References

[1]Bestelmeyer, A., "Zur Theorie des Ballonvariometers," *Physikalische Zeitschrift*, Vol. 11, 1910, pp. 763–768.

[2]Mears, A. H., "Statoscopes and Rate of Climb Indicators," Rept. 126, 1922, NACA.

[3]Eaton, H. N., *Aircraft Instruments*, Ronald Press, New York, 1926, pp. 46–52.

[4]Stewart, C. J., *Aircraft Instruments*. Wiley, New York, 1930, pp. 42-51.

[5]McKay, W., "Dynamic Characteristics of Pressure Operated Aircraft Instruments," Ph.D. thesis, 1935, MIT, Cambridge, Mass.

[6]Oppelt, W. and Wenk, F., "Theoretische Betrachtung des Luftdruckvariometers und Richteinien fur Entwurf and Prufung," *Luftfahrtforschung*, Vol. 14, pp. 537-541, (1937).

[7]Draper, C. S. and Schliestett, G. V., "Dynamic Errors of the Rate of Climb Meter," *Journal of the Aerospace Sciences*, Vol. 5, 1938, pp. 426–430.

[8]Johnson, D. P., "Aircraft Rate of Climb Indicators," TR 666, 1939, NACA.

[9]DeJuhasz, K. J., "Graphical Analysis of Response Characteristics of Rate of Climb Indicators," *Journal of the Aerospace Sciences*, Vol. 11, 1944, pp. 48–54.

[10]Takeda, S., "Theoretical and Experimental Investigation of Rate of Climb Indicators," Rept., Dec. 1957, Technical College of Hosei University, Tokyo, Japan.

[11]Considire, D. M., *Process Instruments and Controls*, McGraw-Hill, New York, 1957.

[12]Andreeva, L. E., *Elastic Elements of Instruments*, Israel Program for Scientific Translations, 1966.

AUGUST 1974 J. AIRCRAFT VOL. 11, NO. 8

In-Flight Oxygen Generation for Aircraft Breathing Systems

Edward J. Boscola
Naval Air Development Center, Warminster, Pa.

Operational and logistics problems associated with liquid oxygen (LOX) breathing supply systems have shown the need for developing methods of generating oxygen directly on board the aircraft for aircrew breathing. Concepts presently being developed are based upon fluomine chemical sorbent and electrochemical concentrator processes. The fluomine process is a temperature cycled chemical system using the fluomine for reversibly sorbing oxygen from engine bleed air. The electrochemical process uses a combination fuel cell and electrolysis cell reaction to generate oxygen. Oxygen from an air stream is reduced on the cathode to form water, the water is then electrolyzed at the anode to evolve pure gaseous oxygen. With the aid of necessary aircraft resources (electrical power, air, heating, and cooling), these techniques extract oxygen directly from engine bleed air during all flight operations. The oxygen generation systems produce oxygen at approximately 99.5% purity and is sufficient to meet the breathing requirements of two men during all in-flight operations. Ground and aircraft carrier support will be eliminated or minimized to improve efficiency and safety of flight operations. Aircraft turn around time with respect to oxygen will be reduced to nearly zero while maintenance periods will have a minimum time of 1000 flying hr.

Introduction

OPERATIONAL limitations imposed as a result of the current method of handling and stowing liquid oxygen (LOX) supply systems often restrict the availability of aircraft for extended missions. In addition, logistics and maintenance problems, dangers of fire, and contamination associated with LOX pose a continued threat to the effectiveness of the total aircraft weapons system.

The limitations and problems associated with LOX become increasingly severe both to carrier-based aircraft and to aircraft operating from advanced sea and ground bases as the performance of tactical aircraft is developed to meet extended operational and mission requirements. The cost of the LOX generating capacity of an aircraft carrier, both in dollars and in carrier space and electrical power output, is prohibitive as are the logistics problems with transporting LOX to the carrier from a shore based source of supply.

