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MOLECULAR SIEVE INERTING SYSTEM FOR AIRCRAFT FUEL TANK, PART NO. 3261021-0101

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Final Report for Period 1 July 1980 - 31 July 1982

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The elimination of fire and explosion hazards in aircraft fuel tanks has been investigated. DOD and FAA tests have shown that a reduction of the oxygen concentration in the ullage gas to under 12 percent will prevent rapid propagation of the flame front and subsequent overpressure explosion. One means of providing the required reduction in oxygen concentration is to provide a source of inert (nitrogen-rich) gas which would replace fuel used, and flush out atmospheric oxygen and dissolved oxygen which may be released from the fuel. Molecu-

Block 20.

lar sieve pressure swing adsorption technology could be used to generate inert (nitrogen-rich) gas. A Molecular Sieve Inert Gas Generator (MSIGG) was designed, fabricated, and delivered to the U.S. Air Force, Wright-Patterson Air Force Base, Ohio where it will undergo extensive laboratory testing to establish the feasibility of using the molecular sieve pressure swing adsorption technology to provide fuel tank inerting protection for large fixed wing aircraft. In preliminary testing prior to delivery the developed system met performance goals and predictions.

PREFACE

This report describes an effort conducted by Clifton Precision Instruments and Life Support Division of Litton Industries, Davenport, Iowa, for Air Force Aero Propulsion Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio, under contract F33615-80-C-2007. This work was accomplished under Program Element 63246F, Project 2348, Task 234801, and Work Unit 23480103. The Air Force project engineers were R. G. Clodfelter and G. W. Gandee.

The work reported herein was performed during the period from October 1980 through July 1982, under the direction of Mr. Dale L. Hankins, Program Manager, Nitrogen Systems. Major participants in the program were Mr. Donald Muhs, Senior Engineer, Mr. Raymond Stanford, Engineer, and Mr. David Alftine, Engineer.

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SECTION I

INTRODUCTION AND SUMMARY

The threat of fires and explosions within the fuel tanks of Air Force aircraft is a concern in both combat and peace time. The highly volatile characteristics of the fuel, JP-4 conforming to MIL-T-5624, result in the formation of flammable mixtures over the normal range of operational temperatures. Prevention of the ignition of these fires and explosions can be accomplished by incorporation of the appropriate protection concept. However, the state-of-the-art concepts such as the reticulated foam or liquid nitrogen inerting impose penalties in terms of weight, maintenance, and logistics. Inerting the fuel tanks has always been one of the most attractive approaches. The displacement of the oxygen in the air with an inert gas such as nitrogen can prevent the ignition of the vapors within the ullage space of the fuel tanks. Prior research and development studies have established that maintaining the oxygen level below the 9 to 12% level can prevent ignition and thus, make the fuel tanks inert. The 9% oxygen level relates to the highly intense ignition source associated with incendiary gunfire. However, less energetic ignition sources or increases in altitude have shown that oxygen levels as high as 12% can prevent ignition.

The C-5A aircraft has a liquid nitrogen system for fuel tank inerting and fire fighting in potential hazardous zones of the aircraft. This system is designed to maintain the oxygen level below 9% for all flight conditions. This system has been effective and is credited with saving one aircraft which had an engine pylon fire. However, the use of a liquid nitrogen system imposes penalties in terms of logistic restrictions and costs associated with the need to replenish the nitrogen after two flights. To overcome these problems, the Air Force has sponsored research and development aimed at the development of an on-board inert gas generator system (OBIGGS) which can provide an unlimited supply of inert gas whenever the need arises. These OBIGGS systems process engine bleed air into an oxygen depleted product that contains no more than 9% oxygen.

This program for generation of an inert gas is based on a pressure swing adsorption (PSA) using a zeolite molecular sieve material. This PSA approach has been successfully applied to not only fuel tank inerting, but also to an on-board oxygen generating system (OBOGS) for crew breathing. The principle of the two systems is the same. The molecular sieve material, depending on its properties can either selectively adsorb oxygen to create an inert gas for fuel tank inerting or a different sieve material can adsorb nitrogen and create 95% pure oxygen for crew breathing. Clifton Precision Instruments and Life Support Division (ILSD) has successfully flight tested OBOGS on the Navy Harrier AV-8A aircraft and the USAF F-16. Air Force plans for the future include the elimination of the liquid oxygen bottle on the F-16 and B-1B and replacement with the OBOGS. The Army will, in the future, use an OBIGGS to protect the fuel tanks of its helicopters. As a result of competitive procurement, the Clifton Precision ILSD unit was chosen for application to the production version of the AH-64 helicopter. Also, the

Navy has successfully flight tested a system in the CH-53A helicopter.

The Army helicopter application is a relatively small unit producing 0.038 lbs/min inert gas to replace the fuel used. In contrast, the contract requirements for the Air Force were based on an 8 lbs/min unit for the KC-135 aircraft. The design of an inerting system is highly dependent on a number of interacting variables such as aircraft mission profile, engine bleed air availability, size of the fuel system, and characteristics of the inerting module. These variables can be translated into a system penalty since the inerting system will add additional weight, use bleed air, and impose some drag. These penalties can be reduced to either a minimum weight penalty or to a minimum bleed air penalty measurable in terms of increased fuel consumption. The constraints of the program were that the inert gas not exceed 9% oxygen within the fuel tanks at any point in the mission. The program provided for the design and fabrication of an 8 lbs/min unit which would be delivered to the Air Force for extensive ground evaluation. Although the design of the system focused on the minimization of bleed air usage, the total evaluation will include its total performance in terms of life, transient response, environmental effects, etc. The unique capabilities of the facilities at WPAFB OH permit highly realistic simulation of the flight environment by making use of the high pressure air source from the Aircraft Engine Nacelle and the fuel tank of the Fuel Tank Simulator. The preconditioned bleed air at the appropriate temperature and pressure will enter the module. The exhaust gas from the module exits at the simulated altitude into a vacuum system. The produced gas flows to the fuel tank which has an altitude and temperature control. The simulated altitude provides inputs to the climb and dive valves which control the inert gas flow. The unit will be extensively evaluated in FY 83.

In order to minimize the cost of the unit, which was designed for laboratory use only, no attempt was made to minimize the weight. Commercial parts have been used where available. This system is approximately 60 inches long, 31 inches wide, and 45 inches high and weighs approximately 800 lbs. However, it is estimated that a flight system to meet the same requirements would weigh less than 585 lbs.

This program was successful in scaling up a molecular sieve unit capable of producing 8 lbs/min of inert gas containing less than 9% oxygen. This unit consists of four pairs of beds, each bed producing approximately 1 lb/min inert gas. The control logic consists of a programmable controller to permit a wide variation of operational parameters and simulated operational modes.

As a result of the success of this program there are three principal recommendations.

1. Pursue molecular sieve pressure swing adsorption as a practical approach to fuel tank inerting.

2. Undertake a flight test program which will include development of flight hardware and controls.

3. Use the adaptability of the molecular sieve pressure swing adsorption technology to take full advantage of systems engineering in integrating the fuel tank inerting equipment into the aircraft.

SECTION II

MOLECULAR SIEVE PRESSURE SWING ADSORPTION

Zeolites are a class of crystalline minerals which have the special property that large (compared to atomic dimensions) channels and cavities are produced by the arrangement of the atoms in the crystal. In addition, the charge distribution on the walls of the cavities interact strongly with some molecules, especially those with large dipole (e.g., H_2O, NH_3) or large quadrupole (e.g., N_2) moments, and less strongly with molecules which may be polarized)e.g., O_2) by electric fields. This strong interaction will hold molecules in the cavities of the crystal.

Studies of the adsorption and desorption process have shown that the interaction is analogous to the physical adsorption process which takes place at the surface of many materials. This implies that the process is completely reversible and does not alter the crystal structure of the zeolite in any way. The process is unlike surface adsorption however, in that the complete cavity volume can be filled with adsorbate rather than just filling sites on the surface of the cavity. Some authors, in fact, refer to the adsorbed phase as the "zeolite liquid phase" since in many cases the density of material in the cavities can approach, and in some cases, exceed the liquid density of the adsorbed material.

The sizes of the channels and cavities in zeolites is determined mainly by the structure of bonds between aluminum, oxygen and silicon atoms. All zeolites, however, contain an additional component which is ionically bound; usually a light metallic atom (e.g., Na, Ca, K, etc.). These cations are loosely bound and may be changed by ion exchange processes without changing the basic structure, i.e., channel and size of the zeolite. This process can however, drastically change the adsorption properties of the zeolite in two distinct ways. The cations generally are placed on the walls of the cavities. They provide the charge centers which attract and hold the adsorbate in the cavity. Changing the type of cation can therefore change the interaction with a given molecule and determine how strongly it is held in the cavity. In addition, exchange of an atom with valence of two: e.g., Ca for two atoms with valence of one, e.g., Na can partially block the channel entrances to the cavities. Thus materials which are adsorbed strongly by the calcium exchanged form may be physically excluded from the cavities and not adsorbed at all by the sodium exchanged form of the same zeolite.

The introduction of methods of synthesizing zeolites on a large scale in the early 1950's has made it possible to apply the unique adsorption properties of zeolites to many fluid separation processes which previously required other slow and/or expensive separation techiques. In addition the synthetic process has yielded many zeolite forms which do not occur naturally and which have a larger range of channel and cavity sizes than natural zeolites. This range of sizes coupled with changes introduced by cation exchange can produce an adsorbent which will selectively adsorb or not adsorb almost any small molecule on the basis of strength of interaction in the cavity, size of the molecule in relation to the channel size, and blockage of the channels by cations.

Zeolite A is a synthetic zeolite $X\ 12/V\ [(AlO_2)_{12}\ (SiO_2)_{12}]$. Where X is the cation and V is the cation valence. Type 4A and 5A molecular sieves are forms of Zeolite A with Na and Ca cations respectively. The 5A form will adsorb both nitrogen and oxygen but adsorbs nitrogen much more strongly. This effect has been used to provide an oxygen enriched product gas for many processes which require high oxygen concentrations but do not require the high oxygen purity of cryogenic separation; for example, oxygenation in waste treatment, supplemental oxygen for medical purposes and breathing oxygen for high altitude flight.

Type 4A molecular sieve has the same alumino-silicate structure but the calcium cation is replaced by sodium cations. The extra charge centers produced by replacement of 6 calcium atoms by 12 sodium atoms partially blocks the channels and effectively excludes the nitrogen molecules. The oxygen molecule is somewhat smaller and does not interact as strongly with the blocking sodium cation and will therefore be able to enter the cavities. Since the oxygen does not have to compete with nitrogen for adsorption sites in the cavity, the oxygen will effectively be held much more strongly in 4A than in 5A zeolite.

The latter process is just what is required to provide air which is depleted in oxygen for fuel tank inerting.

The amount of any fluid which is actually adsorbed, provided channel size, cation channel blockage and cavity interaction are favorable, depends on temperature, pressure and concentrations of other adsorbents. Many separation schemes have been developed in which one or more of these parameters are varied cyclicly to alternately adsorb an unwanted component and produce the desired product on part of the cycle and then to desorb and flush the unwanted component from the molecular sieve and out of the system.

1. PRINCIPLE OF APPROACH.

The rapid cycle pressure swing adsorption (PSA) method uses pressure as the controlled adsorption/desorption variable. In this process, high pressure air is applied to the feed end of the bed. As the high pressure gas moves through the bed of zeolite 4A, many of the oxygen molecules enter the zeolite crystals and are adsorbed. The nitrogen and argon in the air are not as strongly adsorbed, nitrogen due to channel blockage by sodium cations and argon due to the lower interaction strength in the cavities, so that at the product end, the remaining air is depleted in oxygen. As this process continues, the amount of oxygen adsorbed at the feed end of the bed approaches a saturation level for the pressure and temperature at that point. Therefore, as time passes, oxygen will move further into the bed before being adsorbed and if the process is allowed to continue, the oxygen concentration at the output begins to increase. Before this occurs, the pressure at the feed end of the bed is reduced to atmospheric pressure causing most of the adsorbed oxygen to be desorbed and some of the oxygen depleted product is flushed back through the bed to further lower the partial pressure of oxygen in the bed and complete the desorption process.

Using two beds which are pressurized and flushed on alternate half cycles provides an almost continuous flow of product and ensures sufficient pressure for the flushing operation.

Cycle times, adsorption and desorption pressures and amount of molecular sieve depend on the purity of product required, temperature environment and other factors. A great deal of experimental work has been done at Clifton Precision Instruments and Life Support Division to determine the interaction of the various parameters and to develop design procedures to provide timing and molecular sieve quantities which will be required to meet specific applications.

SECTION III

DESIGN TRADEOFFS

Pressure swing adsorption involves a number of process parameters which can be optimized according to a specific application. In the case of the present program, a KC-135 aircraft was selected for an application study. Accordingly, a mission profile was specified which would be representative of the resources available and the demands placed on an inerting system. The mission profile is shown in Table I. Hot, standard, and cold day conditions are tabulated.

