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EVALUATION OF THE LINEAR AEROSPIKE SR-71 EXPERIMENT (LASRE) OXYGEN SENSOR

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Abstract

The Linear Aerospike SR-71 Experiment (LASRE) was a propulsion flight experiment for advanced space vehicles such as the X-33 and reusable launch vehicle. A linear aerospike rocket engine was integrated into a semi-span of an X-33-like lifting body shape (model), and carried on top of an SR-71 aircraft at NASA Dryden Flight Research Center. Because no flight data existed for aerospike nozzles, the primary objective of the LASRE flight experiment was to evaluate flight effects on the engine performance over a range of altitudes and Mach numbers. Because it contained a large quantity of energy in the form of fuel, oxidizer, hypergolics, and gases at very high pressures, the LASRE propulsion system posed a major hazard for fire or explosion. Therefore, a propulsion-hazard mitigation system was created for LASRE that included a nitrogen purge system. Oxygen sensors were a critical part of the nitrogen purge system because they measured purge operation and effectiveness. Because the available oxygen sensors were not designed for flight testing, a laboratory study investigated oxygen-sensor characteristics and accuracy over a range of altitudes and oxygen concentrations. Laboratory test data made it possible to properly calibrate the sensors for flight. Such data also provided a more accurate error prediction than the manufacturer's specification. This predictive accuracy increased confidence in the sensor output during critical phases of the flight. This paper presents the findings of this laboratory test.

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Nomenclature

C_3H_8	propane
CO_2	carbon dioxide
GH_2	gaseous hydrogen
H_2	hydrogen
He	helium
LASRE	Linear Aerospike SR-71 Experiment
LN_2	liquid nitrogen
LO_2	liquid oxygen
N_2	nitrogen
O_2	oxygen
P_{amb}	ambient pressure, psia
PCM	pulse code modulation
PO_2	partial pressure of oxygen, measured
psia	pound per square inch, absolute
PSL	sea level pressure, psia
RH	relative humidity
$V_{\%O_{2(measured)}}$	volume fraction of oxygen, measured
VDC	volts direct current

Introduction

The Linear Aerospike SR-71 Experiment (LASRE) was a flight experiment for a reusable launch vehicle propulsion concept done as a cooperative agreement between government and industry. NASA Dryden Flight Research Center, Edwards, California was responsible for the flight test. The LASRE flight test hardware included four elements identified as the canoe, kayak, reflection plane, and model (fig. 1). The completed assembly of all four elements was designated the pod. The pod was approximately 41.0 ft long and 7.5 ft tall at its highest point, the top of the model.[1] The linear aerospike rocket engine was integrated into the model, which was designed as a semi-span of an X-33-like lifting body shape. (The X-33 is a subscale, suborbital, rocket technology demonstrator vehicle.) The pod was mounted on the aft fuselage of the SR-71 airplane between the twin vertical rudders (fig. 2).

Unlike conventional bell-shaped rocket nozzles, the linear aerospike nozzle could compensate for back-pressure effects and thus provide high performance over a wide range of altitudes. Concern existed that a slipstream effect could reduce effectiveness of altitude compensation. Because no flight data existed for aerospike nozzles, the primary objective of the LASRE program was to evaluate flight effects on the aerospike engine performance over a range of altitudes and Mach numbers. This propulsion system posed a fire or explosion hazard because it contained a large quantity of energy in the form of fuel (gaseous hydrogen), oxidizer (liquid oxygen), hypergolics, and gases at very high pressures.

The primary concern of the project was the combustion of hydrogen in an oxygen atmosphere. Therefore, a propulsion-hazard-mitigation system was implemented, which included pod inert purge (nitrogen), oxygen sensors, fire-detection/pod-temperature thermocouples, and real-time monitoring. Because of the absence of flightworthy hydrogen gas sensors for monitoring hydrogen levels in the pod, the oxygen sensors became a critical part of the nitrogen purge system because they could measure purge operation and effectiveness. Lower Flammability Limits

The lower flammability limits for hydrogen-oxygen, nitrogen mixtures at sea level were about 4-percent hydrogen and 4-percent oxygen (by volume), and were independent of each other (fig. 3).[2] The limits remained about the same throughout the LASRE flight envelope, extending up to 50,000 ft.[3] Calculation of combustion conditions at equilibrium or for detonation showed that, even for low flammable concentrations of hydrogen and oxygen, temperatures and pressures high enough for structural damage could develop. A conservative ground rule stated that the oxygen and hydrogen concentrations must be maintained below 4 percent during the entire mission, because any combustion in the pod was deemed unacceptable.

Description of Nitrogen Purge System

The nitrogen purge system operated by purging the pod cavity with inert nitrogen gas, which was held in a liquid nitrogen dewar in the SR-71. The primary objective of the purge system was to minimize the presence of oxygen in the pod environment by displacing air out of the pod; purging kept the oxygen content registered below the flammability limits of hydrogen in a 4-percent oxygen (by volume) atmosphere. The purge also reduced the presence of fuel by displacing any leaked hydrogen. The valve controllers, instrumentation electronics, and the hydrogen and liquid oxygen valves also were purged with nitrogen gas. This minimized ignition sources by enclosing the electronics with an inert gas.

Location of Oxygen Sensor

The oxygen sensors were a critical part of the nitrogen purge system in that they measured purge effectiveness in opposing the infiltration of outside air and the presence of any leaked liquid oxygen. Because of the oxygen concentration limits imposed for hazard mitigation, the program needed a clear understanding of the characteristics of the oxygen sensors at high altitudes. Twelve oxygen sensors were distributed throughout the pod to monitor and detect the presence of oxygen. Eight were in the canoe, and four were in the model. Figure 4 shows the location of the oxygen sensors in relation to the helium, water, gaseous hydrogen, triethyl aluminum triethyl borane (TEA-TEB), and liquid oxygen tanks.

Justification for the Oxygen Sensor Study

The oxygen sensors were not initially considered to be critical safety elements. As limitations of the propulsion hazard mitigation system became evident, the sensors' importance grew. Their airworthiness was unknown because the electrolytic sensors were commercially available and designed for ground use. The sensors' operation was based on partial pressure of oxygen. The manufacturer's specifications gave an accuracy reading of 1 percent of full scale (1 atmosphere). For a given volume fraction of oxygen, as altitude increased, ambient pressure decreased, and the partial pressure of oxygen decreased, approaching specified sensor accuracy limits. At high altitudes as a result, the oxygen volume fraction determined from sensor readings appeared erratic. These erratic sensor readings prompted a test program that was designed to better characterize sensor performance and accuracy through a comprehensive sweep of altitudes and oxygen concentrations. This paper presents the analysis and test results of the oxygen sensor test.

Use of trade names or names of manufacturers in this document does not constitute an official endorsement of such products or manufacturers, either expressed or implied, by the National Aeronautics and Space Administration.