To eliminate the problems associated with LOX, new forms of oxygen generation methods which produce oxygen directly on board aircraft are presently being developed under a joint Navy/Air Force effort. Navy interest in new oxygen generation techniques is directed primarily toward carrier-launched and retrieved fighter/attack aircraft. However, the equipment can be equally applicable to all fixed-wing and rotary-wing aircraft that require breathing oxygen for the aircrew.

Design Criteria

The basic requirements for oxygen generating systems are shown in Table 1. With the necessary aircraft resources the systems shall generate oxygen at approximately 99.5% purity at a rate sufficient to meet the breathing requirements of two men during all in-flight operations, in addition to start-up and taxiing conditions and underwater emergencies. The maximum electrical power to support the system is 7 kva. The system is intended to replace the current stored LOX system and, thereby, eliminate or minimize ground and aircraft carrier support, improve efficiency and safety of flight operations, and to have a minimum time of 1000 flying hr between maintenance periods. Flight time between servicing is 15 hr and in order to satisfy quick turn-around time requirements, servicing shall not take more than 5 min per aircraft.

Presented as Paper 73-1348 at the AIAA Crew Equipment Systems Conference, Las Vegas, Nev., November 1-9, 1973; submitted December 6, 1973; revision received May 7, 1974.

Index category: Aircraft Cabin Environment and Life Support Systems.

*Program Manager, Crew Systems Department.

Table 1 Oxygen generating system basic operational requirements

Oxygen purity	99.5%
Contaminants	MIL-0-27210
Oxygen generating capacity	2.3 lb/hr per man max
Underwater breathing capability	5 min/man at 33 ft
Mission duration capability	15 hr
Maintenance cycle	1000 flight hr
Servicing time	5 min
System operation	All environment

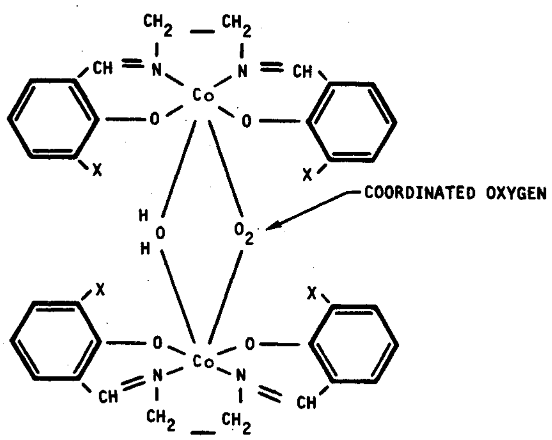

Fig. 1 Metal chelate structure. For salcomine, X = H. For fluomine, X = F.

Methods and Investigations

Selection of the fluomine sorbent process and the electrochemical concentrator proces for laboratory system development was a result of a joint Navy/Air Force evaluation of various oxygen generation methods. A reversible barium oxide dioxide concept (Brin process) and a water electrolysis method were also studied but were disqualified for development consideration because they were considered more complex and had a higher demand for logistics support. In addition, the water electrolysis process appears infeasible because electrical power requirements exceed the capabilities of present day aircraft.

Fluomine Sorbent Process

The fluomine sorbent process is based on the use of a cobalt chelate known commercially as fluomine. The organic chelate structure for the parent compound salcomine and its analog fluomine is shown in Fig. 1. The crystal structure of salcomine has been intensively studied and characterized by many scientists dating back as far as 1933. Hundreds of potential oxygen chelates were made and tested but only one was found to be better than the original parent compound, salcomine. This chelate was designated commercially as fluomine. This fluomine compound can absorb 4.4% oxygen on a theoretical basis or one molecule of oxygen for each two atoms of cobalt. Conversely, salcomine can absorb 4.92% oxygen on a theoretical basis. The reduced oxygen capacity of fluomine is a function of its higher molecular weight. However, this was offset by the fact that the rate of absorption and desorption, stability, and life expectancy were all much better for the fluomine compound when compared to its parent compound salcomine. During the past year, laboratory tests have shown degradation rates higher than originally calculated. Degradation problems are of great concern since this is one criteria that will determine whether fluomine can be used as an oxygen sorbent for aircraft breathing systems. Investigations being conducted under a separate Air Force program have shown the causes and effects of degradation, but the reporting of these are beyond the scope of this paper. Work to date has shown that a high-capacity fluomine chemical for oxygen sorption can be made reproducible, but it will have to be determined how the chemical can be made economically in large production batches.