The delivered unit is to be subjected to a simulation of the actual conditions of the mission profile as shown in Table I. This unit will be evaluated based on the total aircraft system penalty, expressed in terms of fuel usage, accrued during the simulated mission. This penalty relates to the added system weight, bleed air usage, and drag.

The laboratory testing done on this program was governed by the factors associated with the KC-135 aircraft and this mission. Therefore, extrapolating results to other aircraft or significantly different missions should be done with the realization that a specifically optimized system could result in lower penalties.

Table 1. AIRCRAFT MISSION

AIRCRAFT DATA

MISSION SEGMENT		1	2	3	4	5	6	7	8	9	10	11	12	13	14
MISSION TIME (HR)	ALL	.05	.22	.62	1.37	1.95	3.11	3.64	3.71	4.21	4.29	4.54	4.83	4.95	5.10
TIME IN SEGMENT (HR)	ALL	.05	.17	.40	.75	.58	1.16	.53	.07	.50	.08	.25	.29	.12	.15
MODE	ALL	START CLIMB	CLIMB	START CRUISE	START ORBIT	REFUEL	CRUISE	START DESCENT	START AIRWORK	START DESCENT	DESCENT	AIRWORK	START DESCENT	DESCENT	END DESCENT
ALTITUDE (FT)	ALL	0	15000	33000	31000	30000	45500	46000	30000	30000	15000	2500	27000	15000	0
MACH NUMBER	ALL	.42	.55	.78	.68	.68	.78	.78	.67	.70	.52	.39	.65	.52	.38
PRESSURES (PSIA) AMBIENT	ALL	14.7	8.29	3.80	4.17	4.36	2.10	2.05	4.36	4.36	8.29	13.4	4.99	8.29	14.7
PRECOOLER OUTLET	HOT	143.1	102.1	68.3	63.9	57.9	35.8	37.0	46.8	55.9	63.6	108.0	56.4	63.6	114.0
	STD	161.0	116.7	69.8	65.4	59.2	41.7	42.3	52.1	58.1	66.7	104.4	58.8	66.9	113.3
	COLD	209.2	131.1	70.0	65.9	59.4	37.9	39.1	52.3	58.6	67.4	107.7	59.4	67.6	116.9
RAM FREE STREAM TOTAL	ALL	16.6	10.1	5.7	5.7	6.0	3.1	3.1	5.9	6.0	9.9	14.9	6.6	9.9	16.2
TEMPERATURES (°F) AMBIENT	HOT	102.9	44.8	-22.9	-15.7	-12.1	-42.3	-42.1	-12.1	-12.1	44.8	93.4	-1.0	44.8	102.9
	STD	59.7	6.2	-58.2	-51.3	-48.8	-60.0	-60.0	-48.8	-48.8	6.2	50.8	-37.0	6.2	59.7
	COLD	-60.8	-29.0	-85.0	-85.0	-88.3	-101.3	-104.1	-82.3	-82.3	-29.0	-26.1	-71.2	-29.0	-60.0
PRECOOLER OUTLET	ALL	300	300	300	300	300	300	300	300	300	300	300	300	300	300
RAM FREE STREAM TOTAL	HOT	123.1	76.0	30.8	25.7	29.9	9.1	9.3	28.5	31.7	71.7	110.3	38.1	71.7	119.1
	STD	78.0	34.4	-9.0	-13.0	-9.0	-11.5	-11.5	-10.2	-7.0	31.4	66.4	-1.0	32.3	74.6
	COLD	-45.6	-2.2	-38.8	-49.9	-46.7	-57.1	-60.2	-48.0	-45.6	-6.0	-12.7	-32.9	-6.0	-48.5
FUEL FLOW, INSTANTANEOUS (PPH)	ALL	28930	22090	13140	11660	9570	7320	4880	7840	6000	5420	7700	5720	5420	16970
FUEL USED IN PERIOD (LB)	ALL	8353	4999	7000	8996	5902	11822	4004	442	3549	1001	3003	5005	1001	1001
INERT GAS FLOW REQUIRED (PPM)	ALL	3	3	3	3	3	3	3	8	8	8	8	8	8	8
% O_2	ALL	5	5	5	5	5	5	5	9	9	9	9	9	9	9

1. MOLECULAR SIEVE PERFORMANCE DATA.

The starting point for system design is molecular sieve performance data under standard conditions. In the design approach, effects of non-standard conditions were determined by test and applied in terms of coefficients to modify the standard condition performance.

In testing, independent or controlled variables were product percentage oxygen, supply pressure, back pressure, temperature, bed length, moisture content of input gas, and inert gas generator control parameters of purge flow, pressurization time, exhaust time and delay time. For each set of these values, the penalty (fuel consumed per mission divided by product gas generated per minute) was determined. This total penalty is the value sought to be minimized in the lab optimization processes.

Dependent variables were product flow and input flow. From these quantities, productivity (pounds per minute of product gas per pound of molecular sieve) and the ratio of input/output are determined.

Although not collected specifically for this program, typical performance data is displayed in Figure 1.

a. Penalty Mapping.

Between the two extreme optimum conditions of a minimum weight and a minimum input/output system is a spectrum of system configurations optimal for particular penalty situations. Testing established the most profitable region of this spectrum for the penalty conditions. Figure 2 portrays a penalty map for the KC-135 MSIGG showing the variation in penalty between a system designed for minimum weight and a system designed for minimum ratio of input air to output product (I/O). For the KC-135 aircraft, the optimum system is very close to a minimum bleed air (ratio of input air to output product) consuming system.

b. Bed Length.

Bed length is an independent variable that is found to significantly affect productivity and the trade-off between minimum weight and minimum I/O systems. Longer beds are found to be more productive for greater levels of gas enrichment. Also a minimum I/O system will have a longer bed than an equally productive minimum weight system. Initial test data is shown in figure 3. Additional tests were conducted to verify the applicability of existing data for the minimum total penalty case.

c. Altitude Effects.

If the working pressure of a pressure swing adsorption process is defined as the absolute supply pressure minus the pressure to which the unit exhausts, then one can compare system performance at various altitudes. Testing indicates improved performance both in terms of productivity and I/O with an increase in altitude. This test data is shown in figure 4. Productivity is

