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DEVELOPMENT OF RESPIRATION-RATE TRANSDUCERS FOR AIRCRAFT ENVIRONMENTS

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Robert T. McDonald
Northrop Corporation

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James Roman
NASA Flight Research Center

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SUMMARY

Two types of sensors for monitoring respiration rate in aircraft environments have been developed: a low-pressure pneumotachometer designed to monitor the pilot's respiration rate in aircraft that have a low-pressure breathing-oxygen supply, and a high-pressure pneumotachometer designed to monitor the pilot's respiration rate in aircraft with a high-pressure breathing-oxygen supply. For both pneumotachometers, the sensor is placed in series with the oxygen supply line and the pilot's oxygen line. The sensor detects gas flow that accompanies inspiration.

The pneumotachometers were tested in the laboratory and in high-performance aircraft. The sensors are sensitive to gas flow and can detect a shallow breath. Each of the sensors requires very low power consumption and is thus suited for use with internally powered tape recorders.

INTRODUCTION

Development of biomedical sensors has been in progress since 1963 at the NASA Flight Research Center as part of a long-range program to develop medical monitoring in flight (ref. 1).

One facet of the instrumentation development has dealt with means of obtaining respiratory rate in the dynamic environment. Respiration rate provides valuable information regarding physiological functioning. Several different instrumentation techniques have been used in the past to obtain such rate information (ref. 2). Techniques commonly used today include a chest strap with a dimensional transducer, a thermistor placed in front of either nostril, and a heated thermocouple placed in series with the oxygen line.

The chest-strap technique has the advantage of simplicity; however, it is exceedingly sensitive to subject motion and therefore is not usable when the subject is active.

The thermistor is normally heated to a temperature a few degrees above ambient, and its resistance changes are detected when it is cooled to different temperatures for different values of flow. This technique is reasonably good; however, it is difficult to implement reliably when very small power consumption is desired. The requirement for small power consumption leads to a thermistor temperature that is not much higher than ambient. Thus, variations in the temperature of the oxygen supply can cause the signal to be lost, which has proved to be exceedingly troublesome in the flight environment, particularly when the sun was intermittently heating the cockpit. Thermistor sensors can also be used in the oxygen hose; however, the same problems are encountered when the hose is heated by sunlight.

Heated thermocouples have been used successfully in the oxygen line; however, power-drain limitations result in the same compromise with respect to reliability as for the thermistor respiration sensor.

Because of such limitations in the techniques used to obtain respiration rate, the development of a sensitive, reliable respiration-rate transducer with low power drain was initiated at the NASA Flight Research Center. This paper describes the requirements, development, construction, and test results of a low pressure and a high-pressure pneumotachometer which resulted from the program.

SYSTEM REQUIREMENTS

The cockpit environment of a high-performance jet aircraft imposes stringent requirements on a pneumotachometer or other physiological monitoring equipment. These requirements, as they apply to pneumotachometers, are as follows:

1. High acceleration loads, up to 7g, along any axis.
2. Cockpit pressure from sea level to 30,000 feet.
3. Cabin temperature range from 0° C to 45° C.
4. Temperature range of breathing oxygen from 0° C to 40° C.
5. High audio noise level inside aircraft cockpit (130 decibels).
6. Safe functioning of the breathing-oxygen system not compromised by the pneumotachometer.

In addition, the following features are desirable:

1. The sensor should add very little flow resistance.
2. Power requirements should be less than 20 milliwatts.
3. Minimum flow detected by the sensor should be 0.5 liter per second.

Design Concept

The design of the low-pressure pneumotachometer involves the use of a sensitive ceramic microphone as a signal transducer. The pneumotachometer case, which includes the microphone, is placed in series with the oxygen supply hose. When oxygen is passed through the sensor case, it modulates the microphone diaphragm. Consequently, when a subject inspires oxygen, an electrical signal is present at the microphone output terminals. This signal can then be amplified and conditioned for display or data storage.

Figure 1 illustrates how the microphone is used as a signal transducer. Note that the microphone is mounted on the external portion of the sensor case. A small-diameter tube is used to acoustically connect the microphone diaphragm to the center of the sensor case.