Description of Oxygen Sensor

Background and Sensor Description

The oxygen sensor design incorporated three major components: an anode, cathode, and electrolyte (fig. 5).[4] The cathode was the sensing electrode or the site where the oxygen was reduced. When oxygen was sensed, the lead anode was oxidized, in a basic medium, to lead oxide. The overall effect of this design was a fuel cell that was very specific for oxygen, providing no gaseous components appeared in the sample stream capable of oxidizing lead. Because all diffusion processes were temperature sensitive, the sensor electrical output varied with temperature. Therefore, to minimize the effects of ambient temperature changes on the readings, and to prevent freezing, each sensor was maintained at a constant temperature by being wrapped in an actively controlled heater blanket regulated to roughly 115 °F, which was above flight ambient.

Two membranes were inside the sensor, one to the rear of the cell inside the contact plate and a sensing membrane covering the cathode. The entire space between these two membranes was filled with an electrolyte causing the surfaces of the anode and cathode to be bathed in a common pool of electrolyte. The electrolyte was an aqueous solution of potassium hydroxide. To be reacted, an oxygen molecule must diffuse through both the sensing membrane and the thin film of electrolyte maintained between the sensing membrane and the upper surface of the cathode. The rate at which oxygen molecules reached the surface of the cathode determined the electrical output. This rate was directly proportional to the concentration of oxygen in the gaseous mixture surrounding the cell. The sensor, therefore, should theoretically exhibit an absolute zero reading in the absence of oxygen in the cell.

Partial Pressure Effects

Although most commercially available oxygen sensing systems are set up to read the concentration of oxygen in percentage units, the oxygen sensor is actually sensitive to the partial pressure of oxygen (P_{O_2}) in a sample gas mixture. In flight, the pod ambient air pressure (P_{amb}) would vary, so for a fixed volume fraction of oxygen, the measured partial pressure of oxygen ($P_{O_{2meas}}$) would vary proportionally. The volume fraction determined flammability. The volume fraction of oxygen ($V_{\%O_{2(measured)}}$) was calculated by correcting to ambient pressure (P_{amb}), as follows:

$$V_{\%O_{2(measured)}} = 100 * \frac{P_{O_{2meas}} \text{ (from oxygen sensor)}}{P_{amb} \text{ (from pod pressure sensor)}}$$

The manufacturer's quoted accuracy for the sensors (from fig. 5) was ±1 percent of full-scale reading (14.7 psia) at sea level or ±0.147 psia at constant temperature and pressure. Table 1 lists partial pressure of oxygen in pounds per square inch, absolute (psia) from sea level to 80,000 ft for various oxygen concentrations along with the full-scale error. At the higher altitudes and lower oxygen concentrations, the sensor partial pressure readings exceeded the given accuracy limit of 0.147 psia. At 40,000 ft, therefore, a flammable (5-percent) mixture could exist with a measurement of no oxygen.

Flight Performance of Oxygen Sensor

On-Board Calibration of the Sensors

The 12 aircraft installed oxygen sensor outputs were fed into the data acquisition system on the LASRE pod. The data acquisition system included a pulse code modulation (PCM) encoder system and several analog signal conditioning modules.

The signal-conditioning modules contained the 10 kΩ load resistor and then amplified and filtered the sensor signal before being digitized in the PCM encoder to obtain the maximum resolution. The digital data were then transmitted from the aircraft and received at the ground station which applied the calibration relating the digital value (representing the sensor voltage output) to partial pressure oxygen (fig. 6). This relationship was obtained using a two-point calibration process on the LASRE pod using the actual data acquisition system installed in the vehicle. The manufacturer's data sheet indicated that the sensors were linear, and therefore, the two-point calibration would be sufficient. This linearity of the sensors was later confirmed in the calibration laboratory for altitudes below 30,000 ft.

The first calibration point was obtained at ambient conditions where the digitized sensor output was recorded for each of the 12 sensors along with the ambient air pressure. This provided readings for each of the sensors in a 20.945-percent oxygen environment. Initially, the second point was obtained by placing each

Table 1. Partial pressure of oxygen concentration (±1 percent, full-scale (14.7 psia)); error = 0.14 psia.

		Partial pressure of oxygen		
Altitude, ft	Ambient air pressure, psia	5.05-percent O_2 concentration, psia	2.06-percent O_2 concentration, psia	1.02-percent O_2 concentration, psia
0	14.70	0.74	0.03	0.15
2,000	13.66	0.69	0.28	0.14
10,000	10.11	0.51	0.21	0.10
20,000	6.75	0.34	0.14	0.07
30,000	4.36	0.22	0.09	0.04
40,000	2.72	0.14	0.06	0.03
50,000	1.68	0.08	0.03	0.02
60,000	1.04	0.05	0.02	0.01
70,000	0.64	0.03	0.01	0.01
80,000	0.40	0.02	0.01	0.00

sensor in a plastic bag and blowing gaseous nitrogen into the bag to try and get a 0-percent oxygen environment. After numerous flights and tests in which the oxygen sensor readings went below the value obtained from the bagging, however, it became apparent that a truly 0-percent oxygen environment was not attainable with this method. After a study and analysis of the laboratory data from the eleven sensors tested, the most accurate calibrations were concluded to result when assuming that a sensor output of 0 millivolts represented 0-percent oxygen. The second point of the on-board calibration was obtained by disconnecting the oxygen sensors and installing jumper wires in their place, thereby zeroing the inputs to each of the 12 signal–conditioning amplifiers.

These digitized data were then recorded for each of the 12 sensors and provided the "electrical" zeros that represented the oxygen sensor outputs in an absolute 0-percent oxygen environment. For each of the sensors the two calibration points were plotted and a line was drawn between them, and a linear relationship and equation was determined to cover the complete range of the sensors.

History of Oxygen Sensor Performance

The nitrogen purge was ineffective during the first few flights of the LASRE due to substantial infiltration of external air. During these flights oxygen levels increased to nearly 21 percent (as opposed to levels below 4 percent in a purged environment). Within a nonpurged environment the oxygen levels should have maintained a steady 21-percent reading; however, a number of anomalies in oxygen sensor readings occurred. As the aircraft increased altitude through 25,000 ft, the sensor output decreased from the 21-percent reading. The overall effect was a decrease in reading with increasing altitude and increased reading with decreasing altitude.

Figure 7 shows the oxygen sensor flight data in relationship to the altitude. The data show that the oxygen sensors did not maintain a steady 21-percent reading throughout the entire flight as they should have in an uninerted environment. These readings indicated that at altitudes above 25,000 ft, calculated oxygen sensor readings appeared sensitive to altitude nonproportionally with ambient pressure. The wide range of concentrations resulted from flawed calibration procedures discussed in the previous section.

Efforts were made to improve the pod sealing, especially in the interfaces between the model, canoe, and SR-71, using elastic materials such as foam rubber and silicone sealant. The flow rate was doubled to 2.5 lb/min, and a second liquid nitrogen dewar was added to increase the purge flow duration. Additionally, a valved purge vent that could be remotely actuated from the cockpit was installed. With the valve open, the purge gas flowed through the pod and exited out the vent at the aft end of the canoe. This valve allowed any major leaks to be vented out of the pod. With the valve closed, the purge gas maintained a positive pressure in the pod, thus reducing air infiltration. The purge gas flowed out from any remaining leak paths. By the end of the flight test program the purge flow rate was tripled from its initial rate to 3.75 lb/min.