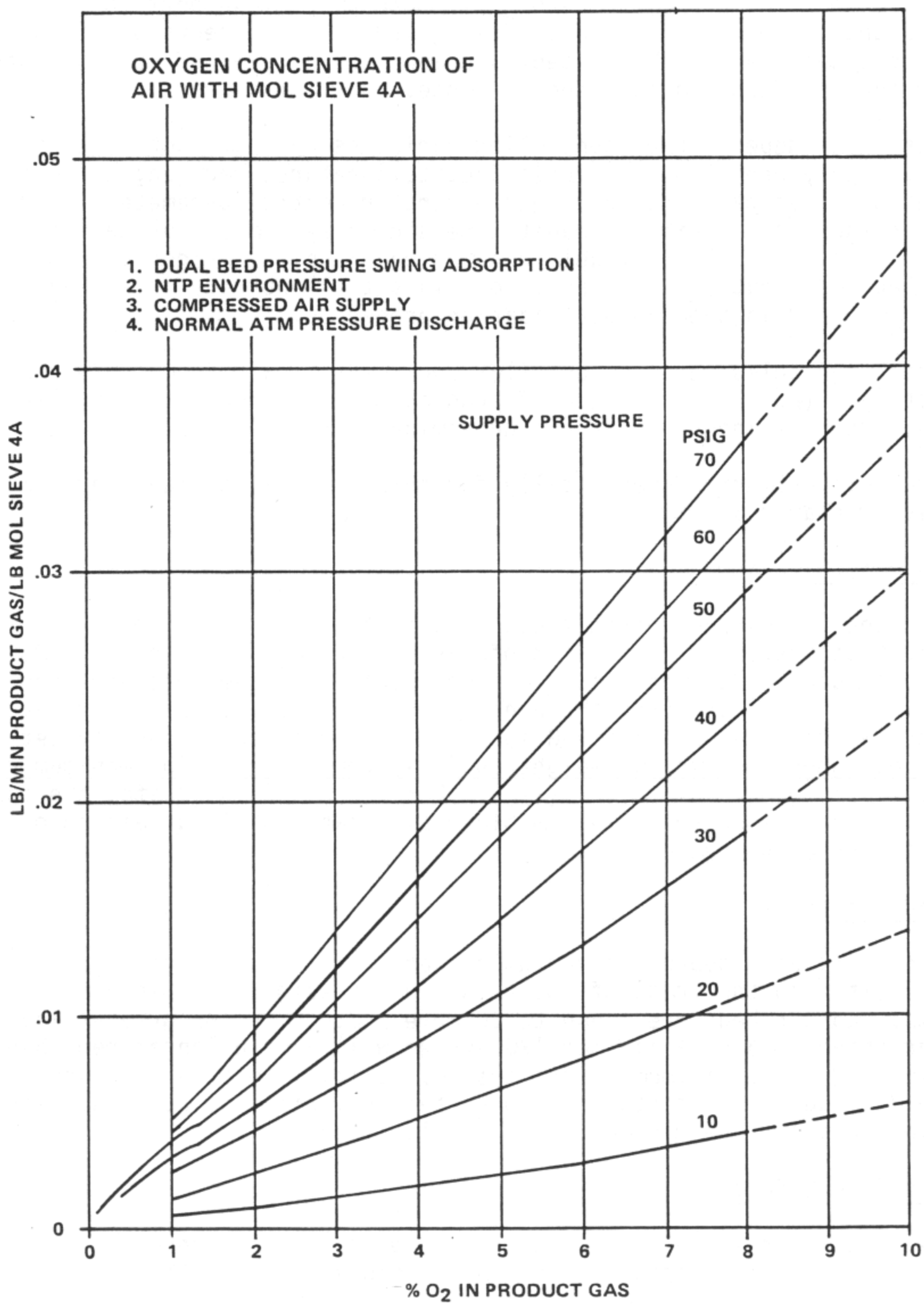

Figure 1. TYPICAL BASE LINE PERFORMANCE TREND DATA

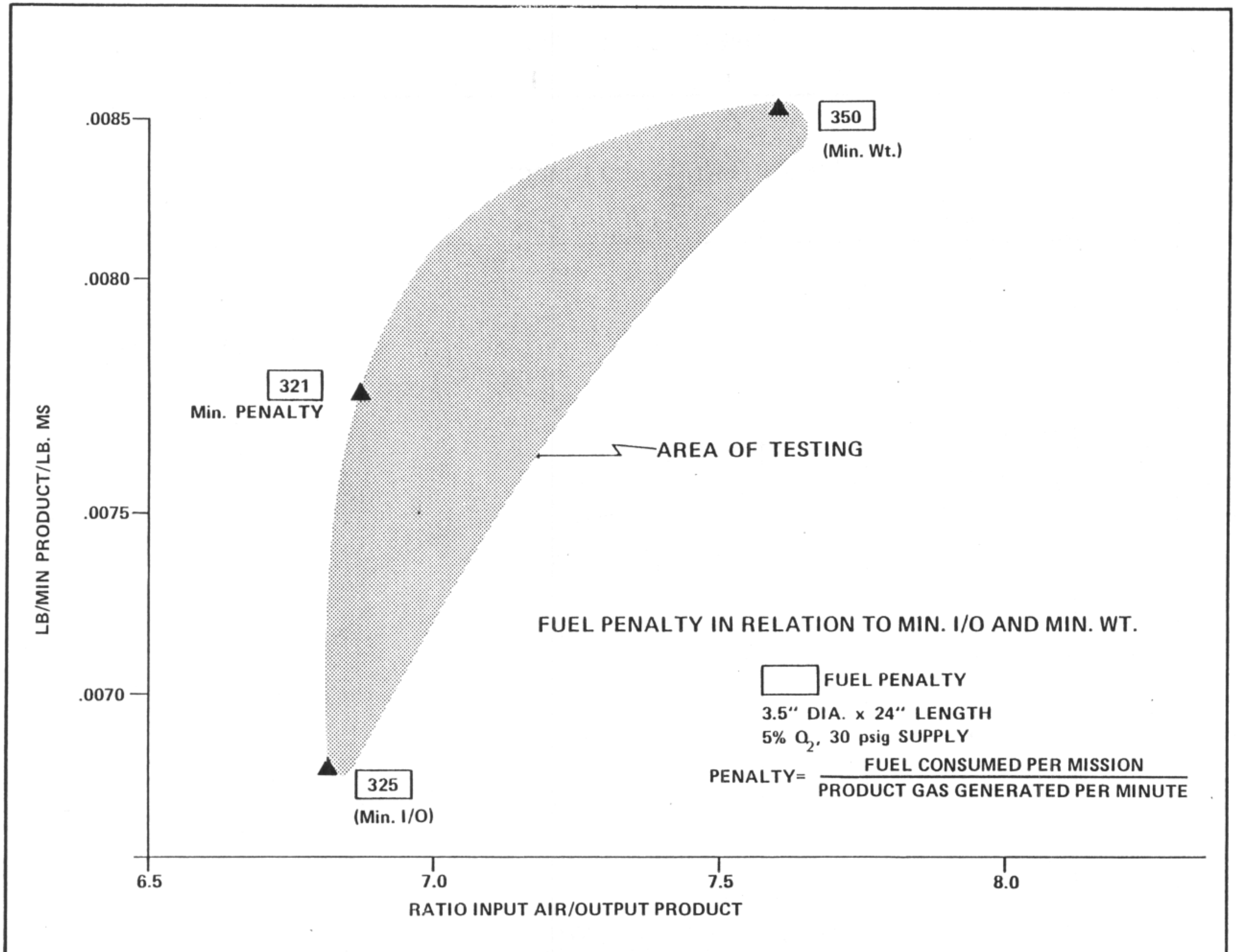

Figure 2. PENALTY MAP FOR USAF LABORATORY TEST MSIGG UNIT

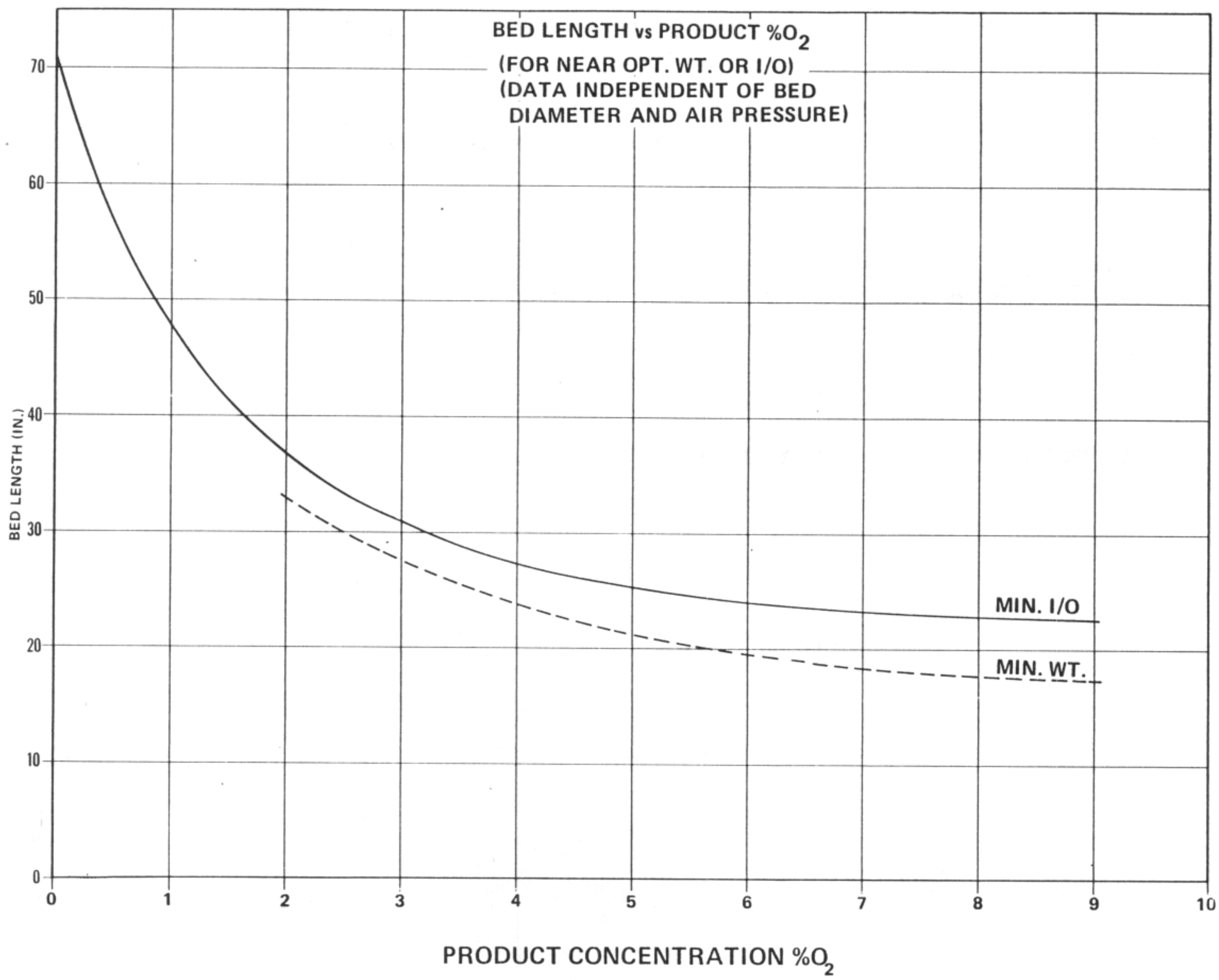

Figure 3. BED LENGTH

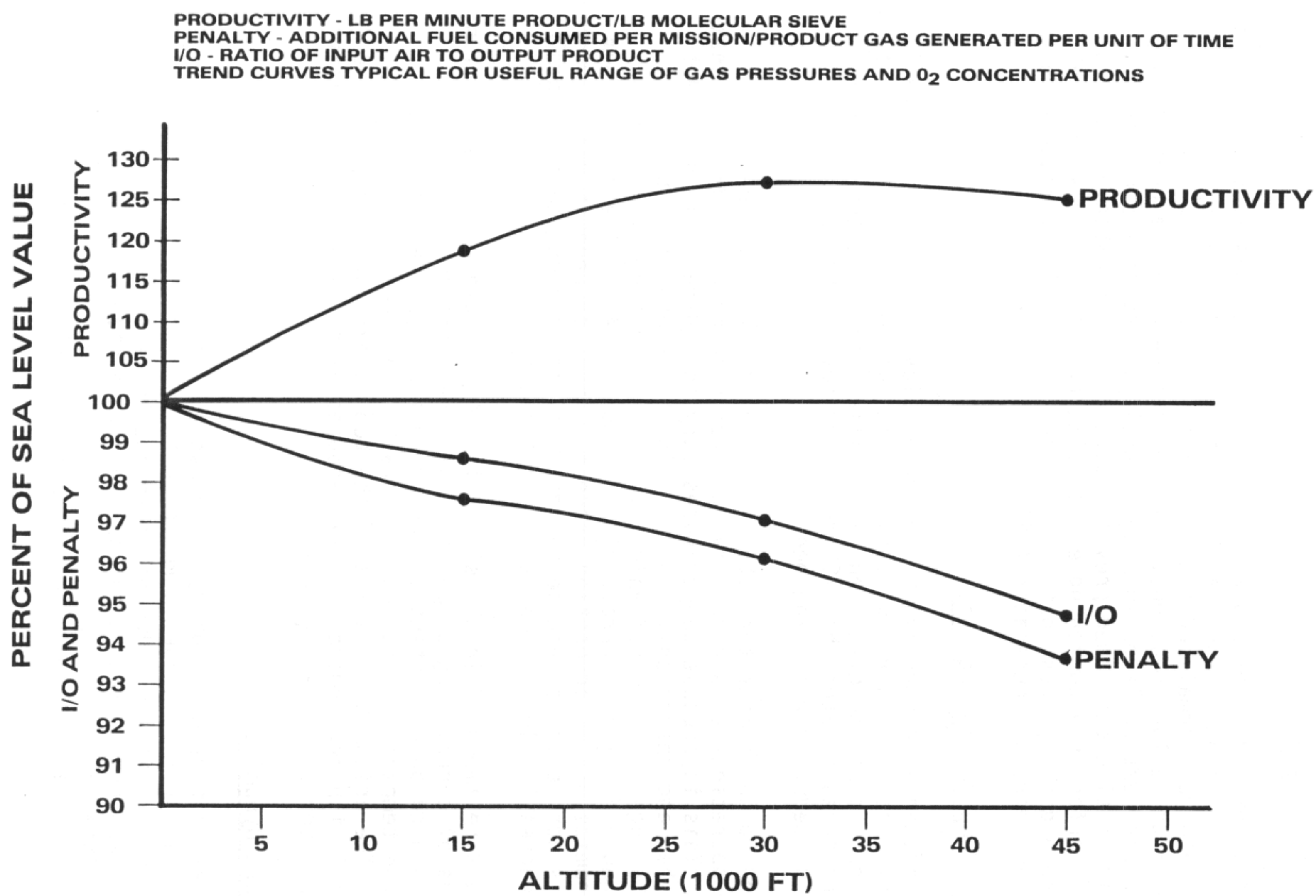

Figure 4. ALTITUDE EFFECTS

defined as pounds per minute of product gas per pound of molecular sieve. Penalty is the amount of additional fuel consumed per mission divided by the amount of product gas generated per period of time.

d. Inlet Air Temperature Effects.

The effect of inlet air temperature on system operation was studied in terms of productivity and input/output ratios. Penalty effects were then determined. Data was normalized against performance at 70 deg F for incorporation into design equations. Test procedure held the product oxygen concentration constant while optimizing control parameters for minimum penalty. This testing confirmed previous data which indicated a peak near 20 deg F with performance worsening either side by approximately 1/3% per deg F. Figure 5 displays test data showing the effect of temperature on the molecular sieve inert gas generator (MSIGG).

e. Operating Temperature Profile.

Temperature influences adsorption by molecular sieve. Therefore, operating temperature affects a pressure swing adsorption system in terms of operating performance, but it has no effect on system life. In fact, the sieve is held at temperatures greater than 700 deg F for several hours as part of the standard procedure for loading beds.

When referring to the temperature at which a molecular sieve inert gas generator is operating it is necessary to adopt some means of defining that temperature. This is because temperatures vary considerably in different parts of the bed and change only slowly as input gas and ambient temperatures change. Also a bed which might begin testing with a uniform temperature would develop a characteristic temperature profile merely from the thermodynamics of the adsorption process. Input or product gas temperature is not reliable because the gas passing through the sieve bed quickly approaches the local temperature of the sieve.

Thermocouples were imbedded in the sieve along the length of the bed to find the best means of correlating temperature with bed performance. Several tests were run with both constant and changing input gas temperatures. Profiles of the temperature changes were graphed and compared with performance. The arithmetic average of the bed temperatures was found to correspond well with performance and was adopted as the standard definition of bed or generator operating temperature.

f. Temperature Dynamics.

Because bed temperature does not remain constant during a mission it is necessary to predict its change in response to the various inputs the MSIGG will see during the mission. Dynamic response tests were conducted to determine the response of bed temperature due to a step change in the input temperature. (See Section V, paragraph 2a.) This empirical response was then modeled in subsequent computer simulation described in Section IV.

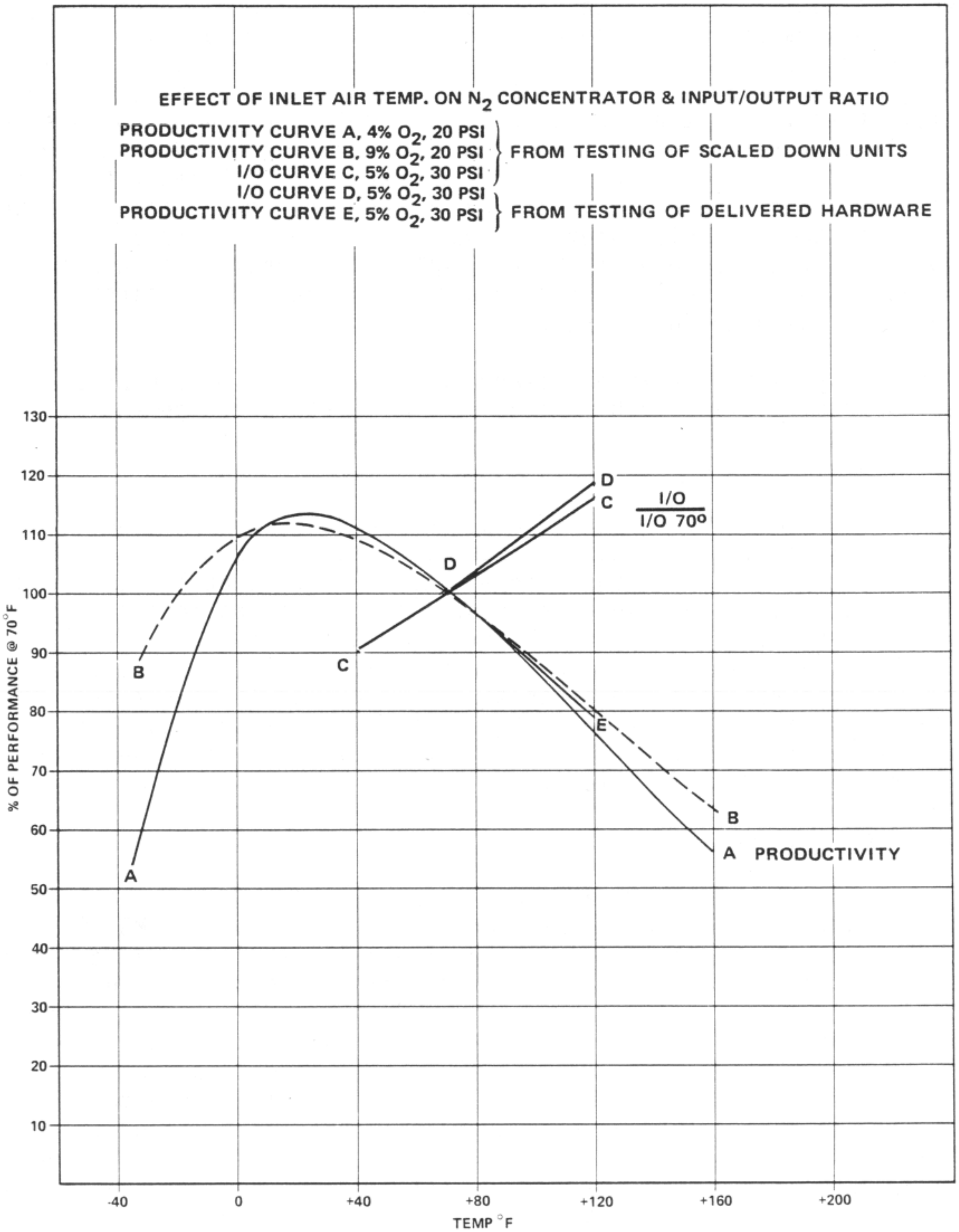

Figure 5. TEMPERATURE EFFECTS

g. Humidity Effects.