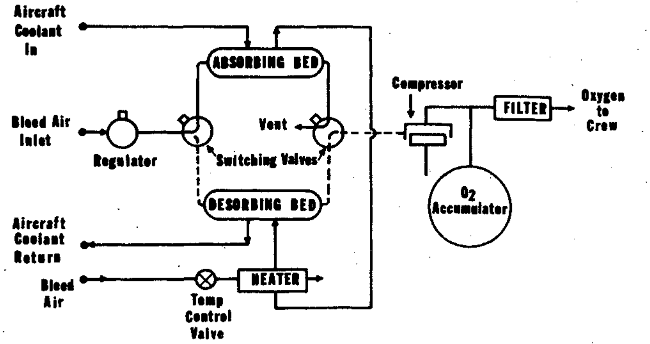

Fig. 2 Aircraft oxygen generator system fluomine sorbent process.

The present system design employs two beds containing approximately 22 lb of fluomine. These beds are cyclically operated to produce oxygen from engine bleed air. Two beds are used so that a constant supply of oxygen can be delivered for aircrew usage. The schematic of the basic system design is shown in Fig. 2. Engine bleed air at 50 lb/hr is regulated to 25 psig and is directed to the sorbent beds where the oxygen in the bleed air stream is absorbed on the solid sorbent material. The oxygen depleted air is vented to ambient. After a 3½ min half cycle, the air flow is halted; the sorbent bed pressure is decreased to 7–8 psia and the bed temperature raised to 220–225°F to release the previously absorbed oxygen. (Each absorb and desorb half cycle is 3½ min. Shorter cycle times can increase oxygen poduction with a lower sorbent weight. But, a higher heat load would be imposed on the aircraft environmental control system.) The desorbed oxygen flows to a three-stage positive displacement compressor to raise the oxygen pressures to those compatible with the breathing regulatory devices (85 ± psig) and storage containers (variable between 1700 psig to 2100 psig).

The oxygen generation rate is controlled by a temperature control bias valve (not shown on schematic). This valve senses oxygen tank pressure and the control pressure of the temperature control valve. As oxygen tank pressure increases, the bias valve controls the pressure bleed off of the temperature control valve. This closes the valve and the desorb coolant temperature is decreased low enough so that oxygen generation is reduced. Conversely, as oxygen tank pressure decreases, a poppet in the bias valve closes so that the temperature sensor alone is now controlling the temperature control valve and maximum oxygen production occurs. This manner of controlling the oxygen generation conforms to the breathing requirements of two men at all cabin altitudes.

The compressor design is shown in Fig. 3 and is considered as a new technology area because of its unique application. The design selected for the system is a three-stage unit with the stages mounted radially around a crankcase. The radial design provides for easy balance. The first two stages use metal bellows for the compression members and the third stage uses a metal diaphragm. The approximate compression ratios of the first two stages are 4:1 and 12:1 for the third stage. With an inlet pressure of 8.16 psia the third stage outlet pressure will be approximately 1780 psia. At these pressures the compressor will flow 6.7 lb/hr of oxygen through the first two stages and 2 lb/hr through