Flight tests after these purge improvements demonstrated adequate purge performance for flight, up to about Mach 0.9 and an altitude of 26,000 ft, with oxygen levels below 4 percent. Figure 8 shows Mach number, altitude, and the measured oxygen levels during a purged portion of a flight. The oxygen sensor on the canoe that read consistently low oxygen levels was placed near a purge "piccolo" tube exit near the front of the canoe. The piccolo tube is a capped-off tube with holes inserted along its length that distribute nitrogen into the pod. The data spike above 4 percent was a telemetry dropout. The rest of the sensors in the canoe tended toward 4 percent. With the oxygen data reading so close to the established limit of 4 percent, sensor accuracy becomes a critical issue. The accuracy data provided by the manufacturer could conceivably make the reading vary by ±0.147 psia.

This accuracy level was unacceptable because at the lower oxygen concentrations and partial pressures this became a substantial error, as shown in table 1. It became necessary, therefore, to create a more definitive measurement of accuracy for these sensors, especially at lower partial pressures and oxygen concentrations. More data were needed to understand the characteristics of the sensors at high altitude. A laboratory study was implemented to investigate sensor performance through a comprehensive sweep of pressure altitude and oxygen concentrations.

Laboratory Test of Oxygen Sensor

Test Description

The need to test these sensors thoroughly was not recognized before sensor installation in the pod. This left the project with a choice of disassembling the pod to remove the sensors for individual calibration or creating an independent test with a sampling of new sensors. Because of cost and scheduling constraints, the best approach was to perform an independent laboratory test that characterized the behavior of the oxygen sensors. The three test objectives were to (1) characterize sensor behavior with increasing altitude (decreasing partial pressure), (2) perform a statistical analysis on the laboratory test results, which would give a confidence level in the mean of the untested pre-installed sensors, and (3) quantify sensor error with decreasing partial pressure. Eleven sensors were tested (eight unused and three used sensors). The used sensors had been previously installed in the pod and later removed because they had reached 75 percent of the manufacturer-specified life, which was a limit set by the project. These sensors were tested along with the unused sensors to determine the effects of age on sensor output. The used sensors displayed erratic behavior previously observed in flight. Only the unused sensors were evaluated for the statistical analysis.

To keep the sensors at a constant temperature, they were placed in heater blanket assemblies similar to those used on the aircraft. The wrapped sensors were installed two at a time in a small test chamber (fig 9). A 10-kΩ load resistor was placed across the output of the sensor as suggested by the manufacturer. The sensors were exposed to the following oxygen concentrations: 0, 1.02, 2.06, 5.05, 10, and 21 percent. Bottled nitrogen was used to make the 0-percent oxygen concentration. Shop air was used for the 21-percent gas concentration. For oxygen concentrations of 1.02, 2.06, 5.05, and 10 percent, highly accurate calibrated gases that used nitrogen as the balance gas were procured. Each concentration was mixed in separate gas cylinders and guaranteed to within ±2 percent of reading.

After the sensors were placed in the test chamber, the calibrated gas was introduced into the chamber through a pressure fitting that was placed in the bottom plate of the chamber. The system was controlled with a pressure controller that evacuated the chamber to the desired pressure. After the calibrated oxygen was introduced into the chamber, the system was cycled through a range of pressure altitudes four times from sea level up to 80,000 ft and then back down to sea level before data were gathered. Sensor measurements were taken at 10,000-ft intervals.

Laboratory Data Acquisition

The oxygen sensor voltage readings were taken for 1 min at every 10,000 ft of pressure altitude interval. The system was held for 1 minute at each altitude before taking data. The data rate was 1 sample per second. A computer automatically recorded the voltage output from the sensor.

Test Results

As discussed earlier, the sensor could be calibrated by taking a two-point calibration. This technique assumes a linear relationship between pressure altitude and the voltage output. Laboratory test indicated that the altitude-voltage data were linear up to a pressure altitude of 30,000 ft. Figure 10 shows the raw calibration for a sensor. Between 30,000- and 40,000-ft altitude the calibration curve became nonlinear. Other data showed that an exact zero voltage reading was not attainable for the 0-percent oxygen concentration. This fact indicated that the two-point calibration was only good up to about 30,000 ft, at which point the nonlinearity would make the calibration inaccurate. This data would explain the erratic readings obtained during flight at altitudes higher than 30,000 ft.

As stated above, data were taken for 0-, 1.02-, 2.06-, and 5.05-, 10-, and 21-percent oxygen concentrations. For the purposes of this discussion only the 0-, 1.02-, 2.06-, and 5.05-percent concentrations are presented here, because the lower concentrations were the region of most interest and the focus of this test. The higher concentration data, however, did exhibit similar trends as the lower concentrations. Accuracy below 40,000 ft for all of the represented concentrations was less than 0.05 percent, which was better than the specified 1-percent accuracy. The data for each sensor remained close to the actual concentration line. Above 40,000 ft, however, the accuracy in the data degraded because of the change in linearity. The solution was to create a fifth-order curve fit that took into account the nonlinear effect of the higher altitudes.

The analysis of laboratory test data justified a generic (sensor-independent) calibration correction. The effective calibration for each sensor became an estimate based on the two-point, on-board calibration process described above multiplied by a generic correction in the form of a fifth-order polynomial in pod pressure. For a fixed pod pressure each result of oxygen sensor linear calibration was multiplied by the same correction constant. Figure 11 is a graph of the pressure altitude versus the percentage of oxygen with a fifth-order correction applied for 0-, 1.02-, 2.06-, and 5.05-percent oxygen mixtures (averaged over the eight tested sensors). This correction pulled the data at higher altitudes closer to an accurate reading along the percentage of oxygen concentration line. Because this generic equation was derived with different sets of data, a data scatter increase of more than 0.5 percent occurred in the reading from sensor to sensor at altitudes greater than 50,000 ft. The trends in the variations from sensor to sensor, however, were consistent at each concentration. These results indicate improved accuracy could be obtained using individual fifth-order corrections for each sensor.

A statistical analysis was performed on the corrected data to quantify the uncertainty between the untested sensors. The t-distribution was the statistical distribution tool chosen for this analysis because of the small number of samples. A 99-percent confidence interval was chosen to keep the results conservative. This meant that there was a 99-percent confidence that the installed sensor's average fell within the sample's mean interval. The pressure altitude was then compared with the 99-percent confidence intervals for the 0-, 1-, 2-, and 5-percent oxygen mixtures of the corrected readings (fig. 12). Based on the t-distribution for the corrected readings, the 99-percent confidence intervals were less than 1.0 percent up to an altitude of 60,000 ft and less than 1.3 percent up to an altitude of 80,000 ft.

Table 2 gives a list of the uncertainty schedule (based on 5-percent mixture) that was created from the t-distribution results. The sensor error was within

Table 2. Total percent O_2 uncertainty for 5.06-percent mixture.