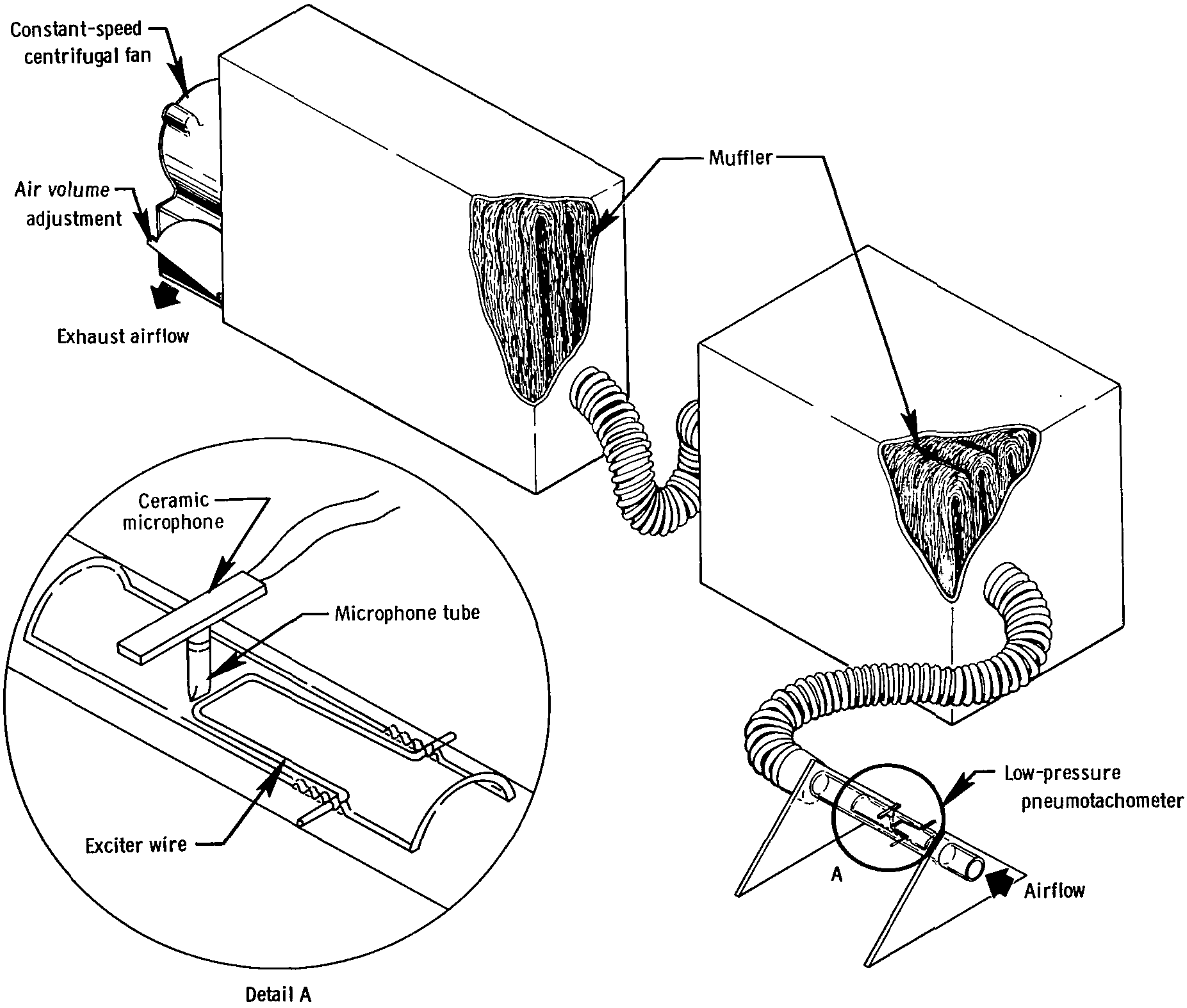

Figure 1.– Experimental model and test apparatus used to evaluate the low-pressure pneumotachometer concept.

During the inspiratory cycle, oxygen passes through the sensor. When the oxygen encounters the exciter wire (fig. 1), the flow around the wire becomes turbulent, which gives rise to an audio tone or sound. This sound is propagated through the tube to the microphone diaphragm.

If the tube length could be increased, it would be possible for the resonant frequency of the tube to coincide with the frequency of the audio tone. This arrangement would provide a much larger electrical output from the microphone.