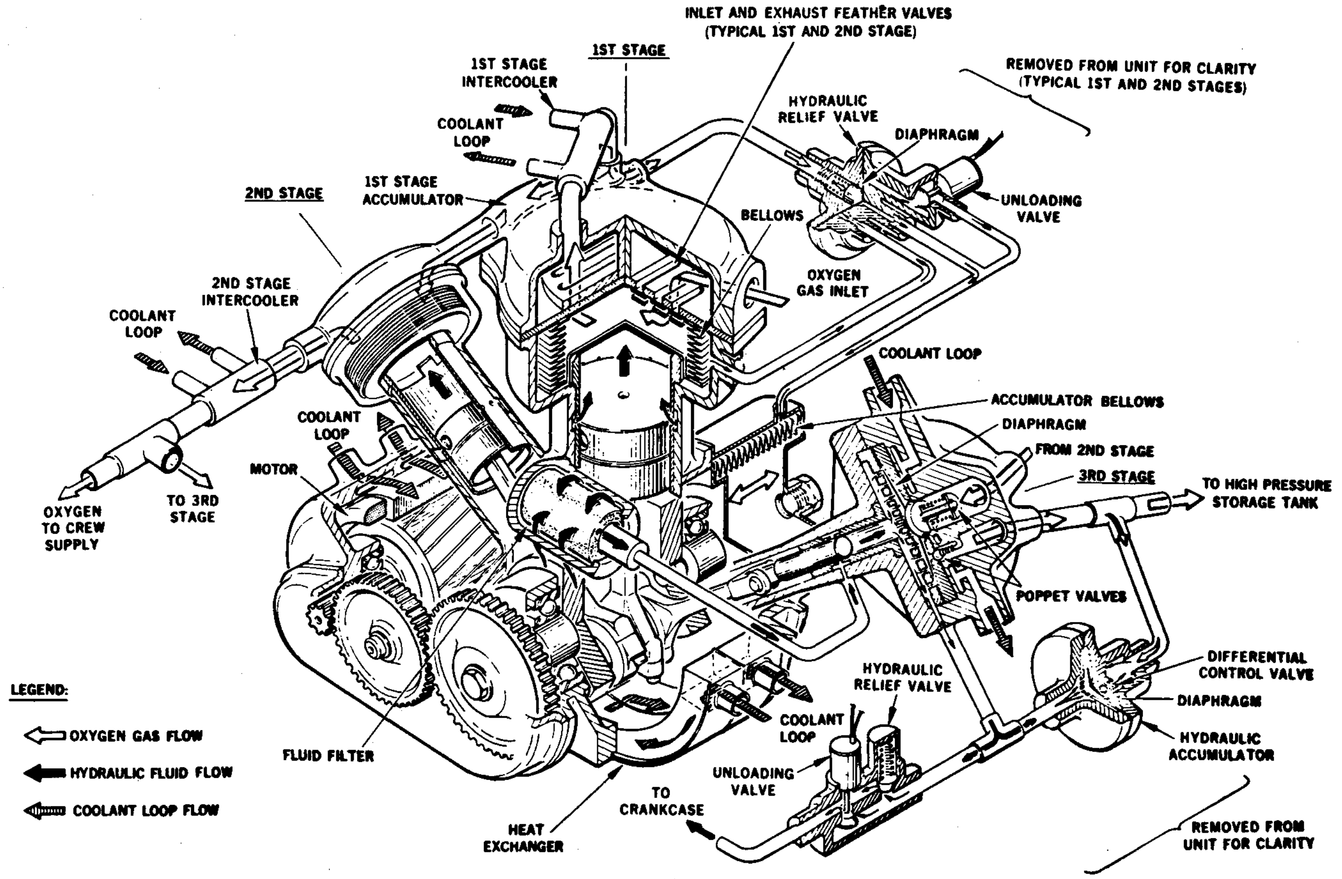

Fig. 3 Three-stage oxygen compressor.

the third stage. The unit uses a pump flooded with Freon E-5. This fluid provides the compression on the bellows and diaphragm by being forced against the compression members by three pistons that are connected to the crankshaft. The compressor uses an electrically driven motor operated by 3 phase, 400 Hz, 220 v a.c. power and is designed for continuous duty throughout all required flight altitudes. The rotor speed is approximately 12,000 rpm for optimum power factor, efficiency, and weight. Spur reduction gears are used to reduce the output speed to approximately 2,000 rpm. The unit weighs 17.0 lb and uses a maximum 1.0 kw electrical power. This particular design was selected because it increases efficiency by providing cooling during compression, provides a good heat transfer path for removal of the heat of compression and provides excellent lubrication for all rotating and sliding members.

