations

Because liquid oxygen delivery systems are owned and maintained by commercial suppliers, hospital personnel are generally unfamiliar with their operation and maintenance. In an emergency their actions may result in compounding an already severe problem. Hospital personnel should be trained in the general operation and maintenance of such equipment, and should have sufficient familiarity to make emergency adjustments safely. The same is true for delivery personnel from commercial suppliers. Often what appears to be a benign adjustment during a routine delivery can precipitate serious clinical consequences. The first three problems listed above are a direct result of these inadequacies. All valves and regulators within the system should be permanently marked with metal tags and color-coded to indicate function (*e.g.,* red for normally closed, and green for normally open), to decrease the chance for operator error. Access to the storage area must be restricted to those individuals familiar with and responsible for the adjustment of the system.

Most liquid oxygen delivery systems receive little preventive maintenance, and alarm activation is often the first indication that a problem exists. This after-the-fact response may occur too late to prevent injury or death. Although in many instances the actual repairs are the supplier's responsibility, the hospital bears the primary liability for any injury to patients, and should routinely monitor the operation of the system. Problems 4–8 were discovered and corrected without disruption of service as a result of maintenance checks. Repeated false alarms cause complacency among personnel which may have serious consequences in the event that a real emergency occurs. A routine check and calibration program for all alarm sensors will identify faulty units and decrease the risk of false alarms. All alarm signals must be directed to personnel who are thoroughly familiar with what action is to be taken (fig. 2). Alarms must be located in an area where they can be effectively monitored 24 hours a day.

In a survey completed by 193 directors of anesthesiology residency training programs in the United States, it was found that 59 (31 per cent) had experienced malfunctions in gas delivery systems. Three deaths were directly attributed to these malfunctions.[2] In the United Kingdom there were 29 deaths resulting from gas supply errors and malfunctions between 1964 and 1973.[12] Two of us (M.L.B., representing the American Association for Respiratory Therapy, and J.H.-W., American Society of Anesthesiologists) are members of American National Standards Committee Z-79 and the International Organization for Standardization, Technical Committee 121. We have found the problems described here to be representative of the difficulties experienced with bulk oxygen delivery systems throughout the developed nations of the world.

Clinical personnel may be lulled into believing that the bulk system cannot or will not fail through their own lack of involvement or understanding. Complete or partial loss of bulk supplies can occur,[13] and the consequences can be severe unless hospital personnel know what to do. Everyone directly involved in the patient support effort should be thoroughly familiar with what action is to be taken, and these procedures should be included as a part of the institution's disaster manual as required by the Joint Commission on Accreditation of Hospitals (JCAH). Although the supplier may be responsible for maintenance and repair of the oxygen system, the hospital must minimize any potential patient hazard, and is ultimately responsible for patient safety regardless of financial arrangements between the hospital and the supplier. In order to accomplish this, hospital personnel must be capable of communicating knowledgeably and effectively with the supplier, and must also be capable of responding quickly and effectively to emergency situations.

We have organized personnel from both clinical and engineering departments into a unit that oversees the operation of the liquid oxygen delivery system and is capable of responding to potential problems. The responsibilities of this group include the daily monitoring of the liquid oxygen delivery system, periodic maintenance checks, coordination of repair activities with the supplier, liaison with other departments, such as plant engineering and nursing, the development of written procedures for the maintenance and repair of the oxygen system, and the implementation of a disaster plan to cope with partial or complete loss of the oxygen supply. Many of the problems that we have detailed elsewhere in this article have been addressed by this approach. Individual and departmental re-