Experimental Model

Construction. – An experimental model was constructed (fig. 1) to prove the feasibility of the microphone concept and to optimize design parameters. The model was fabricated from Plexiglas tubing. A hole placed in the top of the tubing permitted the microphone tube to be inserted. A removable top made from part of the Plexiglas tubing allowed various exciter-wire configurations to be inserted.

A constant-speed centrifugal fan was used to provide constant airflow through the experimental sensor. A muffler was inserted between the fan and the sensor to prevent fan noise from being detected by the microphone. An airflow adjustment on the fan permitted various levels of airflow to be selected.

Preliminary testing. – The experimental model and the air source were connected to a Wedge spirometer. By using the spirometer to calibrate the airflow, the exciter wire was positioned to give maximum microphone output.

The microphone was found to be extremely sensitive even for airflows as low as 0.5 liter per second. The electrical output of the microphone was predominantly a 2 kilohertz sinusoidal signal for 0.5 liter per second of airflow. The predominant frequency increased to 2.5 kilohertz at 5 liters per second of airflow. The amplitude of the microphone signal was logarithmic and varied from 10 millivolts to 50 millivolts peak to peak as the airflow increased from 0.5 liter per second to 5 liters per second, respectively.

With an oxygen mask[1] connecting the experimental model to the subject and to the Wedge spirometer, the microphone output was composed of periodic audio bursts. Each audio burst corresponded to the subject's inspiratory cycle.

Signal conditioning. – The audio frequency bursts at the microphone output were adequate for oscilloscope display, but the frequencies were too high to be recorded on a low-speed magnetic-tape recorder[2]. Thus, signal conditioning had to be applied before the information was stored on tape.

Signal conditioning should also be used for the following reasons: (1) the signal-to-noise ratio can be improved appreciably by filtering, which is important in view of

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[1]The oxygen mask allows air or oxygen to enter from the inlet port when the subject inspires. The inlet port is blocked when the subject expires, and air leaves through another port.

[2]Physiological parameters monitored in an aircraft environment are normally FM recorded on magnetic tape for analysis later.

the high audio noise level inside a jet aircraft; and (2) the microphone output signal level is too low for long, shallow breaths to be recorded on magnetic tape without some amplification.

A block diagram of the signal conditioner, including approximate signal waveforms, is shown in figure 2. The microphone signal was routed to the high-gain amplifier through a mini-fuse. Even though the microphone did not require power from the amplifier to function, the mini-fuse precluded the possibility of an unsafe current level flowing through the microphone. The microphone signal was amplified and filtered by the high-gain amplifier. The mid-band gain of this stage was 500, and the pass-band

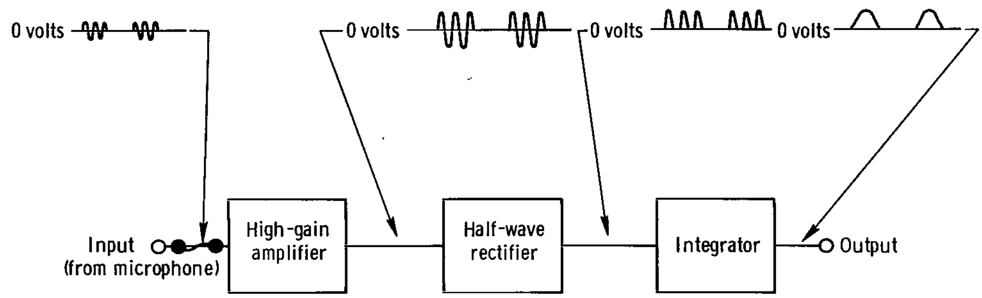


Figure 2.— Block diagram of signal conditioner, including signal waveforms.

was from 1.7 kilohertz to 3.5 kilohertz. The output of the high-gain amplifier was fed into a rectifier circuit. This circuit passed only the positive portion of the amplified signal. The signal was then routed to the integrator circuit. This circuit had a fast-discharge time constant; consequently, several input pulses were required before an output signal occurred. After the input pulses stopped, the output discharged to zero in approximately 100 milliseconds, which afforded additional filtering of the microphone signal and made it less sensitive to noise spikes. The output signal was composed of low-frequency components which could be recorded on magnetic tape.