Altitude, ft	Partial pressure O_2 for air, psia	Sensor uncertainty, percent	System uncertainty, lb/in^2	System uncertainty, percent	Total uncertainty, percent
0	14.696	0.10	0.0045	0.03	0.13
2,000	13.664	0.10	0.0045	0.03	0.13
10,000	10.106	0.10	0.0045	0.04	0.14
20,000	6.753	0.11	0.0045	0.07	0.18
30,000	4.364	0.15	0.0045	0.10	0.25
40,000	2.720	0.45	0.0045	0.17	0.62
50,000	1.682	0.89	0.0045	0.27	1.16
60,000	1.040	1.00	0.0045	0.43	1.43
70,000	0.644	1.09	0.0045	0.70	1.79
80,000	0.401	1.27	0.0045	1.12	2.39

±0.15-percent reading of oxygen below 30,000 ft and increased with altitude. The static system errors came from the amplifiers in the signal-conditioning board and PCM encoder, and added a constant 0.0045 lb/in^2 (also shown converted into percent partial pressure); a total uncertainty for the system was determined with respect to altitude.

Figure 13 gives a graphical representation of the manufacturer's error of 1-percent full-scale versus the total uncertainty generated from laboratory data. The grey area is the laboratory-generated uncertainty, and shows a much better accuracy than the specified 1-percent accuracy. Overall, the data gave a more definitive answer as to how the uncertainty changes with decreasing partial pressure. The total uncertainty taken from these data was added to the oxygen data during flight and used to make safety-of-flight go/no-go calls through real-time monitoring in the control room. Laboratory data produced a real-time oxygen reading that had a realistic error margin built in.

Concluding Remarks

The LASRE experiment incorporated several propulsion hazard mitigation systems. Included in the propulsion hazard mitigation system was a pod inert purge system along with oxygen sensors. These sensors were placed in the system to measure purge operation and effectiveness. As the project progressed, the criticality of the sensors grew.

Flight data show that a better understanding of oxygen-sensor characteristics was needed at higher altitudes (or reduced pressures). Also, sensor accuracy became very critical because the data indicated that the sensor readings were close to the 4-percent oxygen limit imposed for hazard mitigation.

Because the sensors actually measured partial pressure of the gas, its accuracy in terms of volume-fraction-of-gas degraded at high altitudes. This behavior in the characteristics of the sensors at high altitude was caused by decreased sensor sensitivity as ambient pressure decreased. Test results show that the two-point calibration did not account for the nonlinear change in the slope above 30,000 ft. To account for this change, a fifth-order curve fit was applied to the data in the control room. Based on the t-distribution for the corrected readings the 99-percent confidence intervals were less that 1 percent up to an altitude of 60,000 ft. The uncertainty results of this analysis were added to the oxygen data during flight and monitored in real time in the control room, thereby allowing control room personnel to make informed, conservative flight safety go/no-go calls.

The oxygen sensors chosen for this program were used outside of their intended original design for ground-level use. Clearly, it was important to test and validate the oxygen sensors before use. However, individual calibration of the sensors was impossible. The laboratory test data made it possible to properly calibrate the sensors for flight. The test data also more accurately predicted error than the manufacturer's error specifications. Extensive calibration, correction, and statistical analysis resulted in a set of sensors that could measure oxygen concentrations at 50,000 ft with the accuracy expected at sea level. The laboratory tests made it possible to fine-tune the interpretation of sensor data and increased the confidence in the sensor output during the critical phases of the flight.

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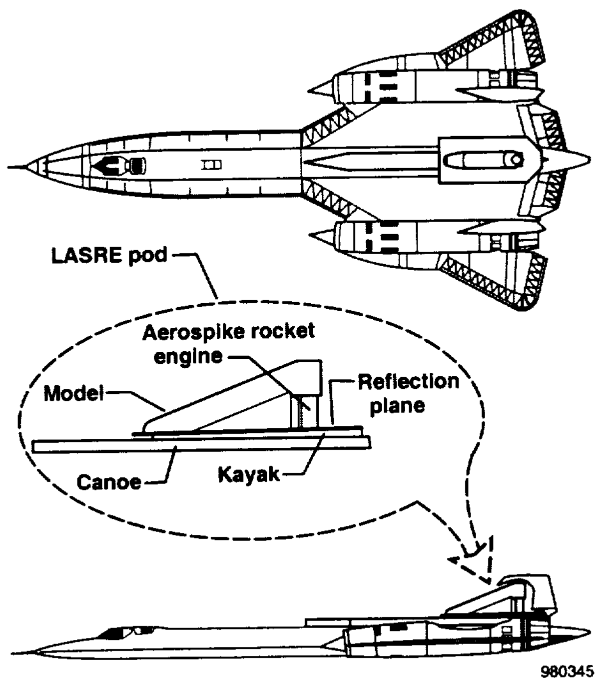

Figure 1. LASRE configuration-mounted SR-71 aircraft.

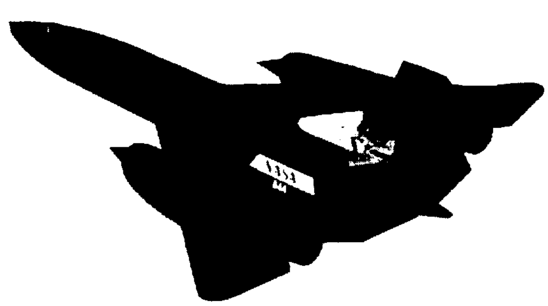

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Figure 2. SR-71 and LASRE in flight.