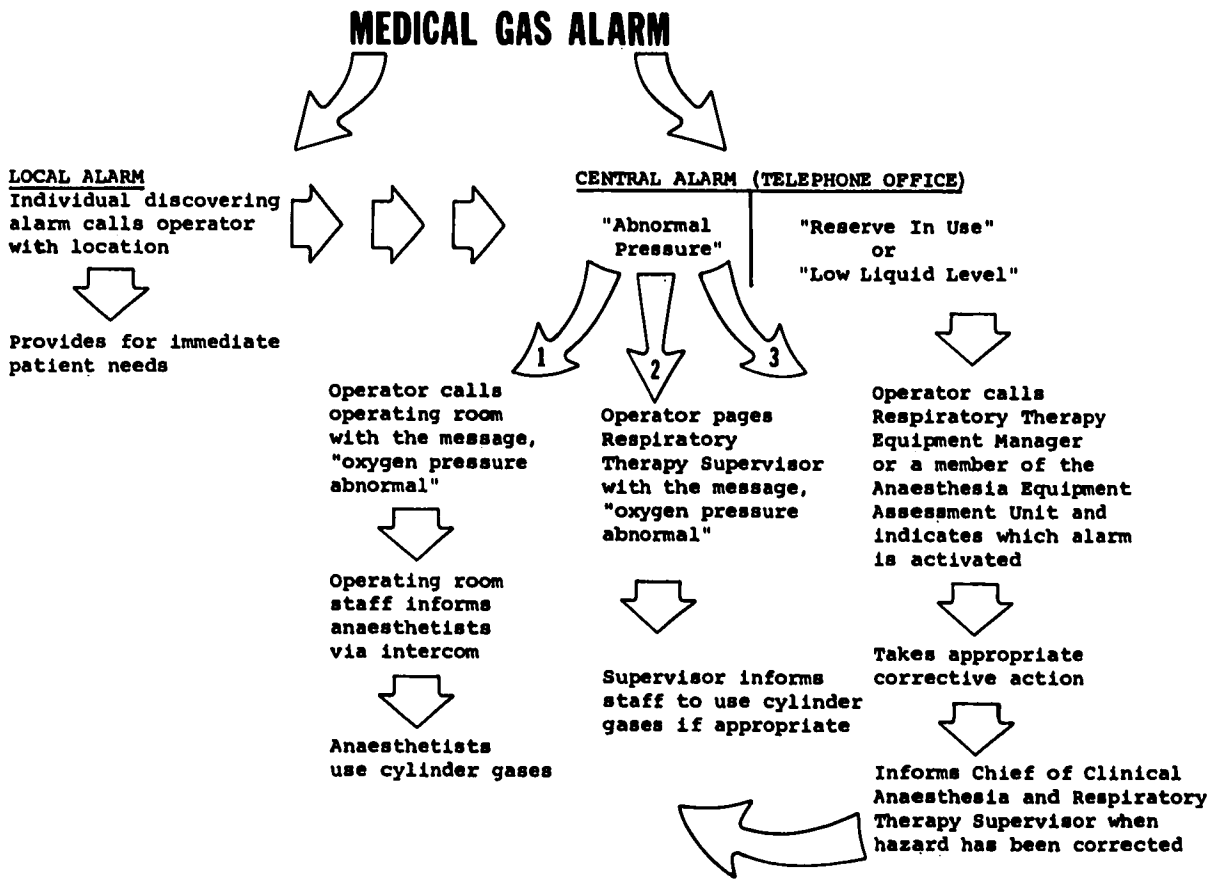


FIG. 2. Protocol for the response to any medical gas alarm. Numbers indicate the order in which clinical presonnel are contacted.

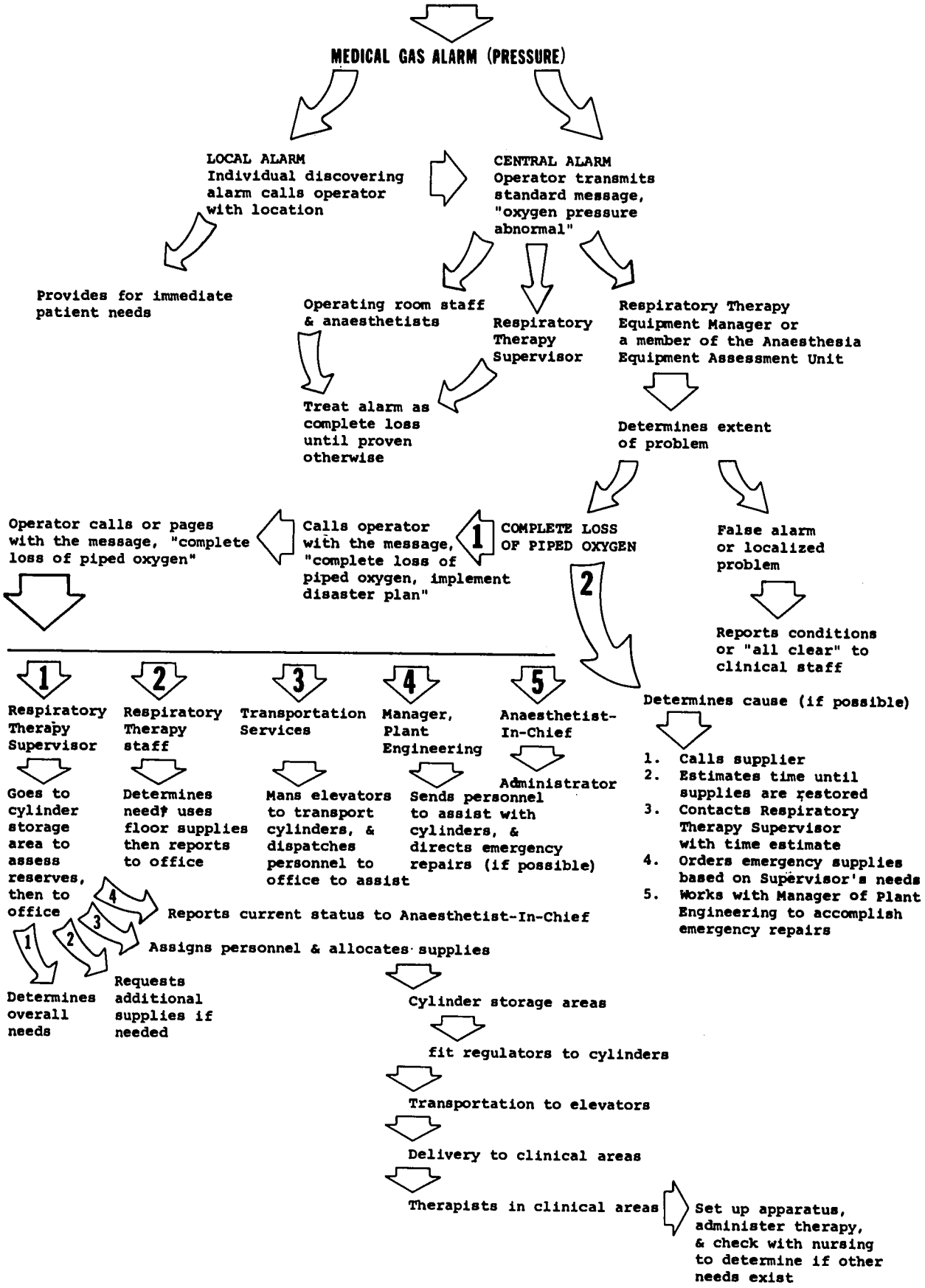
sponsibilities have been defined, and the Department of Anesthesia has accepted a major role in the daily decisions that involve system safety and reliability. The active involvement of clinical personnel with a matter previously relegated to the Plant Engineering Department has greatly improved communications within the hospital and with the supplier. Minor problems can now be dealt with before they reach serious proportions, and the resulting cooperative atmosphere is more conducive to frank and open discussion among the parties involved. Written procedures for the operation and maintenance of the liquid oxygen delivery system are available.§ The organization of an effective response to the loss of piped oxygen supplies must include reliable communication pathways and individual responsibilities that take into account practical circumstances (figs. 2 and 3). The details of such a plan must be discussed and rehearsed in advance in the form of mock disaster drills if an effective response is to be expected during a real emergency. Loss of the piped oxygen supply could easily be precipitated by an external disaster that may have already taxed the hospital's resources,[13] and an adequate response under these circumstances must be considered as well. Centralized communication and standardized messages decrease the possibility of error and speed the transfer of information to all parties involved.