The power consumption of the signal conditioner was approximately 12 milliwatts. This small amount of power was provided from an internally powered tape recorder and did not appreciably change total recording time.

Prototype Sensor

Construction. — A prototype pneumotachometer sensor was constructed so that testing could be conducted in high-performance aircraft. The prototype sensor was basically the same configuration as the final experimental model. Design parameters were optimized with the experimental model, thus eliminating the necessity for further experimentation.

Figure 3 is an exploded view of the prototype sensor showing how the sensor was constructed. The sensor case was fabricated from aluminum and had standard oxygen fittings. The fittings enabled the sensor to be inserted into an aircraft oxygen system.

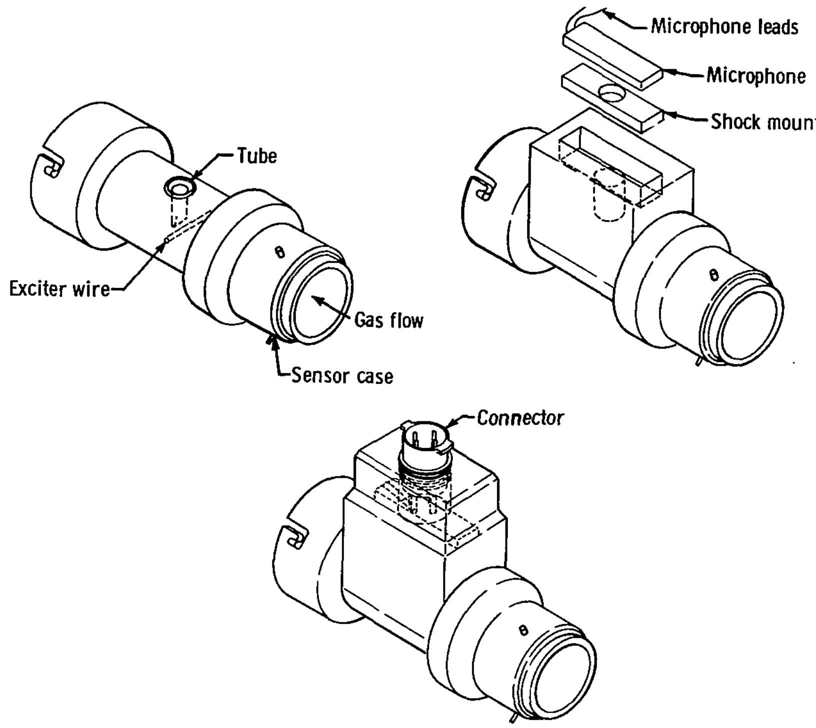


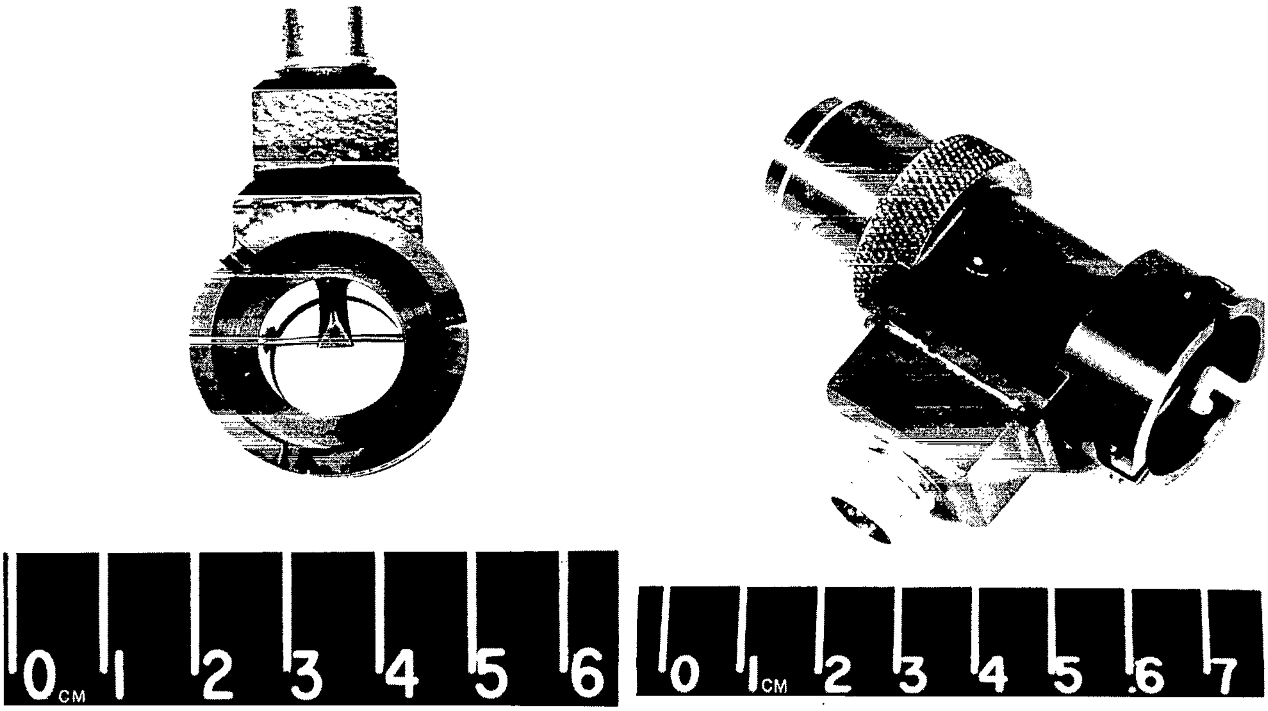
Figure 3.— Exploded view of low-pressure pneumotachometer.