Shown in Fig. 4 is a nonfunctional mockup of the system design which was fabricated during the design study phase conducted in 1971. The system configuration in its final form will be altered because of design improvements and aircraft integration.

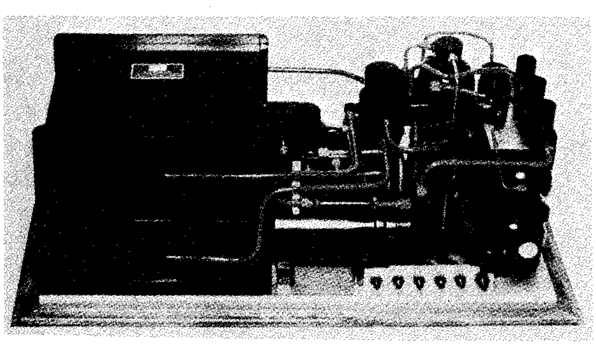

Fig. 4 Aircraft oxygen generator system fluomine sorbent process.

Electrochemical Concentrator Process

The electrochemical concentrator process operates on an ion exchange principle. Electrical power is used to electrochemically "pump" oxygen from an air stream through a sulfonated solid polymer electrolyte. The electrochemical cell is shown schematically in Fig. 5 with the following reactions:

$$\text{(Cathode)}\ O_2 + 4H^+ + 4e^- \longrightarrow 2\,H_2O$$

$$\text{(Anode)}\ 2\,H_2O \longrightarrow 4H^+ + 4e^- + O_2$$

Oxygen molecules from an air stream are catalytically combined at the cathode with hydrogen ions contained within the electrolyte and electrons from an external power source to form water molecules. These molecules

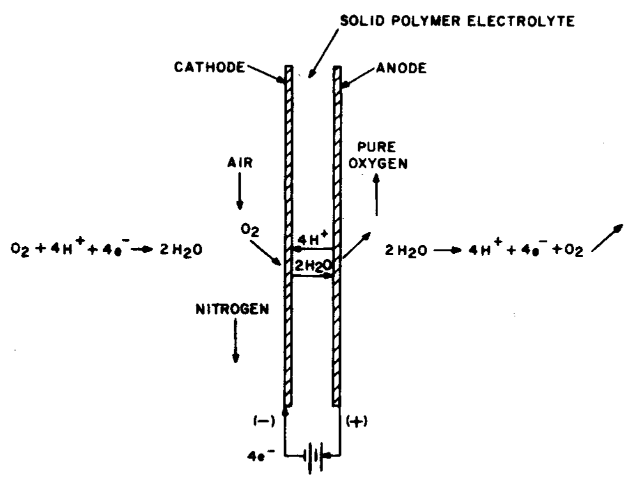

Fig. 5 Oxygen concentrator cell schematic.

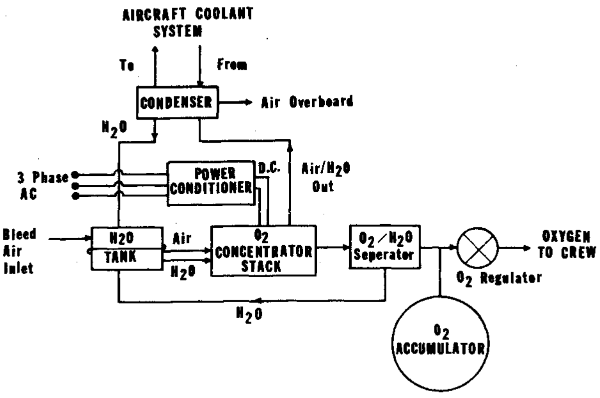

Fig. 6 Aircraft oxygen generator system electrochemical concentration process.

migrate through the electrolyte to the anode where they are electrolyzed, the oxygen evolving as a pure gas and the hydrogen returning to the electrolyte in ionic form. The hydrogen remains in ionic form at all times, never going through the molecular phase. There is no net consumption or production of water during the reactions within the cell. However, water is required to keep the cell at 100% humidity to maintain efficient cell performance.