In addition to separating oxygen and nitrogen, molecular sieve readily removes water vapor. Historically the greatest commercial use for molecular sieve has been in dryers of both the batch and regenerative types. In the application of a nitrogen concentrator, water vapor in the supply air is adsorbed preferentially to oxygen and so is quickly removed from the gas stream. On depressurization and purging the water vapor also desorbs in the same manner as oxygen. Both processes are completely regenerative in the cycling process. Because the sieve preferentially adsorbs water vapor, the first small fraction of the bed is considered to be dedicated to moisture removal. Tests were conducted to determine, in the worst case, how much of the bed should be so dedicated. In a test, warm air 100% saturated with moisture was used as bleed air to supply an inert gas generator. At various distances into the molecular sieve bed gas samples were extracted and analyzed by an Alnor Dewpointer, Model 7000U. The results of this test showed that essentially all moisture had been removed in the first inch of bed length as indicated in figure 6.

In designing any system it is necessary to increase the molecular sieve bed length by approximately 1 inch to provide for moisture management.

h. Time to Stabilization.

The MSIGG must have the dynamic response to meet the control requirements of the expected mission. In a test to determine response time to changed conditions, the unit was turned on from a cold start, that being a worst case situation, and the oxygen content of the product gas logged every 15 seconds. Results were that in the 5% oxygen desired case the unit was at 7% oxygen within the first minute and below 5.3% in 2 minutes. The 9% case was similar. The gas was measured after mixing in a product plenum tank that was as large as the total volume of the beds. The response at the outlet of the concentrator is therefore significantly faster than the above times. Figure 7 shows this data graphically.

i. Eight Bed System Testing.

Consideration of test facility altitude simulation capacity and flexibility for future testing led to the requirement of modularizing the MSIGG. One way to have accomplished this would have simply linked four quarter-capacity bed pairs together. The additional consideration of supplying the peak flows demanded during the initial inrush portion of each cycle with a minimum pipe size led to a different and novel approach. It was proposed that eight beds be supplied from a common manifold and exhaust waste gas to a common manifold. Each bed would have discrete valves controlled by a master timer which in the lab model would be a programmable controller. Product gas would be delivered to a common manifold and from this same manifold purge gas would be taken by each bed through its own crossflow valve whenever that bed was depressurized. The pressure time cycle of each bed would be identical but offset in time by a period equal to the cycle time divided by the number of active beds.

MOISTURE PENETRATION IN MOLECULAR SIEVE BED

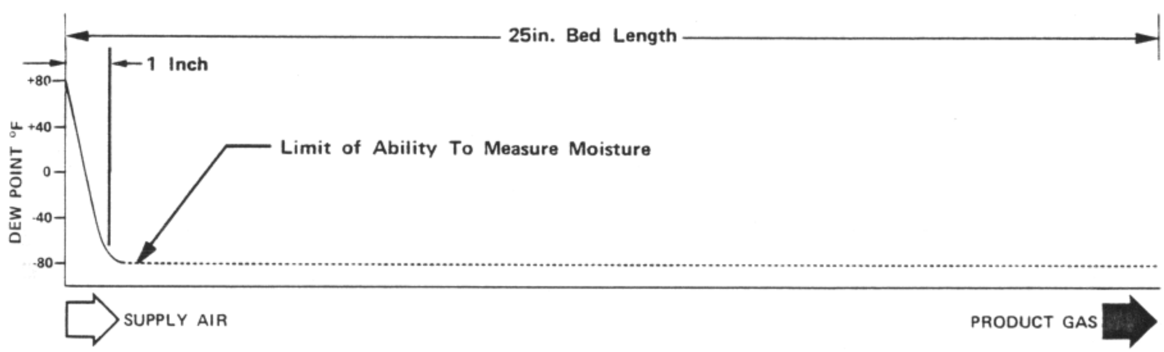

Figure 6. MOISTURE PENETRATION IN MOLECULAR SIEVE BED

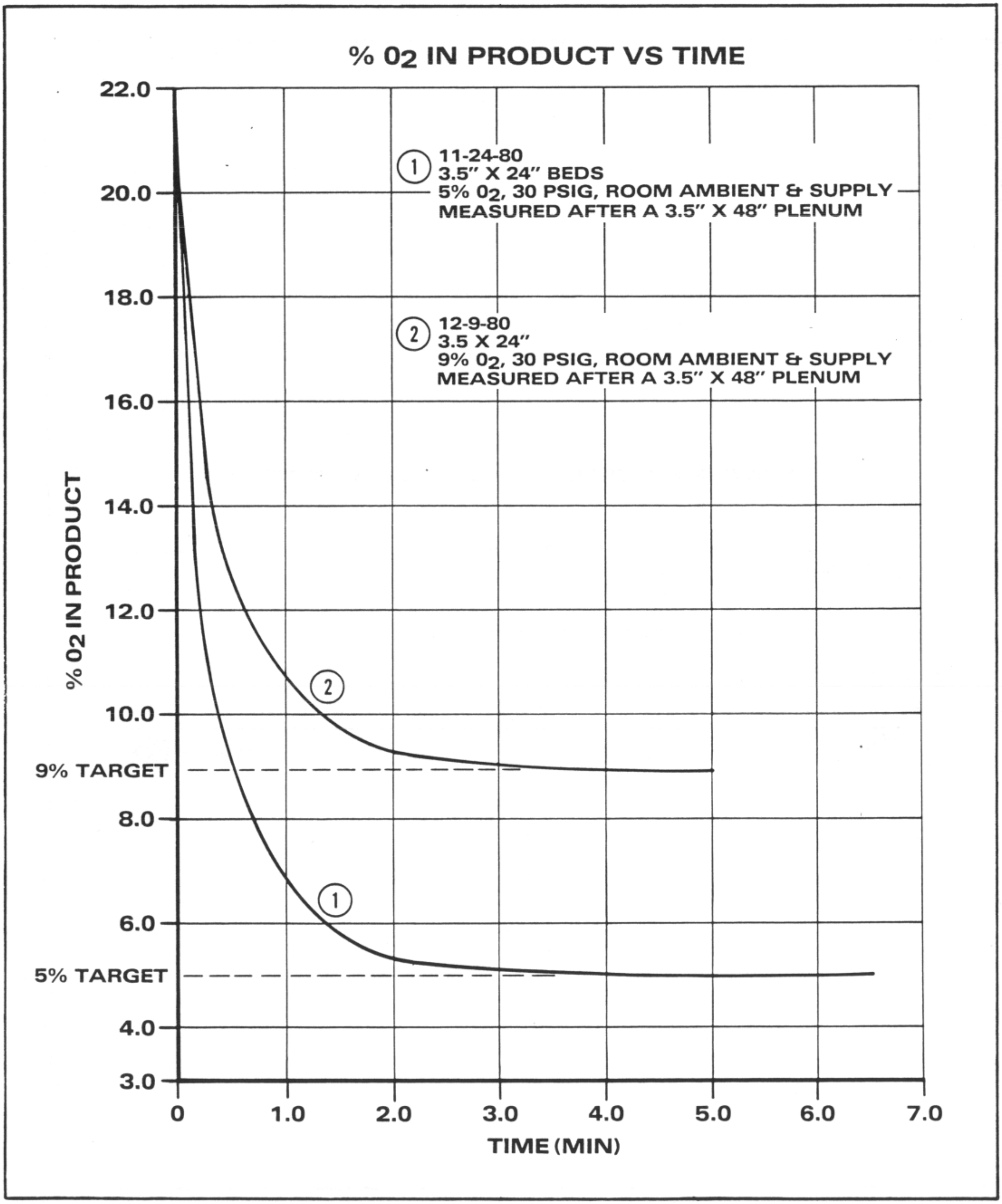

Figure 7. TIME TO STABILIZATION

In order to prove this concept a small scale eight bed system was constructed from commercially available components. This system was tested and optimized by the applicable penalty equation. Total penalty values for the eight bed system were found comparable to two-bed, paired systems and determined the direction for design of the full scale system.

j. Single Crossflow System Test.

The eight bed concept as conceived and finally implemented incorporates a purge crossflow needle valve for each bed. It was hoped that a means could be devised whereby a single valve could serve to throttle the crossflows in all the beds. A schematic was envisioned and incorporated into the small scale eight bed unit. Subsequent testing yielded performance enough inferior to the conventional technique that the concept was abandoned.

k. Control Simulation Testing for Pressure Variation.

Testing done to this point was mainly optimization testing where control parameters were all tuned to produce the optimum performance (minimum penalty) at the given conditions. In actual operation, however, optimum performance under all conditions would be impossible without an elaborate and expensive control system. On the other hand a simple, completely passive, fixed control system would either not meet all specified conditions or be grossly wasteful. A compromise control scheme was envisioned which would modulate supply pressures and product flow in either the 5 or 9% modes but leave other control parameters fixed.

It was necessary to determine by test how severe the penalty was for such off-optimum performance. The test involved holding settings and product flows constant at the values optimum for a particular pressure, but then varying the supply pressure. Results indicated a reasonably linear response of product oxygen percentage to product pressure was maintained within the variations expected in actual operation. This testing did then validate the envisioned control scheme.

SECTION IV

SYSTEM DESIGN

1. DESIGN OBJECTIVES.

The primary design objective of this contract was to demonstrate the capability of a molecular sieve inert gas generation system (MSIGG) to produce an oxygen depleted product gas which would inert the fuel tank ullage of a KC-135 aircraft and which would have the necessary dynamic response to meet the inertant requirements during climb, cruise, and descent modes of a mission profile. During both climb and cruise mode an MSIGG product flow of 3 pounds per minute of 5% maximum oxygen was required while 8 pounds per minute of 9% maximum oxygen concentration was required during descent.

Additional objectives of this program were that:

- the test system be as representative as possible of future flight hardware in terms of operation, configuration, and penalties, but with concessions due to the experimental nature of the test system.
- the test system minimize the total aircraft penalty per pound of inert gas produced. Total penalty is the fuel use penalties due to bleed air consumption, ram air consumption, and the installed weight of the test system.
- the size of the test system be sufficiently close to the aircraft application so that performance scaling would be valid.
- the test system have sufficient flexibility to allow useful testing for other aircraft and missions.

2. DESIGN ASSUMPTIONS.

Several assumptions were made to simplify design of the test system:

- Due to test facility equipment limitations, the test system will see room temperature startup in the simulation of cold day missions.
- Minimizing gross weight of the test system was not a design consideration.
- Bleed air would be provided through a pre-cooler at a maximum output temperature of 300 deg F.

- Criteria for evaluation of the test system would be performance, response, reliability, and penalty. Penalty factors to be applied were those provided in a Boeing Pre-Test Planning Document, Rev. 1, dated 31 July 1980.

- Inerting the ullage created in the KC-135 during refueling operations is excluded from consideration.

3. SYSTEM DESCRIPTION.

a. Physical and Functional Description.

The Clifton Precision MSIGG as configured for this contract is a molecular sieve pressure swing adsorption nitrogen separator intended for laboratory testing and simulation of operation in flight applications. Figures 8 and 9 indicate the overall configuration and size of the test system. Figure 10 is an operational schematic diagram. Key features of the system follow. (Reference figure 10 for component designators in parentheses.)

- Eight canisters (FL1 typical) containing approximately 50 pounds each of molecular sieve form the beds that are cyclicly pressurized.