The microphone tube was placed through a small hole in the side of the sensor case. The hole was countersunk to mate or accept the upper portion of the microphone tube, which was flared. This arrangement enabled the tube to be positioned properly and precluded the possibility of the tube loosening and falling into the sensor case. An epoxy housing was fabricated on the side of the sensor case to house the shock mount and microphone. The shock mount had an opening directly over the microphone tube and thus caused very little acoustical attenuation. The shock mount was necessary to isolate the microphone from aircraft vibrations.

The ceramic microphone was placed directly on top of the shock mount, and the microphone diaphragm was alined with the center of the microphone tube. The microphone and shock mount were held in place with Neoprene cement. The microphone leads were then soldered to the epoxy-housed connector. The epoxy shell that housed the connector was then cemented to the shell that housed the microphone. Figures 4(a) and 4(b) show the final assembly of the prototype pneumotachometer.

Test data. – Laboratory test data derived from the prototype pneumotachometer are shown in figure 5. The two signal waveforms were recorded while a subject breathed normally.

The low-pressure pneumotachometer was subjected to a high audio noise environment by placing the sensor near the tailpipe of an F-104 jet aircraft while the engines were running at 80 percent of full power. This audio noise environment was much higher than that normally found inside the cockpit. The pneumotachometer was insensitive to the high noise level; the signal-to-noise ratio was decreased less than 5 percent.



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(a) End view.

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(b) Side view.

Figure 4.– Low-pressure pneumotachometer prototype.