Although medical gas delivery systems are required to be constructed in accordance with standards developed by the National Fire Protection Association (NFPA), the Compressed Gas Association (CGA), and the American Society of Mechanical Engineers (ASME), there is no single standard that addresses all aspects of medical oxygen delivery systems, certain components are not covered by any standard, and no agency is assigned to enforce existing standards. For example, pressure-relief devices should be required on both the inner and the outer storage vessel. This is a requirement for vessels used in the production of cryogenic

§ The complete procedure has been deposited with NAPS. If you wish to order cite Document 03653 from Microfiche Publications, 305 East 46th St., New York, N. Y. 10017, remitting $3.00 for microfiche or $9.25 for photocopies.

FIG. 3. Protocol for the response to complete loss of piped oxygen. Numbers indicate the order in which personnel are contacted and the order of task execution.

COMPLETE LOSS OF PIPED OXYGEN



*Only those patients being treated for hypoxemia or respiratory failure are to be provided with emergency supplies.

liquids,[14] but not for storage vessels at medical sites. Requirements for minimum surface area and pressure testing of vaporizers are needed. At present no standard provides guidance or regulation in the manufacture and testing of vaporizers. Redundant main line pressure regulators should be required. This would prevent the shutdown of the entire system that is necessary in order to perform a frequent routine repair procedure, and would greatly decrease the length of time that the hospital would be without piped oxygen should the primary regulator fail. The use of a T fitting in the main supply line remote from the main storage area would provide a ready means for attaching emergency supplies in the event that both the main and the reserve supply are damaged.[13] The size and threading of this fitting should be standardized to prevent confusion and delay during such an emergency. Provisions for system design that take potential environmental damage into account should be recommended by national standards committees so that users in high-risk areas may be aware of additional safety options. For example, horizontal rather than vertical placement of storage vessels greatly decreases the risk of damage during high winds, and permanent flexible connections between system components might provide some protection from shifts in the terrain beneath the supply system, or between the supply and the hospital. Vertical cylinders should also be bolted to a suitable foundation in order to withstand high winds. No existing standard specifies this. Requirements for the foundation to support the enormous weight of these systems are left to the local building codes and the supplier's previous experience. In 1977, our main tank started to list due to soil compression. A crane was needed to lasso the tank. Crane operators were continuously required for the week it took to reinforce the foundations. A single standard covering all aspects of system construction and function would greatly decrease the present confusion and would provide a much more realistic educational tool for users and suppliers alike.

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