- Supply gas at a pressure and temperature corresponding to the output of a dedicated heat exchanger enters the unit through a coalescsing water separator (FL2).

- A variable pressure regulator (R1) reduces pressure to the minimum level required by the existing condition of gas temperature and aircraft altitude. The regulator supplies air to a manifold common to the eight beds.

- Waste gas from each bed is exhausted to a second common manifold.

- Each bed has inlet and exhaust valves (V1 and V2) controlled by a timer which in the test system is a programmable controller.

- Product gas is delivered through check valves (V5) to a common manifold at the opposite end of the beds.

- A pressure regulator (R3) maintains a set pressure in the product line and in conjunction with test facility supplied fixed orifices maintains a constant product pressure with varying flow depending on system pressure.

- Purge gas is taken from the product manifold and is available to each bed while that bed is being regenerated. This purge gas sweeps away oxygen rich gas adsorbed into the molecular sieve during the pressurization portion of a pressure swing cycle.

- The number of active beds can be reduced to permit flexibility in testing.

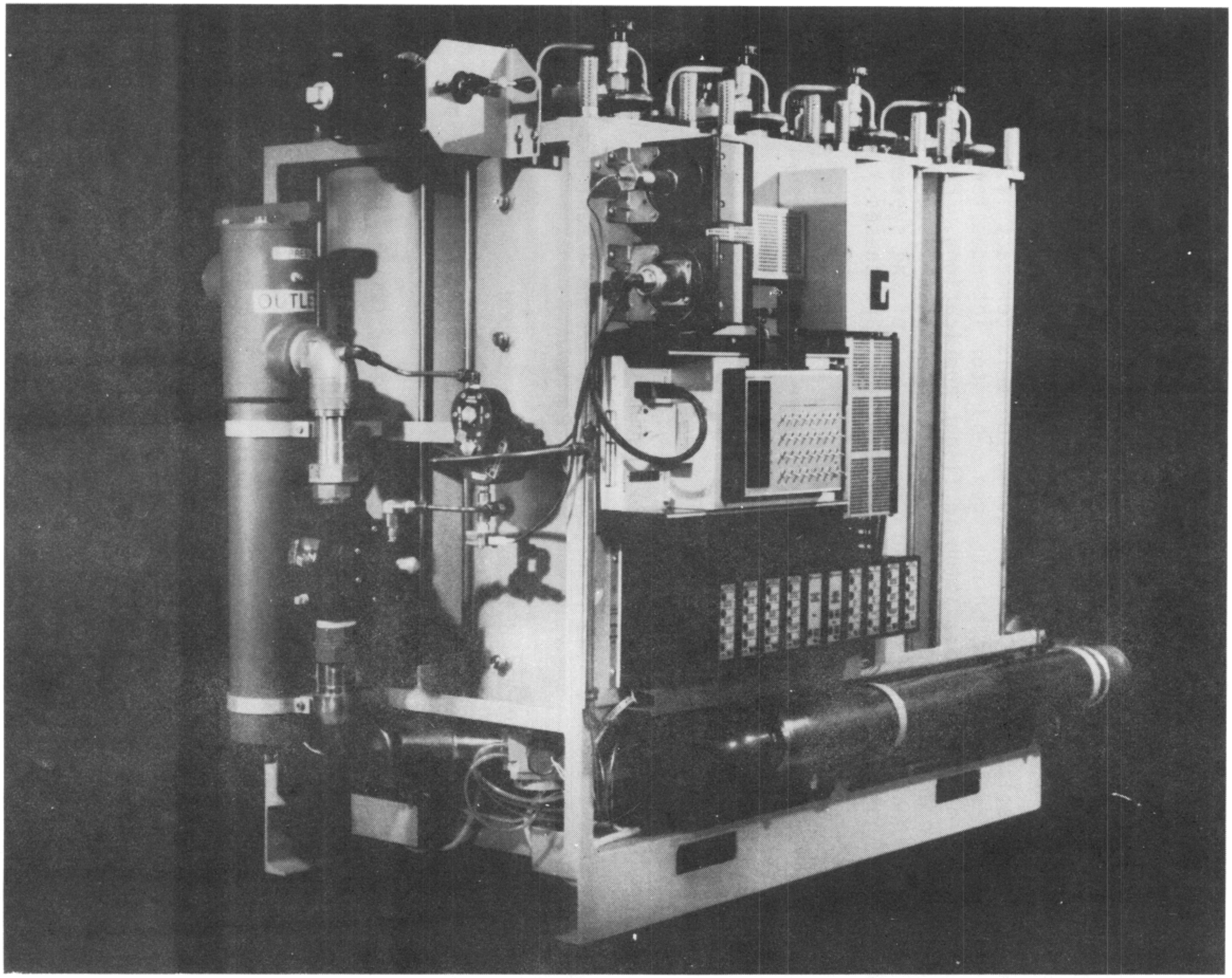

Figure 8. 8 LB/MIN MOLECULAR SIEVE INERT GAS GENERATOR

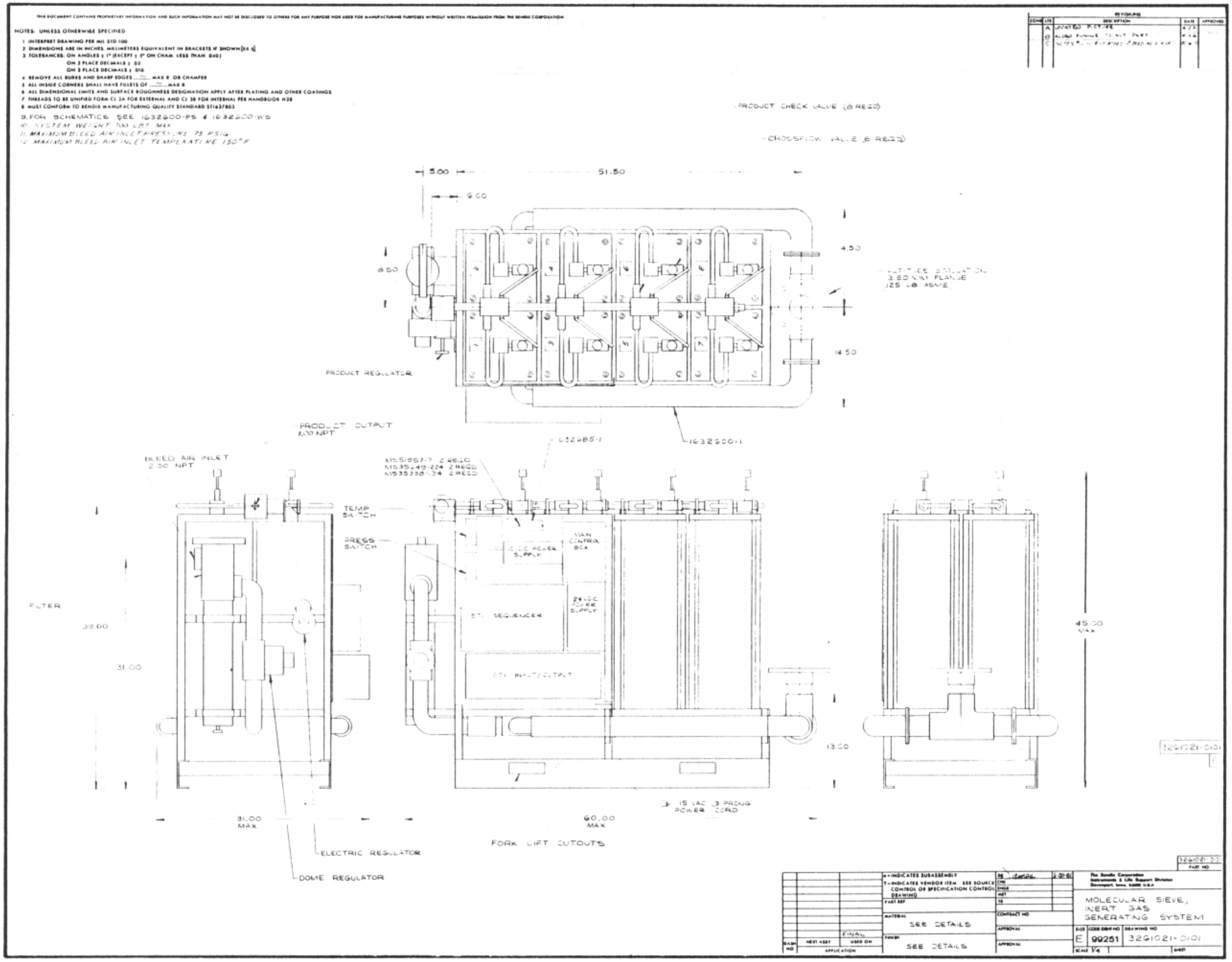

Figure 9. ASSEMBLY DRAWING

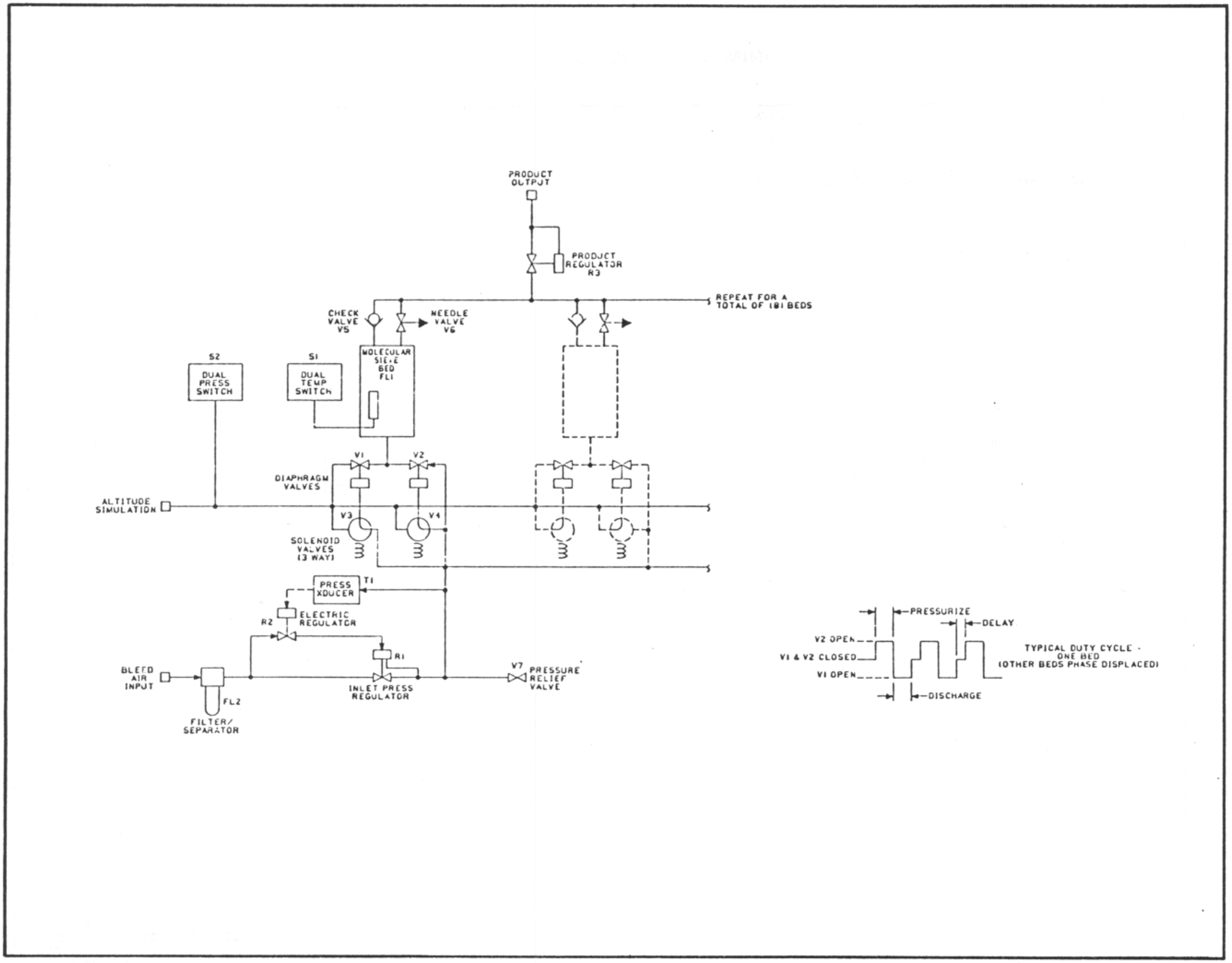

Figure 10. MSIGG OPERATIONAL SCHEMATIC

b. Description of Controls.