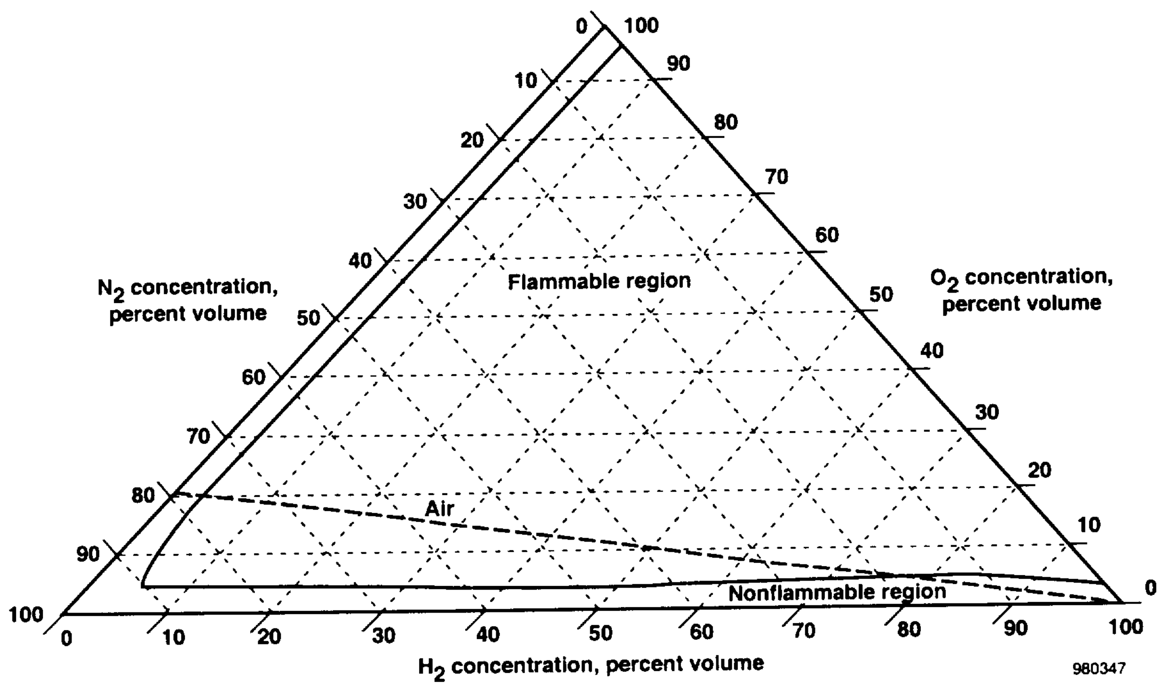


Figure 3. Flammability limits for H_2 - O_2 - N_2 mixtures at sea level.

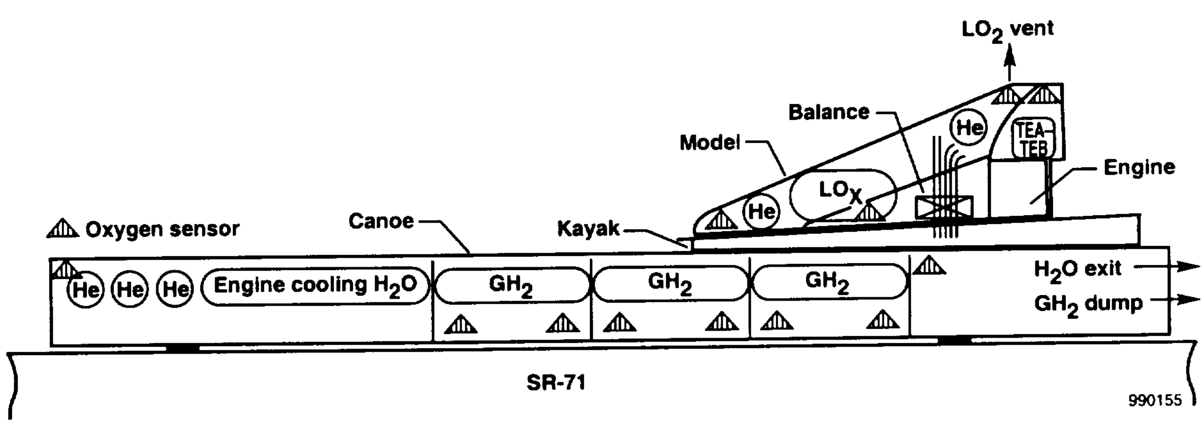
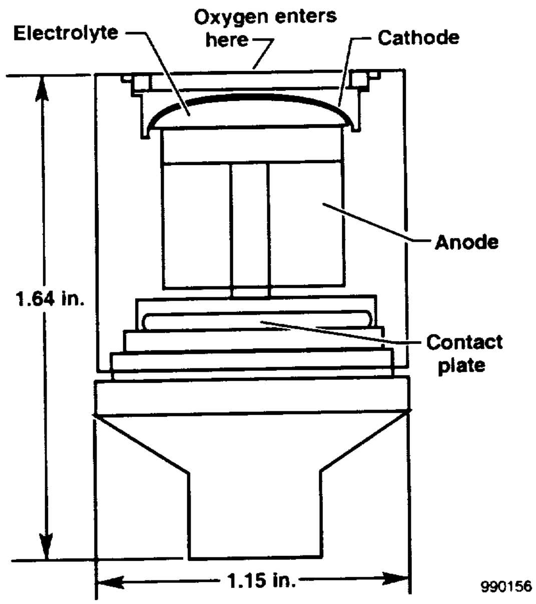


Figure 4. O_2 sensor location in LASRE pod.



Sensor specifications

Measurement range	0–100 percent oxygen
Output voltage	• 7–13 mV in air, 25 °C, sea level (standard) • 9–14 mV in air, 25 °C, sea level (optional)
Response time	• Less than 5 to 90 percent of final value • Less than or equal to 30 sec from air to 0.1-percent O_2
Accuracy	±1 percent of full scale at constant temperature and pressure
Electrical interface	R21A and R22A: 3-pin Molex® mating plug P/N 2201-2097 R17A: 3.5mm (0.140 in.) Switchcraft mating miniature phone plug, P/N 740 (screw terminal) or 750 (clamp-lug terminal)
Operating and storage temperature	0–50 °C (32–122 °F)
Operating humidity	0–95 percent relative humidity
Recommended load	10,000 Ω
Zero offset voltage	Less than 50 μV in 100-percent N_2 at 25 °C
Cross interference	Less than 0.1-percent O_2 response to: 15-percent CO_2, balance N_2 10-percent CO, balance N_2 3,000 ppm NO, balance N_2 3,000 ppm C_3H_8, balance N_2
Temperature compensation error	±5 percent of reading over the operating temperature range (worst case tracking error of ±10 percent of reading within the first hour after a maximum temperature step)
Pressure dependence	Directly proportional (i.e., a 10-percent increase in pressure will yield a 10-percent increase in output)
Expected lifetime	36 months in air, 25 °C, 50-percent relative humidity, ambient pressure
Weight	32 gm (1.2 oz)

Figure 5. Internal drawing of oxygen sensor with specifications.

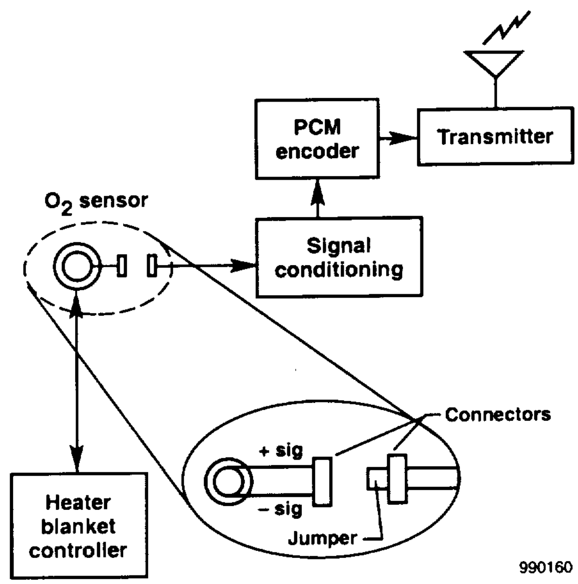


Figure 6. Oxygen sensor signal conditioning.