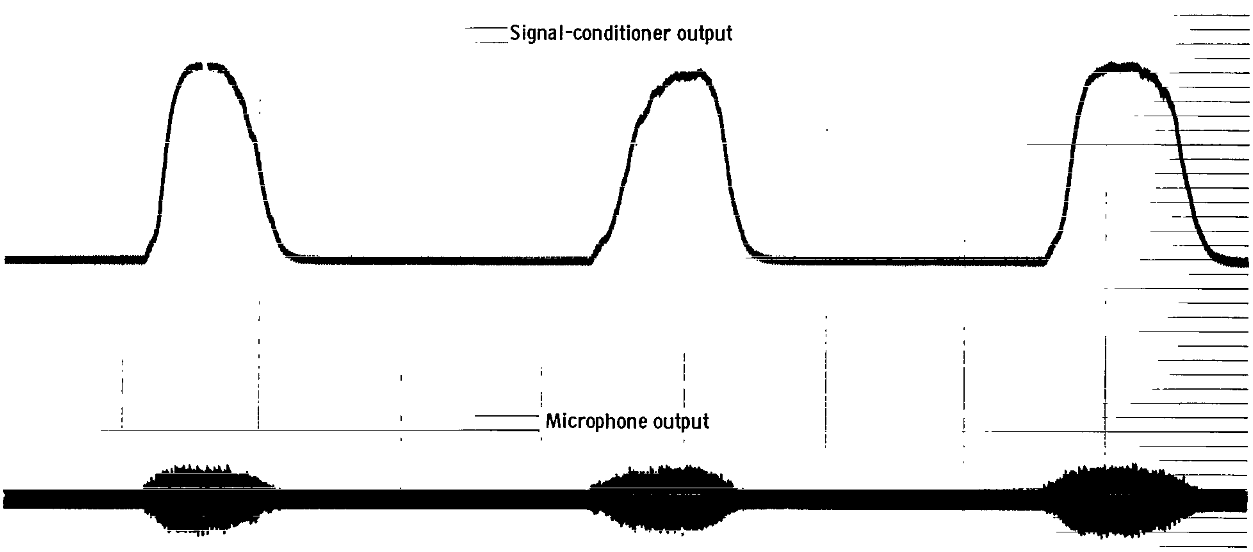

Figure 5.– Laboratory oscillogram showing microphone and signal-conditioner output signals from the low-pressure pneumotachometer.

A number of flights were made on which the low-pressure pneumotachometer was used. Oscillograms of the midflight segments of three flights are shown in figure 6. Inasmuch as the pilots and the missions differed for each flight illustrated, no attempt should be made to compare frequencies or amplitudes of the signals shown. The pneumotachometer yielded good respiration-rate information for the entire duration of each flight.