The system is required to function in either a high or low flow mode depending on a demand signal from a pressure switch in the fuel tank ullage area. In the high flow mode, 9% oxygen product at 8 pounds per minute is required while the low flow mode calls for 5% gas at 3 pounds per minute. The product flow is controlled by a choked orifice while a product regulator maintains a fixed pressure upstream of the orifice. With constant flow, the oxygen concentration of the product gas is dependent upon supply pressure. Therefore the unit incorporates three temperature and two altitude states to adjust supply pressure to be adequate for conditions. The temperature and altitude states incorporated with corresponding inlet pressures (psig) are tabulated below:

High Flow Mode

	Altitude (ft)	
	<30,000	>30,000
Temperature (°F)	Pressure (psig)	
<46	35.5	24.2
46 - 62	35.5	25.7
>62	35.5	35.5

Low Flow Mode

	Altitude (ft)	
	<30,000	>30,000
Temperature (°F)	Pressure (psig)	
<46	25.7	19.2
46 - 62	27.8	20.4
>62	35.5	24.2

The inlet pressure settings are biased for 5% production since the unit will spend most of the time in that mode. Control of the pressurization cycle is provided by an industrial programmable controller which energizes small solenoid pilot valves that enable the large inlet and exhaust valves on each bed. The controller paces each bed through identical cycles, offset in time from each other to provide relatively constant input and output. The timing cycle is different for the 5 and 9 percent modes. The controller program accommodates running from two to eight beds to allow testing of a wide range of conditions.

c. Description of Major Components.

Figure 9 is the top assembly drawing showing the major components.

The water separator is a commercial industrial coalescing filter which removes particulate liquids and solids from the supply stream. The filter has a 0.013 inch dia. continuous drain which alleviates the need for servicing unless contaminated by solid particles. In a flight version, the continuous drain could be replaced by some type of automatic drain that would reduce the drain air flow.

The pressure regulator consists of two parts. A small electrically controlled regulator (R2) provides pilot air at a pressure proportional to a voltage signal coming from the programmable controller. This pilot pressure then controls a large dome-loaded pressure regulator (R1) that regulates the main supply flow of the unit. Both of these regulators are commercial devices.

The bed canisters (FL1) are thin wall aluminum tubing with end caps machined from aluminum plate held in place against pressure forces by stainless steel tie rods. "O" rings provide a gas seal on each end plate. The molecular sieve is contained between filter plates and restrained from moving under pressure forces by spring loading.

The inlet and exhaust valves (V1 and V2) were specially developed for this application. Each valve is a fast response, high flow, pilot operated, diaphragm valve. Mounting is directly to the inlet end cap thus reducing air losses in plumbing and dead spaces. A small commercial solenoid valve (V3 and V4) supplies the pilot signal to the large valves.

The programmable controller is a standard industrial microprocessor-based controller with the ability to continuously recycle without unacceptable delays for resetting of program counters. It provides separate cycles for 5 or 9% production and all necessary logic to control inlet pressure based on operating conditions. Input/output modules provide access to and from the controller and power signals to the controlled valves. A switch and indicator panel provides a visual display of valve solenoid activation.

d. Relation to Flight Hardware.

Although functionally performing similar to flight hardware the test system was fabricated with commercial components and with commercial materials and alloys where practical to minimize program cost.

In a design for flight application, the commercial materials would be replaced by aircraft components and materials. In addition, the commercial programmable controller used to operate pressurization and exhaust valves would be replaced by an aircraft quality microprocessor.

4. COMPUTER SIMULATION.

Early in the project several considerations indicated the need for computer simulation in the design of this unit. First, the actual requirements against which the units would be evaluated were much more complex than the three fixed points given in the statement of work. Second, the actual worst case requirement was not immediately apparent due to inherently slow thermal response of the sieve beds. Third, it was decided to simulate the heat exchanger output. A heat exchanger is desirable in a molecular sieve system to lower bleed air temperature to a range that will result in maximum productivity of the sieve (see figure 5). It was eliminated from the test hardware to reduce program cost. Simulation of the heat exchanger required computing a schedule of its output throughout the mission range. It was desirable to model several candidate heat exchangers and see effects on total penalty. Although a single iteration in a tally of total penalty is a significant manual calculation, the computer allowed small iterations and summing the hot, standard, and cold day runs. This made possible studies otherwise unfeasible.

The computer simulation program developed to aid in the design used equations based on molecular sieve performance data as the basis of the MSIGG model. Inputs to the model are taken from files containing the pneumatic and flight data for the hot, standard, and cold day missions. The development of this computer simulation program was not a specific requirement of the effort on this contract.

The program runs the generator for small increments of time during which changes in bed temperature etc. are calculated and stored as starting conditions for the next increment.

Sample outputs of the program are shown in figures 11 and 12.

SECTION V

SYSTEM TEST

1. INSTRUMENTATION.

The MSIGG was instrumented for testing as indicated in figure 13. Data was gathered automatically using a H-P 9825 calculator. Voltage signals from the temperature, pressure, and oxygen sensors were converted to digital data by A/D converters within the calculator multiprogrammer. All data were sampled sequentially and continually at a rate of about 150 Hz. Flows were calculated and integrated over one complete cycle of the MSIGG. Cyclic variations in oxygen concentration were smoothed by a 5 cubic foot plenum and averaged over the cycle.

2. OPTIMIZATION TESTS.

a. Temperature Correction.

The various performance measurements such as input/output ratio, productivity, and fuel penalty are known to depend upon the temperature of

```
RUN
MISSEDT 04/01/81 09:18:31
ENTER MISSION PROFILE FILE NAME
?KC135#16
NUMBER OF SEGMENTS IN MISSION      16
INITIAL ULLAGE      1000.0 GAL
BLEED PENALTY RATES
( % INCREASE IN FUEL USE RATE PER LB/MIN BLEED AIR USE)
FOR TAKEOFF      0.0160%
FOR CLIMB        0.0240%
FOR CRUISE       0.0680%
FOR DIVE         0.0790
RAM AIR PENALTY RATE
(% INCREASE IN FUEL USE RATE PER LB/MIN RAM AIR)      0.0040%
WEIGHT PENALTY RATE
( % INCREASE IN FUEL USE RATE PER 1000 LBS SYSTEM WEIGHT      0.3000%
MAX OVERPRESSURE ALLOWED IN TANK         2.1  PSI
MAX UNDERPRESSURE ALLOWED IN TANK:        0.6  PSI

SEGMENT #  4
MISSION TIME AT START OF SEGMENT          0.6  HRS
ALTITUDE AT START OF SEGMENT      33000.  FT
MACH NUMBER FOR SEGMENT       0.7800
FUEL FLOW FOR SEGMENT       13140. LBS/HR
          HOT  DAY
MAXIMUM AVAILABLE BLEED FLOW        241.0 LBS/MIN
BLEED PRECOOLER OUTLET TEMPERATURE       300.0 DEG. F
BLEED PRECOOLER OUTLET PRESSURE       68.3 PSI
          STD  DAY
MAXIMUM AVAILABLE BLEED FLOW        241.0 LBS/MIN
BLEED PRECOOLER OUTLET TEMPERATURE       300.0 DEG. F
BLEED PRECOOLER OUTLET PRESSURE       69.8 PSI
          COLD DAY
MAXIMUM AVAILABLE BLEED FLOW        241.0 LBS/MIN
BLEED PRECOOLER OUTLET TEMPERATURE       300.0 DEG. F
BLEED PRECOOLER OUTLET PRESSURE       70.0 PSI
TARGET DEMAND FLOW FOR SEGMENT        3.0 LBS/MIN
TARGET O2 FOR SEGMENT        5.0%
```

Figure 11. PRINTOUT OF SIMULATION PROGRAM

```
RUN PENALTY
PENALTY 04/07/81 11:52:24
DUAL HEAT EXCHANGER
ALT. COMP.
ENTER MISSION PROFILE FILE NAME
?KC135#16
ENTER WEIGHT OF SIEVE (LBS)
?392
ENTER SYSTEM WEIGHT/SIEVE WEIGHT RATIO
?1.5
ENTER 1,2 OR 3 FOR HOT,STD OR COLD DAY
?1
ENTER 0 TO GET DEMAND FROM MISSION PROFILE
      1 TO SPECIFY HIGH AND LOW DEMAND
NOTE: DEMAND MUST BE ENTERED IF TANK PRESSURE
DEMAND SWITCHING IS REQUIRED
?0

0 FOR NO CONTROL
?1
ENTER HEAT EXCHANGER SET POINT TEMPERATURE (DEG F)
?[illegible]
ENTER          K FACTOR (0=>.0006946281)
?0
ENTER 1 FOR TEMPERATURE SWITCH POINTS
      0 OTHERWISE
?1
ENTER TEMPERATURE       1
?40
ENTER TEMPERATURE.      2
?60
ENTER TEMPERATURE       3
?120
ENTER TEMPERATURE       4
?142
ENTER 1 FOR ALTITUDE SWITCH POINTS
      0 OTHERWISE
?1

ENTER LOW ALTITUDE SWITCH POINT (FT)
?14000
ENTER HIGH ALTITUDE SWITCH POINT (FT)
?22000
ENTER 1 FOR FLIGHT DATA PRINTOUT 0 OTHERWISE
?0

MISSION TIME                 298.94 MIN
OUTSIDE AIR TEMPERATURE        60.9 DEG F
BED TEMPERATURE                87.7 DEG F
BED PRESSURE                   39.5 PSIG
BLEED PRESSURE AT BED          48.3 PSIG
HX INLET TEMPERATURE          300.0 DEG F
HX OUTLET TEMPERATURE          93.9 DEG F
BLEED FLOW                     33.5 LBS/MIN
RAM AIR TEMPERATURE            98.6 DEG F
RAM FLOW                       85.8 LBS/MIN
O2 FROM IGG                     8.8 PER CENT
O2 IN-ULLAGE                    8.8 PER CENT

     SEGMENT NUMBER       2
TIME IN SEGMENT   =          0.17   HRS
BLEED PENALTY     =          32.2   LBS OF FUEL
RAM PENALTY       =          22.2   LBS OF FUEL
WEIGHT PENALTY    =           8.7   LBS OF FUEL
MAX O2 IN ULLAGE  =          12.4%
MIN O2 IN ULLAGE  =           4.6%
MAX BLEED         =         29.97   LBS/MIN
MAX BED TEMP      =         63.68   DEG F
MIN BED TEMP      =         59.44   DEG F
BED PRESS. MAX T  =          22.8   PSIG
PRESS. AVL.       =         152.2   PSIG
MAX O2 FROM IGG   =           5.0%
```

Figure 12. PRINTOUT OF SIMULATION PROGRAM WITH FLIGHT DATA

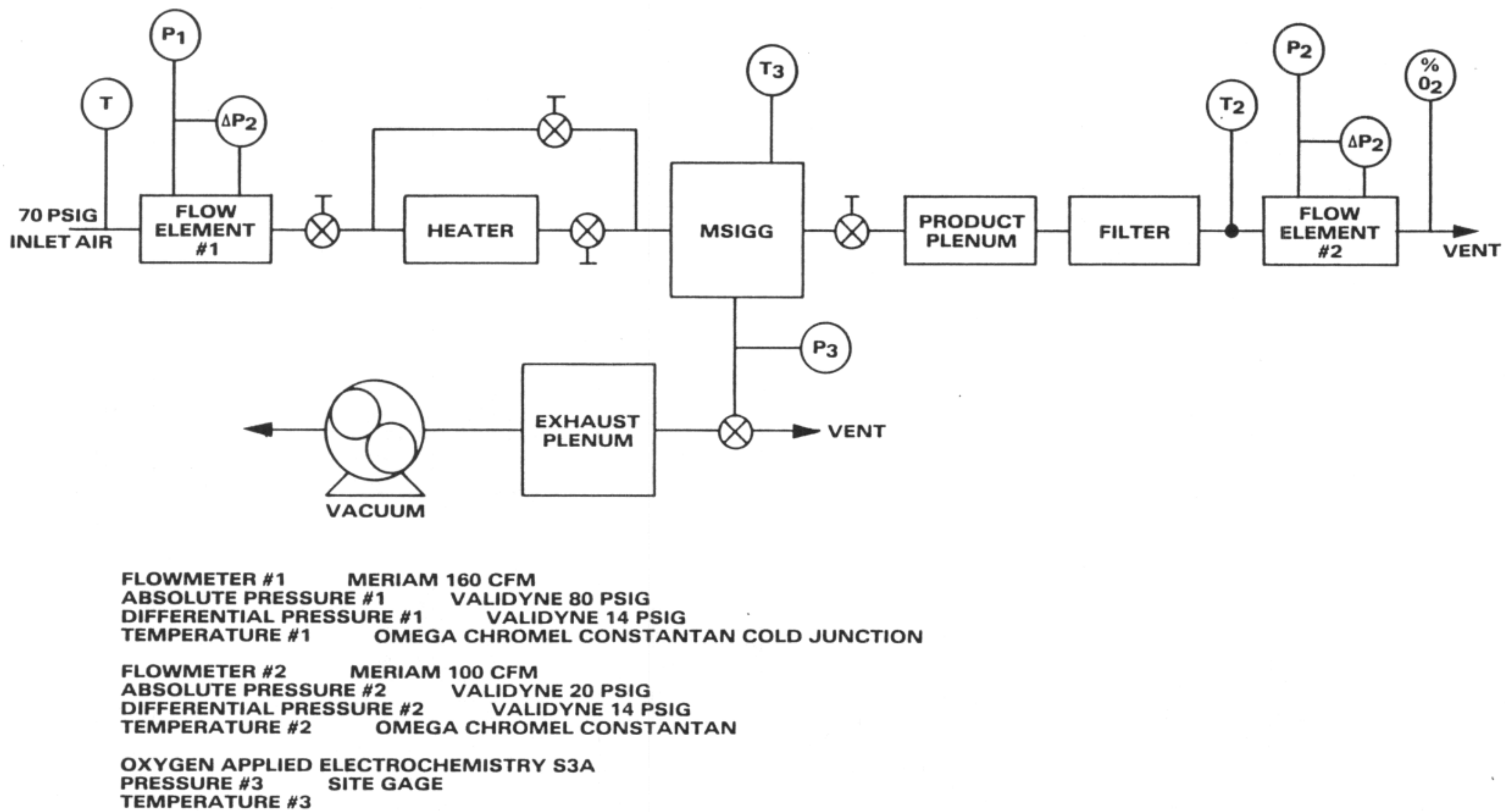

Figure 13. TEST SET UP

the molecular sieve bed. Furthermore, the temperatures of the inlet air and of the sieve bed change substantially during the day while testing. Therefore, to obtain meaningful data it is necessary to measure temperature dependence and correct all results to a standard temperature.