A general description of the system is shown in Fig. 6. Engine bleed air at 116 lb/hr at a pressure of 25 psig passes through a heat exchanger jacket around a water tank and into the air cavities of the electrochemical cells in a concentrator stack. This stack consists of 120 single cells arranged between lightweight pneumatic end plates. As current flows through the cells, the water molecules are electrolyzed into oxygen and two protons. The protons carry the current through the solid polymer electrolyte and combine with oxygen in the bleed air to form water. This water, plus water which is carried by the protons across the electrolyte, is evaporated into the air stream. This evaporation is the mechanism which removes waste heat from the cells. The operating temperature of the cells is regulated to 180°F by controlling the flow of bleed air through the cells. The oxygen as it is generated is fed through a Coolanol 25 oxygen chiller to an oxygen/water separator where water is separated and returned to the water tank. The oxygen passes through a check valve and into the accumulator. The air/water mixture passes through the condenser where the mixture is cooled to approximately the Coolanol 25 inlet temperature of 75°F. The condensate and air mixture passes through an air/water separator. The condensate drains into the water tank and the air is exhausted overboard. The power conditioner rectifies 115 v a.c. power and controlled d.c. power is supplied to the cells in the concentrator stack. The oxygen generation rate is controlled by the power conditioner and these rates conform to the breathing requirements of two men at all aircraft cabin altitudes.

The maximum design oxygen generation pressure is 380 psi. At this pressure, the accumulator is sized so that ample reserve oxygen is available for emergency conditions. Since the oxygen generator is capable of generating at high pressure, there is no need for a compressor. However, each cell must seal against the oxygen generation pressure of 380 psi. Since the solid polymer electrolyte tends to creep with time, the mechanical loading on the membrane should be kept below 750 psi. This is done by using sealed fluid pressure against the cell stack to apply the proper sealing force. For this application, the stack end domes are designed as thin ellipsoidal shells, containing bonded butyl bladders to pressurize the stack core with nitrogen to about 500 psig.

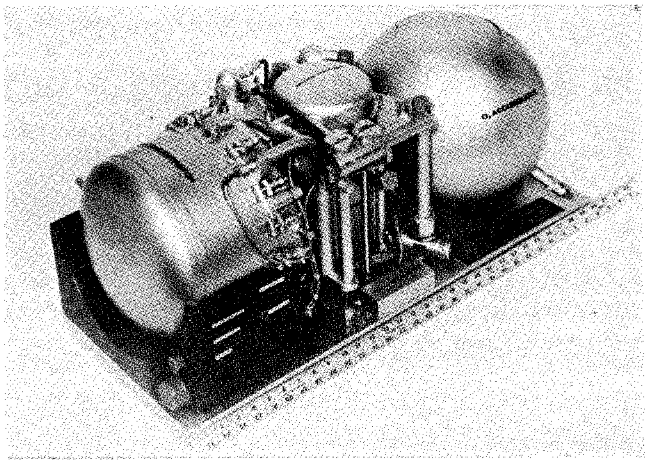

Fig. 7 Aircraft oxygen generator system electrochemical concentration process.

Table 2 System characteristics summary 100% open loop 2 man systems

	Fluomine	Electro-chemical
Oxygen generated		
Rate, lb/hr	4.60	4.60
Temp., °F	220	180
Pressure	7 psia	380 psig
Process medium		
Fluid	Bleed air	Bleed air
Rate, lb/hr	50	116
Temp., °F	−35 to +65	100 to 400
Pressure, psig	25	25
Thermal conditioning		
Fluid	Coolanol 25	Coolanol 25
Rate, lb/hr	800	882
Temp., °F	75–130	75–130
ECS load, btu/hr	14,000 max	29,600 max
Oxygen storage		
Usable oxygen, lb	1.0	0.77
Pressure, psig	1800	380
System weight, lb	110	65
System volume, ft^3	2.8	2.8
Electrical power, KVA	1.1	7.0

A nonfunctional mockup of this system design also fabricated during the design study phase is shown in Fig. 7. A summary of the system characteristics of the fluomine and electrochemical methods are shown in Table 2.