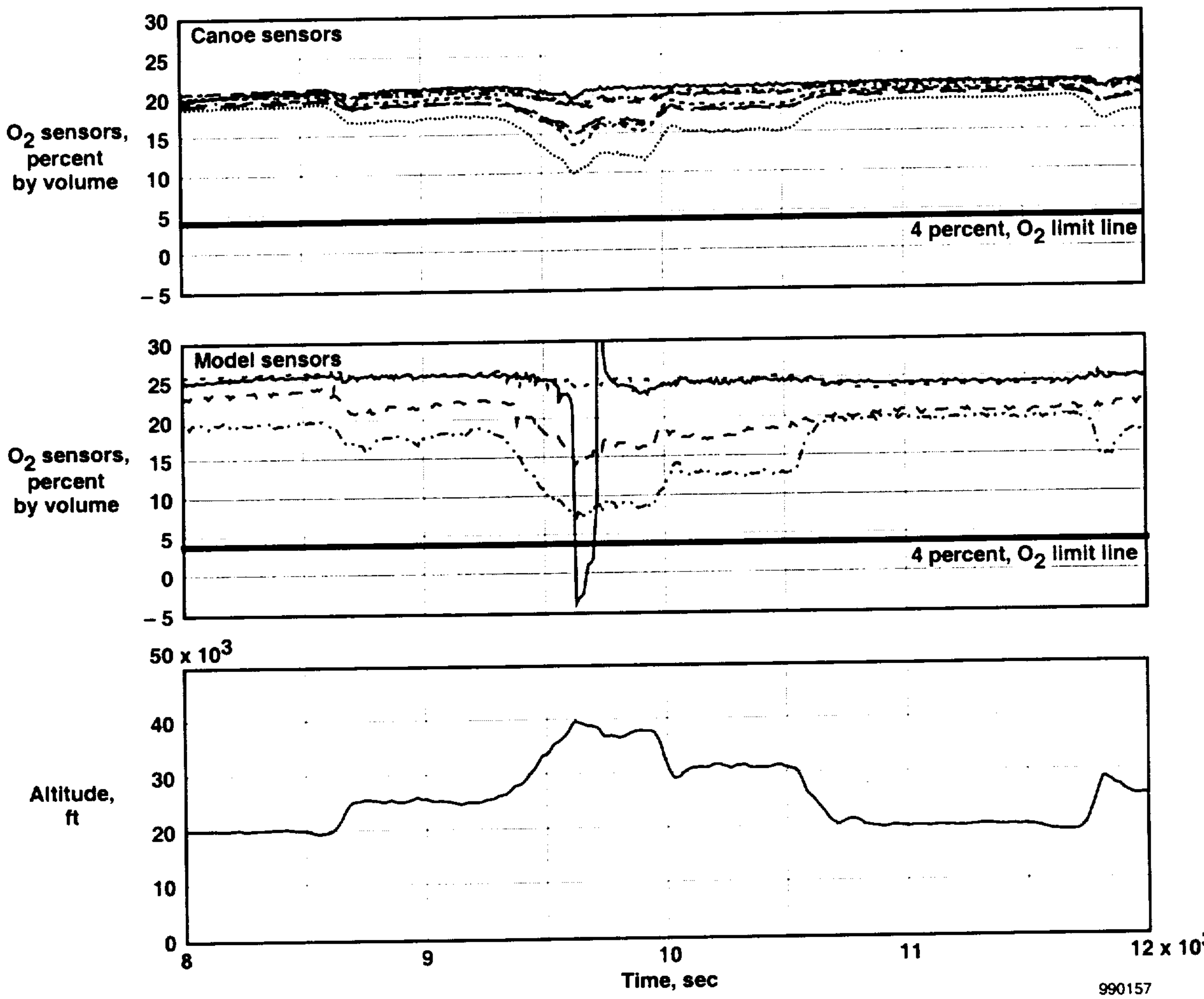


Figure 7. Oxygen sensor in-flight behavior without purge.

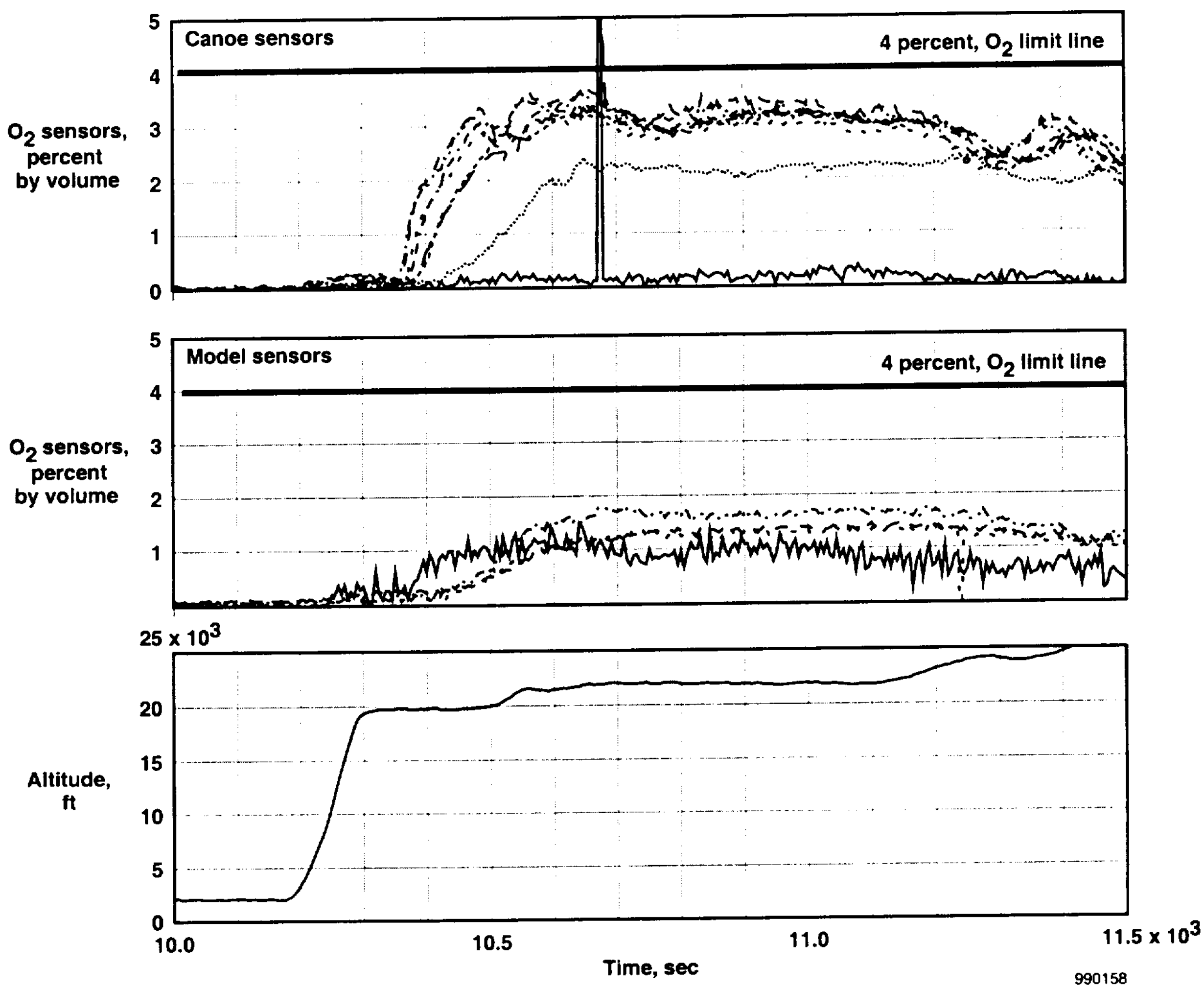


Figure 8. Nitrogen purge effectiveness in flight.