A heater was installed in the inlet air line. Testing was begun in the morning with the inlet air and the sieve bed at room temperature. Inlet air pressure was held at 30 psig and the product air flow was regulated to keep the product oxygen concentration at 5%. The inlet air was heated so as to raise the bed temperature at a rate of about 5 deg F per hour. I/O, productivity, and penalty were measured at 5 minute intervals, and then fit to a linear function of temperature. The following normalized temperature dependence was obtained:

$$\frac{\text{Input}}{\text{Output}} \left(\frac{\text{Lb Supply Air Per Unit Time}}{\text{Lb Product Gas Per Unit Time}} \right) \qquad .0037/\text{deg F}$$

$$\text{Productivity} \left(\frac{\text{Lb Product Gas/Min}}{\text{Lb Mol Sieve}} \right) \qquad -.0063/\text{deg F}$$

$$\text{Penalty} \left(\frac{\text{Additional Fuel - Lb/Mission}}{\text{Product Gas - Lb/Min}} \right) \qquad .0040/\text{deg F}$$

All future data were then corrected to 80 deg F using these factors.

b. Penalty Minimization.

Performance of the MSIGG is dependent, among other factors, upon timing and crossflow rate. Fuel penalty (discussed elsewhere) was selected as the criterion of performance. Numerous tests were performed to select the optimum valve and timing settings for product gas oxygen concentrations of 9% and 5% combined with inlet air pressures of 30 and 40 psig.

After preliminary tests to obtain approximate settings for crossflow and delay time, the ratio of pressurization to exhaust times was varied. Least penalty was obtained with those times equal.

Next, I/O, productivity, and penalty were measured using the following test points:

Bed Pressurization and Exhaust Time	2-2/3, 3-1/3, 4 seconds each
Crossflow	150, 180, 210 liters/minute
Product Oxygen	5, 9 percent
Supply Pressure	30, 40 psig
Valve Delay Time	2/3, 1-1/3, 2, 2-2/3, 3-1/3 seconds

This resulted in a total of 180 test points, each requiring a minimum of 20 minutes for stabilization.

I/O and productivity were measured and corrected to 80 deg F. Penalty was calculated and optimum settings were selected. Crossflow was established at 210 lpm. Two timing modes were chosen:

	Low Flow ($5\%\ O_2$)	High Flow ($9\%\ O_2$)
Bed Pressurization and Exhaust Time	2-2/3 sec.	2-2/3 sec.
Valve Delay Time	1-1/5 sec.	1-1/3 sec.

c. Performance.

With timing and crossflow adjusted for minimum penalty as above, the MSIGG was operated to determine its performance under varying conditions. For these tests, product gas flow rate was held constant at either low (3#/min) or high (8#/min) flow. Inlet air temperature was held close to bed temperature. Inlet pressures, exhaust vacuum, and bed temperature were varied in the range shown below:

Input Pressure	20, 25, 30, 40, 50	psig
Exhaust Vacuum	0, 5, 10	in. Hg
Bed Temperature	80, 100, 120	deg F

Product oxygen concentration and I/O ratio were measured. Tables 2 and 3 tabulate the results of this testing.

Table 2. PERFORMANCE AT LOW FLOW (3 LB/MIN)

I/O	Product Flow (lb/min)	Penalty*	$\%O_2$	Vac (In. Hg)	Input Pressure (psig)	Bed Temp (°F)
4.37	3.00	219.0	8.00	0.00	20.00	76.4
5.20	3.00	254.0	6.11	0.00	25.00	77.0
6.12	3.00	292.0	4.80	0.00	30.00	79.1
7.88	3.00	365.0	3.45	0.00	40.00	79.8
9.58	3.00	436.0	2.88	0.00	50.00	81.5
4.78	3.00	236.0	6.30	5.00	20.00	76.6
5.63	3.00	272.0	4.83	5.00	25.00	76.4
6.51	3.00	308.0	4.00	5.00	30.00	78.5
8.22	3.00	380.0	3.05	5.00	40.00	79.6
9.92	3.00	451.0	2.60	5.00	50.00	80.9
5.17	3.00	252.0	4.90	10.00	20.00	76.6
6.06	3.00	288.0	3.95	10.00	25.00	76.7
6.89	3.00	324.0	3.47	10.00	30.00	78.5
8.56	3.00	394.0	2.80	10.00	40.00	79.4
10.18	3.00	462.0	2.50	8.50	50.00	80.5
4.29	3.00	216.0	8.90	0.00	20.00	100.0
5.17	3.00	253.0	6.90	0.00	25.00	100.0
6.03	3.00	290.0	5.50	0.00	30.00	100.0
7.72	3.00	359.0	4.00	0.00	40.00	100.0
9.29	3.00	425.0	3.35	0.00	50.00	100.0
4.77	3.00	236.0	6.90	5.00	20.00	100.0
5.53	3.00	268.0	5.58	5.00	25.00	100.0
6.35	3.00	303.0	4.65	5.00	30.00	100.0
8.13	3.00	376.0	3.50	5.00	40.00	100.0
9.82	3.00	447.0	3.01	5.00	50.00	100.0
5.04	3.00	248.0	5.70	10.00	20.00	100.0
5.96	3.00	286.0	4.53	10.00	25.00	100.0
6.73	3.00	318.0	3.96	10.00	30.00	100.0
8.45	3.00	390.0	3.22	8.50	40.00	100.0
9.95	3.00	453.0	2.91	7.50	50.00	100.0
4.14	3.00	211.0	9.30	0.00	20.00	122.0
4.99	3.00	246.0	7.40	0.00	25.00	122.0
5.75	3.00	278.0	6.10	0.00	30.00	123.0
7.43	3.00	347.0	4.57	0.00	40.00	123.0
8.95	3.00	412.0	3.90	0.00	50.00	123.0

$$* \frac{\text{Additional Fuel - Lb/Mission}}{\text{Ouput - Lb Product Gas/Min}}$$

Table 2. PERFORMANCE AT LOW FLOW (3 LB/MIN) - CONTINUED

I/O	Product Flow (lb/min)	Penalty*	$\%O_2$	Vac (In. Hg)	Input Pressure (psig)	Bed Temp (°F)
4.57	3.00	228.0	7.49	5.00	20.00	120.0
5.40	3.00	263.0	6.06	5.00	25.00	120.0
6.20	3.00	296.0	5.10	5.00	30.00	120.0
7.82	3.00	364.0	4.01	5.00	40.00	122.0
9.51	3.00	434.0	3.50	5.00	50.00	122.0
4.96	3.00	245.0	6.18	10.00	20.00	120.0
5.84	3.00	281.0	5.14	10.00	25.00	120.0
6.52	3.00	310.0	4.50	10.00	30.00	120.0
8.24	3.00	381.0	3.70	8.50	40.00	121.0
9.41	3.00	430.0	3.43	8.00	50.00	122.0

$$* \quad \frac{\text{Additional Fuel - Lb/Mission}}{\text{Output - Lb Product Gas/Min}}$$

Table 3. PERFORMANCE AT HIGH FLOW (8 LB/MIN)

I/O	Product Flow (lb/min)	Penalty*	$\%O_2$	Vac (In. Hg)	Input Pressure (psig)	Bed Temp (°F)
2.07	8.00	101.0	14.32	0.00	20.00	82.0
2.43	8.00	116.0	12.44	0.00	25.00	83.0
2.78	8.00	130.0	10.94	0.00	30.00	84.0
3.44	8.00	158.0	8.55	0.00	40.00	84.5
4.09	8.00	184.0	7.07	0.00	50.00	85.0
2.27	8.00	108.0	12.63	5.00	20.00	78.0
2.62	8.00	123.0	10.98	5.00	25.00	80.0
2.96	8.00	137.0	9.50	5.00	30.00	80.0
3.69	8.00	168.0	7.37	5.00	40.00	80.0
4.28	8.00	193.0	6.21	5.00	50.00	81.0
2.43	8.00	115.0	11.30	10.00	20.00	77.0
2.76	8.00	129.0	9.70	10.00	25.00	77.0
3.09	8.00	143.0	8.59	10.00	30.00	80.0
3.75	8.00	171.0	6.58	9.00	40.00	82.0
4.36	8.00	196.0	6.04	7.50	50.00	83.0
2.07	8.00	100.0	14.70	0.00	20.00	100.0
2.40	8.00	114.0	13.04	0.00	25.00	100.0
2.74	8.00	128.0	11.50	0.00	30.00	101.0
3.39	8.00	156.0	9.16	0.00	40.00	102.0
4.00	8.00	181.0	7.71	0.00	50.00	102.0
2.22	8.00	107.0	13.28	5.00	20.00	99.0
2.58	8.00	122.0	11.60	5.00	25.00	100.0
2.91	8.00	135.0	10.25	5.00	30.00	100.0
3.60	8.00	164.0	8.14	5.00	40.00	101.0
4.27	8.00	192.0	6.90	5.00	50.00	102.0
2.36	8.00	112.0	12.05	10.00	20.00	97.0
2.71	8.00	127.0	10.61	10.00	25.00	98.5
3.06	8.00	142.0	9.30	10.00	30.00	100.0
3.70	8.00	168.0	7.73	9.00	40.00	102.0
4.26	8.00	192.0	6.78	7.50	50.00	101.0
2.04	8.00	99.0	15.20	0.00	20.00	116.0
2.39	8.00	114.0	13.44	0.00	25.00	116.0
2.71	8.00	127.0	12.04	0.00	30.00	117.0
3.36	8.00	155.0	9.69	0.00	40.00	115.0
4.02	8.00	182.0	8.33	0.00	50.00	118.0

$* \ \dfrac{\text{Additional Fuel - Lb/Mission}}{\text{Output - Lb Product Gas/Min}}$

Table 3. PERFORMANCE AT HIGH FLOW (8 LB/MIN) - CONTINUED

I/O	Product Flow (lb/min)	Penalty*	%O_2	Vac (In. Hg)	Input Pressure (psig)	Bed Temp (°F)
2.20	8.00	106.0	13.93	5.00	20.00	116.0
2.50	8.00	118.0	12.29	5.00	25.00	115.0
2.88	8.00	134.0	10.91	5.00	30.00	116.0
3.54	8.00	162.0	8.91	5.00	40.00	117.0
4.13	8.00	186.0	7.69	5.00	50.00	118.0
2.34	8.00	111.0	12.79	10.00	20.00	117.0
2.63	8.00	124.0	11.53	10.00	25.00	117.0
3.01	8.00	139.0	9.86	10.00	30.00	116.0
3.67	8.00	167.0	8.30	8.50	40.00	116.0
4.25	8.00	192.0	7.47	7.50	50.00	118.0

* $\frac{\text{Additional Fuel - Lb/Mission}}{\text{Output - Lb Product Gas/Min}}$

For purposes of modeling the MSIGG, equations were written for I/O ratio and for product oxygen concentration. These equations are:

$$I/O = A1 + A2xV + A3xP + A4xT$$

$$\%O_2 = B1 + B2xV + B3/P + B4xT$$

Where: V = Exhaust Vacuum (in. Hg)*
P = Inlet Pressure (psig)*
T = Bed Temperature (deg F)

*Relative to test site ambient

The constants (A1, A2, A3, A4, B1, B2, B3, B4) were fit to the performance data using least squares analysis. The resulting values of these constants and average error of fit are:

	Low Flow 3#/min.				High Flow 8#/min.			
	I/O Ratio		% Oxygen		I/O Ratio		% Oxygen	
	A1	1.74	B1	-1.58	A1	.984	B1	-.006
	A2	.0779	B2	-.176	A2	.0316	B2	-.208
	A3	.168	B3	138.7	A3	.0668	B3	219.7
	A4	-.00802	B4	.0256	A4	-.0025	B4	.0379
Average Error		.087		.38%		.027		.31%

d. Thermal Response.