Aircraft Investigations

To assess the impact of an On-Board Oxygen Generating System on airframe operation, it was necessary to select an aircraft design to be used for its performance parameters. Eight airframes were used for this purpose. The principal airframe used was the F-14 since this aircraft represented the current state-of-the-art for high performance aircraft. The Oxygen Generating Systems and their performance characteristics were reviewed to establish operational elements for system/aircraft integration. At the present time, most resources are committed to the existing airframe systems. In some cases, it may be fairly easy to expand the aircraft resource capacity, but in others extensive changes may be required for proper system/aircraft interfacing. Because of the present system heat loads and/or heating air required, the oxygen systems cannot be easily accommodated by existing aircraft environmental resources. Therefore, the investigation of heat load minimizing techniques is necessary. Different heat sinks and heating sources may be necessary since the environmental resources vary among the many types of aircraft.

The use of aircraft resources to operate the oxygen generation system places an additional weight penalty on the aircraft when compared to the present LOX system. The sea level flight condition is the most penalizing to the airframe since it represents the highest oxygen consumption and resource requirements. A relative gross takeoff weight penalty for a three-hour sea level mission based on the original design study system characteristics has shown a gross take off (GTO) weight penalty of 275 lb for the fluomine system and 196 lb for the electrochemical system. Actual GTO calculations are difficult but estimates indicate that the GTO will be higher than the figures given above after all the various weight penalty factors are clearly defined with respect to the operational system.

Conclusions

Development of the fluomine sorbent process has been in progress since December 1971 and is approximately 95% complete. Immediate problems concern the compressor and the fluomine chemical. The compressor design has been finalized, but fabrication and tests must be concluded. An evaluation of chemical degradation rates, contaminants, and reproducibility is being conducted under a separate Air Force program and the acceptability of its use as an oxygen sorbent for aircrew systems will be known by mid-November 1973.

Development of the electrochemcal system started the beginning of last year. System design, concentrator stack design, and system component designs have been completed. Development, fabrication, and tests are currently in progress. This program is approximately 95% complete.

While some system development problems exist, the major difficulty of these concepts is integrating and utilizing the aircraft environmental control system for removal of the high external heat loads produced by the systems. This problem does not have an obvious solution. However, methods to reduce and remove this heat load with minimized effect on aircraft performance are being investigated.

Laboratory tests are scheduled to begin in the third quarter of 1974 with completion by late 1974. Sufficient test data under varying laboratory, flight and ground operating conditions must be accumulated to ensure that there will be no sudden changes to the chemical composition and/or electrolytes which will allow contaminants or volatile gases to exceed the maximum acceptable concentration levels for aircrew breathing.

The successful development of an efficient oxygen generation supply system will improve over-all military air operation and effectiveness and reduce logistics support and aircraft carrier fire hazards. This development program could also significantly improve the potential of obtaining a true "shirt-sleeve"-type of aircraft environment.

References

[1] "Aircraft Oxygen Generator System Design Study," 71-7386, AiResearch Manufacturing Company, April 1971; USN Contract N00156-71-C-0586.

[2] "On-Board Oxygen Generator System Design Study," 71DE2, General Electric Co.; USN Contract N00156-71-0478.

[3] "The Study of On-Board Oxygen Generating Systems," Final Rept. D682-12, Oct. 1972, Grumman Aerospace Corp.; USN Contract N62269-C-0144.

[4] "Bulk Processing of Fluomine Interim Report," 73-9071, Feb. 1973, AiResearch Manufacturing Co.; also USN Contract N62269-72-C-0025.

[5] "On-Board Oxygen Generating Systems," presented at 44th Annual Scientific Meeting of the Aerospace Medical Association, Las Vegas, Nev., May 1973.