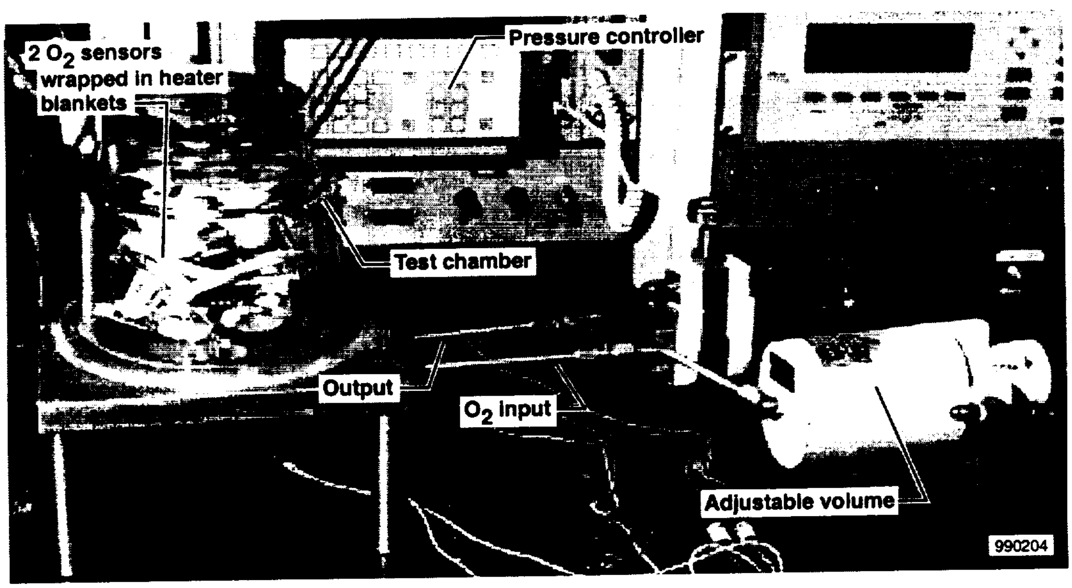


Figure 9. Oxygen sensors in test chamber.

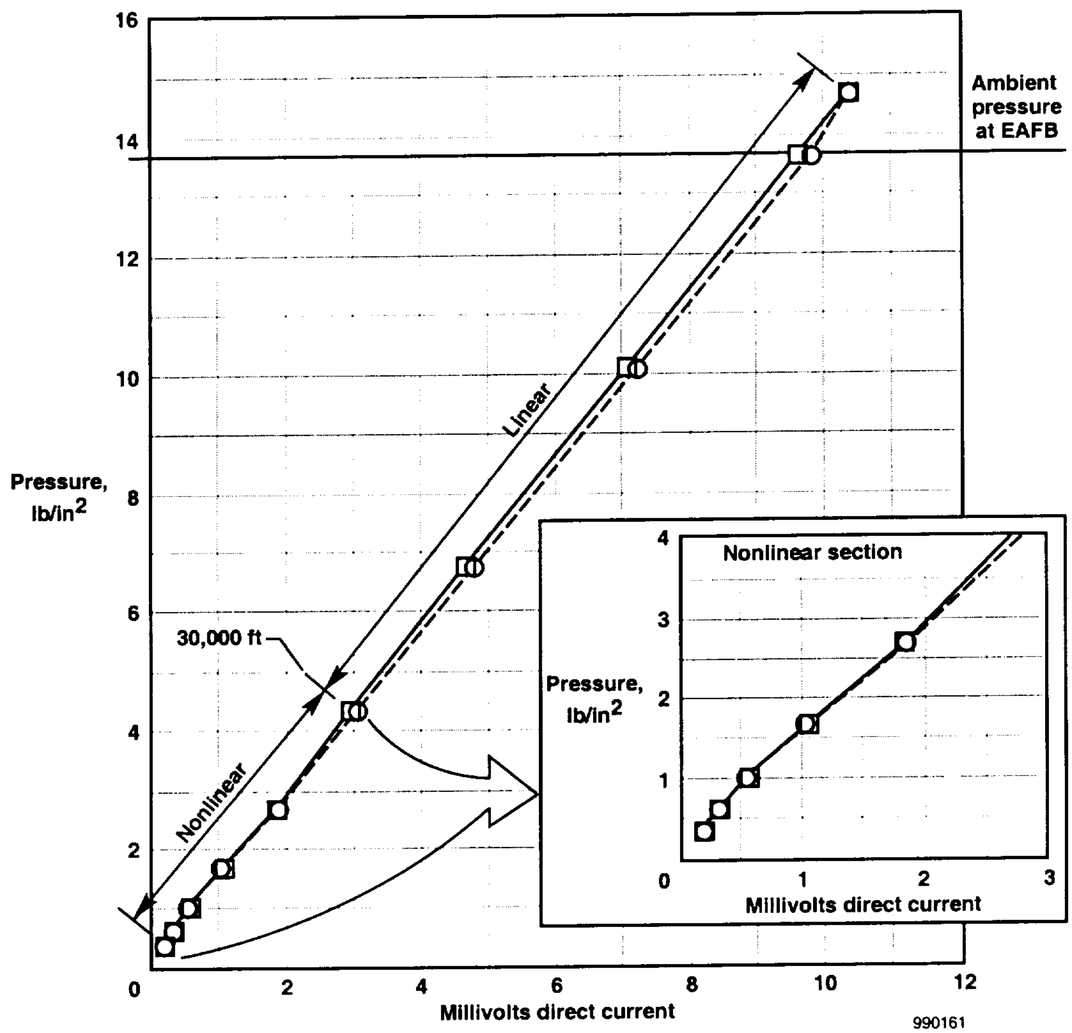


Figure 10. Raw data from oxygen sensor altitude chamber test.