In order to provide a mathematical model for the thermal response of the system, the MSIGG was subjected to a step change in inlet air temperature at a constant product flow rate and pressure, and the resulting temperature profile was recorded. The product flow rate was 3 lb/min and this inlet pressure was 30 psig. Testing was begun in the morning at 82 deg F. The inlet air temperature was raised to 115 deg F, and held constant for 4 hours. The average bed temperature increased at a nearly constant rate (12 deg/hour) for 2-1/2 hours, and then remained constant at about 112 deg F. At noon the inlet air was reduced to 82 deg F, and held constant. The average bed temperature decreased at about 12 deg/hour to 82 deg F in about 2-1/2 hours.

SECTION VI

MAINTAINABILITY

The Molecular Sieve Inert Gas Generator (MSIGG) P/N 3261021-0101 S/N 204001E developed under contract F33615-80-C-2007 is a laboratory prototype designed to prove design principles and provide test data supporting use of this type of gas generator for an airborne fuel inerting system.

The MSIGG is comprised of multiple molecular sieve containers (8 cylindrical beds) each utilizing the pressure swing adsorption (PSA) process to convert engine bleed air into a nitrogen rich (low oxygen concentration) gas. This gas is used to inert the ullage in fuel cells. Each bed has a system of valves to control the gas flow into and out of the molecular sieve bed and to provide a uniform flow of product gas to the inerting system manifold.

During the PSA process, bleed air is alternately forced into and purged from each cylindrical container of molecular sieve material which preferentially passes nitrogen rich gas to the output manifold and exhausts oxygen rich gas to ambient. This high capacity system requires careful attention to charging and exhaust valve flow characteristics as well as crossflow purging gas flow rates.

The valve design in this test unit is a piloted diaphragm type in which the cyclic control is provided by solenoid spool valves and a process control system which permits optimization of the PSA process at certain operating parameters. This optimization procedure primarily involved various charging, dwell and exhaust cycle times relative to bleed air consumption and product gas quality. Initial test results indicate that departure from optimum inlet pressure and operating cycle times would cause significant fuel and weight penalty in an airborne system.

Until such time as the airborne system operating parameters and the design features are clearly defined, maintainability analysis and recommendations must be based on some of the following basic assumptions.

An airborne MSIGG will be a multiple bed system, will weigh several hundred pounds and will incorporate some sort of built-in-test or self-monitoring capability. The PSA cycles and air consumption rates will be optimized for the specific class of aircraft or inerting gas flow needs. This optimization will minimize fuel and weight penalty, enhance reliability and simplify the design of cyclic timers, pressure control devices and crossflow bleed and check valves.

The self test or performance monitor is essential to indicate if a fault exists and also provide fault isolation to the defective bed or valve assembly.

Ideally, the valve assembly will be modular in design, permitting on-aircraft repair by removal and replacement of the valve assembly module.

The MSIGG incorporates input air filters to remove water droplets and particulate matter. This filter may be integral with the MSIGG or if more easily accessed could be a separate line replacement unit. The filter element would be serviced or replaced, on condition if a differential pressure indicator is utilized, or as scheduled preventive maintenance if no indicator is provided.

Shop repair of the MSIGG would require equipment for testing which is not normally available at intermediate level repair facilities. This equipment would include high capacity, low pressure air compressors and high capacity vacuum systems.

We estimate that the total quantity of MSIGG will be relatively small. Consequently, a level-of-repair analysis would probably dictate any off-aircraft repair of the MSIGG or any of its subassemblies be accomplished at depot facilities. It is conceivable that one or more of the molecular sieve beds could be replaced at the organizational level if the design incorporated this capability; however, a more thorough level of repair analysis is needed to reach this conclusion. Any repair to the molecular sieve bed itself involving the processing and packing of sieve material is definitely depot level repair, and this fact leads to a predilection that repair of the MSIGG by replacement of molecular sieve beds should be at the depot level also.

At this juncture it appears to be most cost effective to limit repair of the MSIGG to on-aircraft replacement of selected subassemblies. Replacing a filter element and/or the valve module would account for approximately 50% of all repair tasks. One half of the remaining faults could also be repaired at this level if the fault isolation by Built-In-Test Equipment (BITE) or a performance monitor could be developed reliably and inexpensively.

It would appear that the valve module as envisioned herein could be broken down into smaller subassemblies for repair at the organizational level; however, the fault isolation capability required in the BITE or performance monitor would be increasingly complex, as well as the valve construction, increasing cost and unreliability to the point that diminishing returns would make it impractical.

The logistic support analysis would need to be accomplished early in the design development phase of the flight article MSIGG to determine the most cost effective concept.

The-mean-time-to-repair (MTTR) for the MSIGG at the organizational level would be 0.5 maintenance man hours (MMH) by one aircraft mechanic with adequate training, spares and simple hand tools normally found in the aircraft mechanic tool box. Training would be accomplished in one to two weeks. The removal and replacement of the MSIGG on the aircraft would require two or more men, specific handling equipment and/or devices to install or remove the MSIGG which would weigh several hundred pounds. The above MTTR does not include access or system test after repair. It presumes that built-in-test equipment (BITE) is able to fault isolate to the defective module within 5 minutes and that BITE would be effective in identifying 98% or more of all failure modes. Some simple support equipment (SE) may be required for fault isolation to the final subassembly.

If pressurized air is available from the auxiliary power unit (APU) then system test could also be accomplished with fault correction verified by the BITE and SE in form of a simple battery operated hand-held oxygen analyzer and a port to draw a sample of the MSIGG product gas. System test would be accomplished in approximately 20 minutes by one trained aircraft grade mechanic.

Table 4 shows the distribution of predicted failures based upon a preliminary inherent reliability estimate. The components used in this study are basically those used in the prototype test unit. The electronic performance monitor failure rate is an arbitrary number assumed from similar designs or equipment. The inherent reliability of this particular unit provides a mean-time-between-failure (MTBF) of approximately 1200 flight hours.

SECTION VII

RELIABILITY

Several reliability analyses were conducted as part of the design effort of the MSIGG. These included a mean-time-between-failure (MTBF) prediction and a Failure Modes and Effects Analysis (FMEA).

The following sources were used in obtaining failure rate data for the MTBF prediction:

a. Rome Air Development Center, Non-electronic Parts Reliability Data, NPRD-1.

b. MIL-HDBK-271C, Reliability Prediction of Electronic Equipment.

c. Clifton Precision, Standard Parts Failure Rate Data.

d. Martin-Marietta Co. and McDonnell Aircraft failure rate data.

e. Engineering estimates.

Table 4. DISTRIBUTION OF PREDICTED FAILURES

Component (Qty)	Failure Rate Per Million Hrs	Ratio of Component Failure Rate to Sum of all Failure Rates	Inherent MTBF - F.H.
Valve Ass'y Module (8)	383.975	.4742	2604
Pressure Valve (8 X 18.990)			
Check Valves (8 X 11.937)			
Discharge Valve (8 X 3.481)			
Packing Preform (35 X 2.387)			
Orifices (8 X 2.164)			
Misc. (8 X .982)			
Molecular Sieve Beds (8)	204.704	.2528	4885
Packing Preform (44 X 2.387)			
Spring, Plates (80 X 1.043)			
Molecular Sieve (8 X 1.43)			
Misc. (8 X .600)			
Electronics Module (1)	75.000	.0926	13333
Pressure Transducer (1)	54.106	.0668	18482
Pressure Switch (1)	39.030	.0482	25621
Filter Assembly (1)	14.084	.0174	71003
Pressure Regulator (1)	10.000	.0124	100000
Relief Valve (1)	9.207	.0114	<100000
Temperature Switch (1)	6.535	.0081	<100000
Control Box (1)	4.988	.0062	<100000
Pressure Regulator (1)	4.072	.0050	<100000
Regulator (Output) (1)	2.998	.0037	<100000
Misc.	.982	.0012	<100000
Totals	809.681	1.000	

Considerable failure rate data for an Aircraft, Uninhabited, Transport (AUT) environment was available. The only significant area where an engineering estimate was made was for the electronic package. Since the inerting system to be delivered is considered experimental, the controller and sequencing modules on this system will not be utilized on prototype flight hardware which might be delivered on future programs. Such hardware would utilize an electronic package of less than 100 parts. Therefore, a conservative estimate of 75 failures per million hours for the electronic package was employed in the MTBF prediction.

The remainder of the MTBF prediction generally reflected the "as-built" hardware, although it is recognized that some features will undoubtedly be redesigned for flight hardware as further considerations for weight, space, and environmental conditions are incorporated. For example, the needle valves controlling the crossflow on each bed would be replaced by a fixed orifice design.

The preliminary prediction yields a total failure rate of 753.008 failures per million hours. This computes to an MTBF of 1328 hours. A breakdown of the predicted failure rates and MTBF for the major components is shown in Table 5.

It is anticipated that the reliability can be improved considerably for flight hardware as test instrumentation features are eliminated, designs are simplified, and component reliability is improved.

It should be noted that the failure rate of the molecular sieve employed in this design approaches zero. After considerable experience with this substance in health care, oxygen generation, and fuel inerting applications, ILSD is not aware of any random failures in over 5,000,000 hours of operation. The life of the molecular sieve appears to be limitless and it can readily be regenerated in case it is degraded by contamination by some external cause.

An FMEA was conducted at the major component level. As in the prediction, the "as-built" hardware was analyzed except for the electronic controls. It is recognized that future designs may eliminate some failure modes and provide for different control plans.

The FMEA did reveal the need for a monitoring system that will indicate when system performance has degraded beyond acceptable levels. Since for most failure modes the system pressures are directly related to output concentration, the monitoring system should measure pressures at critical points and provide a visual or audible signal when performance is degraded beyond the established limits; or, the system could trigger automatic corrective action.

A copy of the preliminary FMEA is included in this report. Component references are those found in figure 9 and identified on figure 10 by component reference designator.

Table 5. RELIABILITY APPORTIONMENT
USAF OBIGGS - P/N 3261021-0101

COMPONENT	SYMBOL	FAILURE RATE (PER 10^6 HOUR)	MTBF
Filter	FL2	14.084	71,003
Pressure Regulator	R1	10.000	100,000
Relief Valve	V7	9.027	110,779
Electric Regulator	R2	4.072	245,580
Pressure Xducer	T1	54.106	18,482
Electronics	-	75.000	13,333
Dual Press. Switch	S2	39.030	25,621
Bed & Valve Ass'ys (8)	FL1	347.159	2,881
Vacuum Valves (8)	V1	27.848	35,909
Pressure Valves (8)	V2	151.920	6,582
Dual Temp. Switch	S1	6.535	153,022
Other Misc. Hardware	-	160.856	6,217
Check Valves (8)	V5	95.496	10,472
Needle Valves (8)	V6	17.312	57,763
Control Box Assembly	-	4.988	200,481
Output Regulator	R3	2.998	333,556
Other Misc. Hardware	-	79.736	12,733
TOTAL		753.008	1,328

SECTION VIII

CONCLUSIONS

The design, fabrication, and testing of the MSIGG has been accomplished within all performance goals and predictions. Involved in this was the new concept of multiple sequentially cycled beds and a control system that compensates for varying operating conditions which are demonstrated feasible.

A flight version of the MSIGG appears very practical. Based on our independent research and results of this project to date, a flight worthy MSIGG can be designed to operate efficiently over a wide range of bleed air temperatures and pressures consistent with specific inert gas flow and oxygen concentration requirements. Generally, the pressure swing adsorption process works most efficiently with high inlet pressures and cool inlet temperatures (see figures 1 and 5); however, beneficial altitude effects, optimized bed sizes, cross flows, cycle timing, etc. can compensate for lower pressures and higher temperatures. If we could specify MSIGG input gas temperature and pressure, they would be 34°F and 40 psig. Deviations from these conditions are compensated for in the characteristics of the PSA process and system design parameters.

SECTION IX

RECOMMENDATIONS

With feasibility of PSA technology now demonstrated, the next step is production of a flight-demonstrable MSIGG prototype. Such a system can be integrated with other aircraft systems to achieve performance not obtainable with the laboratory test system described in this report. To summarize, we recommend:

1. pursuit of molecular sieve pressure swing adsorption technology as a practical approach to fuel tank inerting.

2. initiation of a flight test program to include development of flight worthy hardware and controls.

3. using the adaptability of molecular sieve pressure swing adsorption to take full advantage of a completely aircraft integrated, systems engineered approach to fuel tank inerting.

*USGPO: 1983-659-062-1131