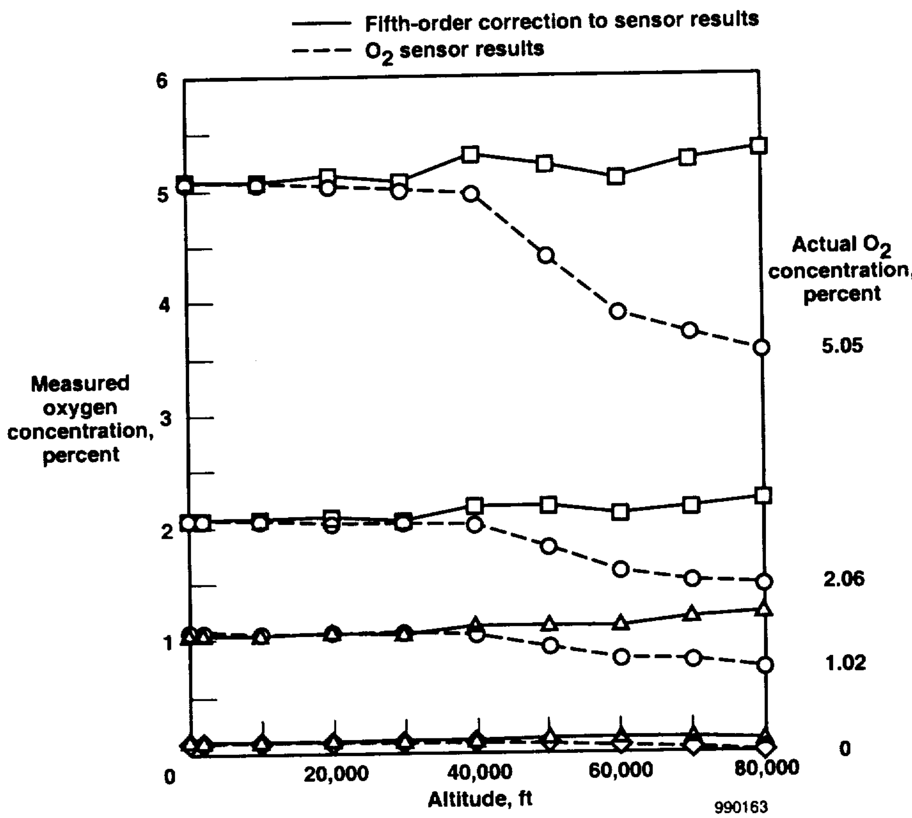


Figure 11. Pressure altitude versus percent oxygen with mixture concentrations of 0, 1.02, 2.06, and 5.05 percent with fifth-order correction.

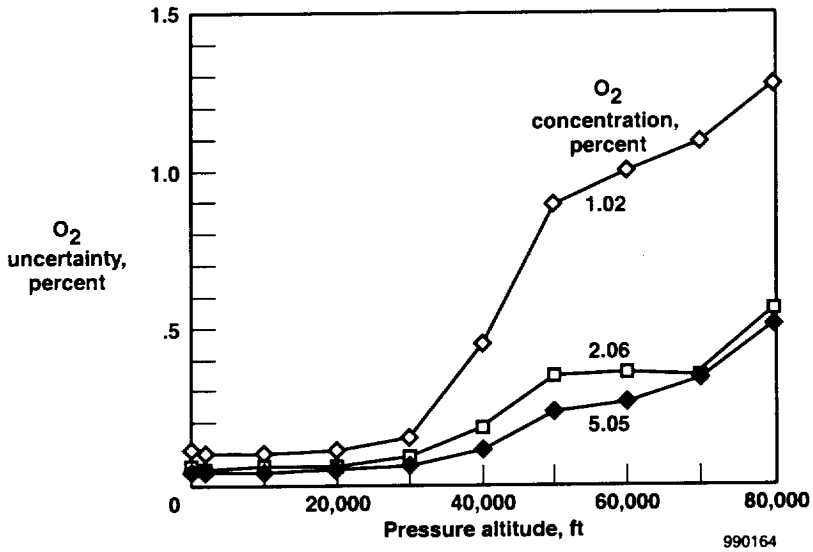


Figure 12. Pressure altitude compared with 99-percent confidence intervals t-distribution.

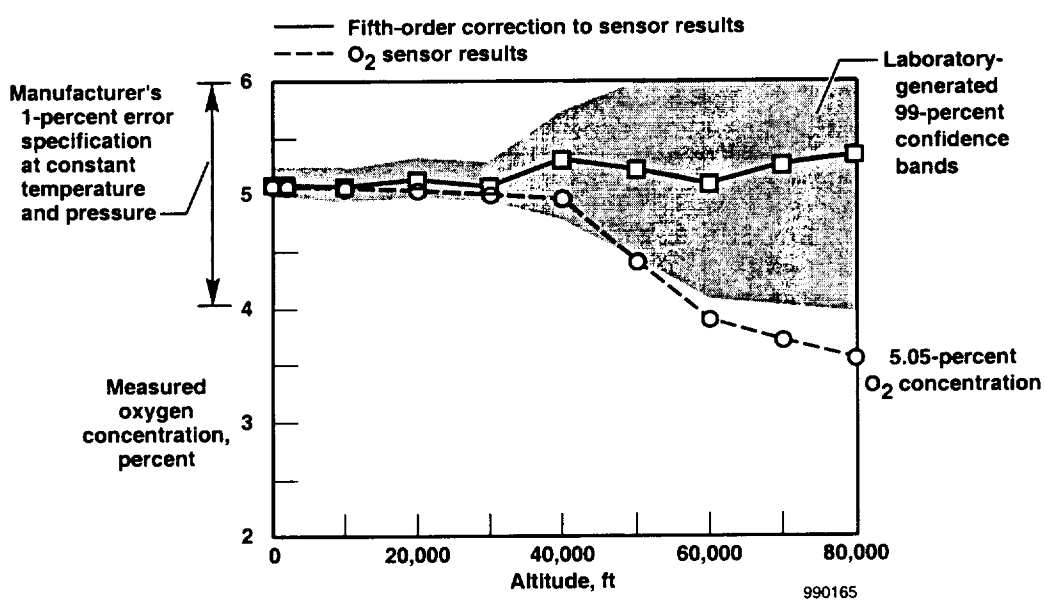


Figure 13. Manufacturer's error of 1 percent, full-scale versus the total uncertainty

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13. ABSTRACT (Maximum 200 words)

The Linear Aerospike SR-71 Experiment (LASRE) was a propulsion flight experiment for advanced space vehicles such as the X-33 and reusable launch vehicle. A linear aerospike rocket engine was integrated into a semi-span of an X-33-like lifting body shape (model), and carried on top of an SR-71 aircraft at NASA Dryden Flight Research Center. Because no flight data existed for aerospike nozzles, the primary objective of the LASRE flight experiment was to evaluate flight effects on the engine performance over a range of altitudes and Mach numbers. Because it contained a large quantity of energy in the form of fuel, oxidizer, hypergolics, and gases at very high pressures, the LASRE propulsion system posed a major hazard for fire or explosion. Therefore, a propulsion-hazard mitigation system was created for LASRE that included a nitrogen purge system. Oxygen sensors were a critical part of the nitrogen purge system because they measured purge operation and effectiveness. Because the available oxygen sensors were not designed for flight testing, a laboratory study investigated oxygen-sensor characteristics and accuracy over a range of altitudes and oxygen concentrations. Laboratory test data made it possible to properly calibrate the sensors for flight. Such data also provided a more accurate error prediction than the manufacturer's specification. This predictive accuracy increased confidence in the sensor output during critical phases of the flight. This paper presents the findings of this laboratory test.

14. SUBJECT TERMS
Aerospike, Flammability limits, High speed civil transport, Linear aerospike SR-71 experiment, Nitrogen purge system, Oxygen sensor, Partial pressure

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