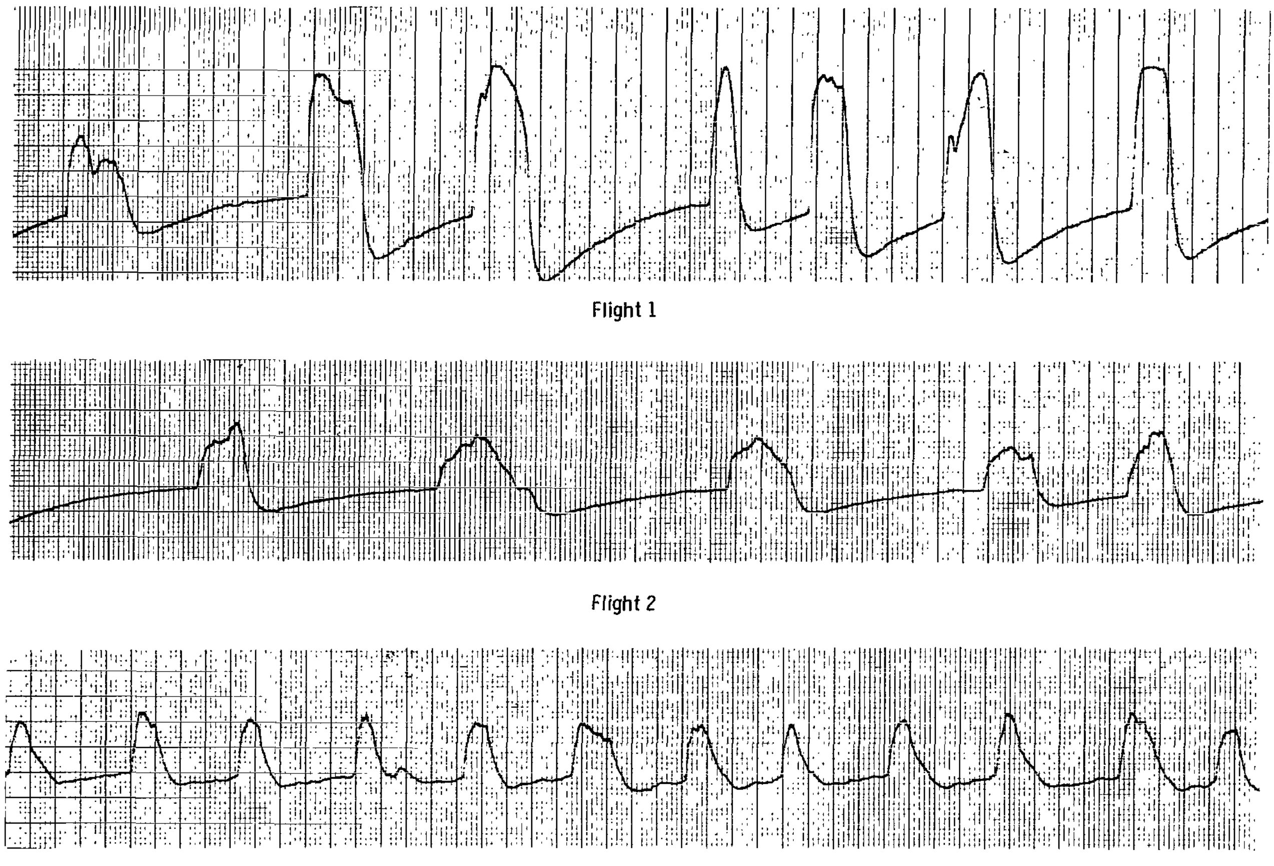

Figure 6.– Oscillograms of midflight segments of three test flights on which the low-pressure pneumotachometer was used.

DEVELOPMENT OF A HIGH-PRESSURE PNEUMOTACHOMETER

Design Concept

The design concept for the high-pressure pneumotachometer is similar to that used for the low-pressure pneumotachometer. A sensitive ceramic microphone is also used for the signal transducer.

The flow values in the high-pressure system are lower than those in the low-pressure sensor. The oxygen is at high pressure, approximately 75 pounds per square inch, until it is regulated down to near cockpit pressure at the pilot's face mask. If a pilot inspired 1.0 liter of oxygen through a mask at sea level in 2 seconds, the average flow would be 0.5 liter per second. The average flow in the high-pressure sensor, on the basis of Boyle's law, would be 0.1 liter per second or one-fifth as much for the same mask flow. However, at an altitude of 30,000 feet, the cockpit would be pressurized to approximately 16,000 feet. The oxygen regulator would then supply oxygen at approximately 7.6 pounds per square inch, and the high-pressure source would fall to 68 pounds per square inch[1]. The average flow through the high-pressure sensor at this altitude would be approximately 0.055 liter per second. Consequently, the high-pressure sensor must be much more sensitive to oxygen flow than the low-pressure sensor.

Figure 7 illustrates how the microphone is used as a signal transducer in the high-pressure pneumotachometer. As shown in the diagram, oxygen passes through the inlet port, out through the escape hole into the sensor chamber, and finally out the outlet port. The microphone is mounted inside the sensor chamber and directly over the escape hole. Consequently, any oxygen that passes through the escape hole will strike the microphone diaphragm before it passes out through the outlet port. The diaphragm is thus modulated by the passage of oxygen.

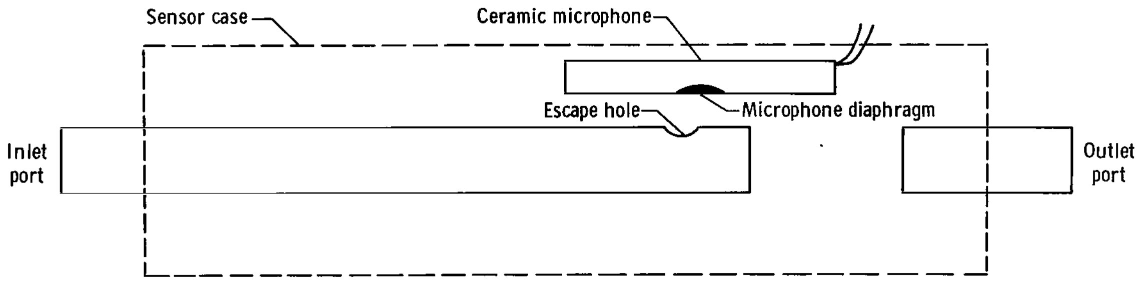

Figure 7.– Conceptual diagram of high-pressure pneumotachometer.

Experimental Model

Construction. – An experimental model was constructed to prove the feasibility of a high-pressure sensor. The design and construction of the sensor was similar to that of the configuration shown in figure 7.

Photographs of the disassembled experimental model are shown in figure 8. The sensor body was fabricated from aluminum. The cylindrical sensor body was milled on one side to form the inner chamber. A ledge around the top of the chamber was formed so that a top could be added that housed the microphone assembly. Both ends of the sensor body were drilled to accept high-pressure oxygen fittings. One of the oxygen fittings was modified by welding a short tube onto the fitting. The end of the tube inside the chamber was capped, and a small hole was drilled near the end to form

[1]The high-pressure source is maintained at approximately 60 pounds per square inch differential regardless of cockpit pressure.

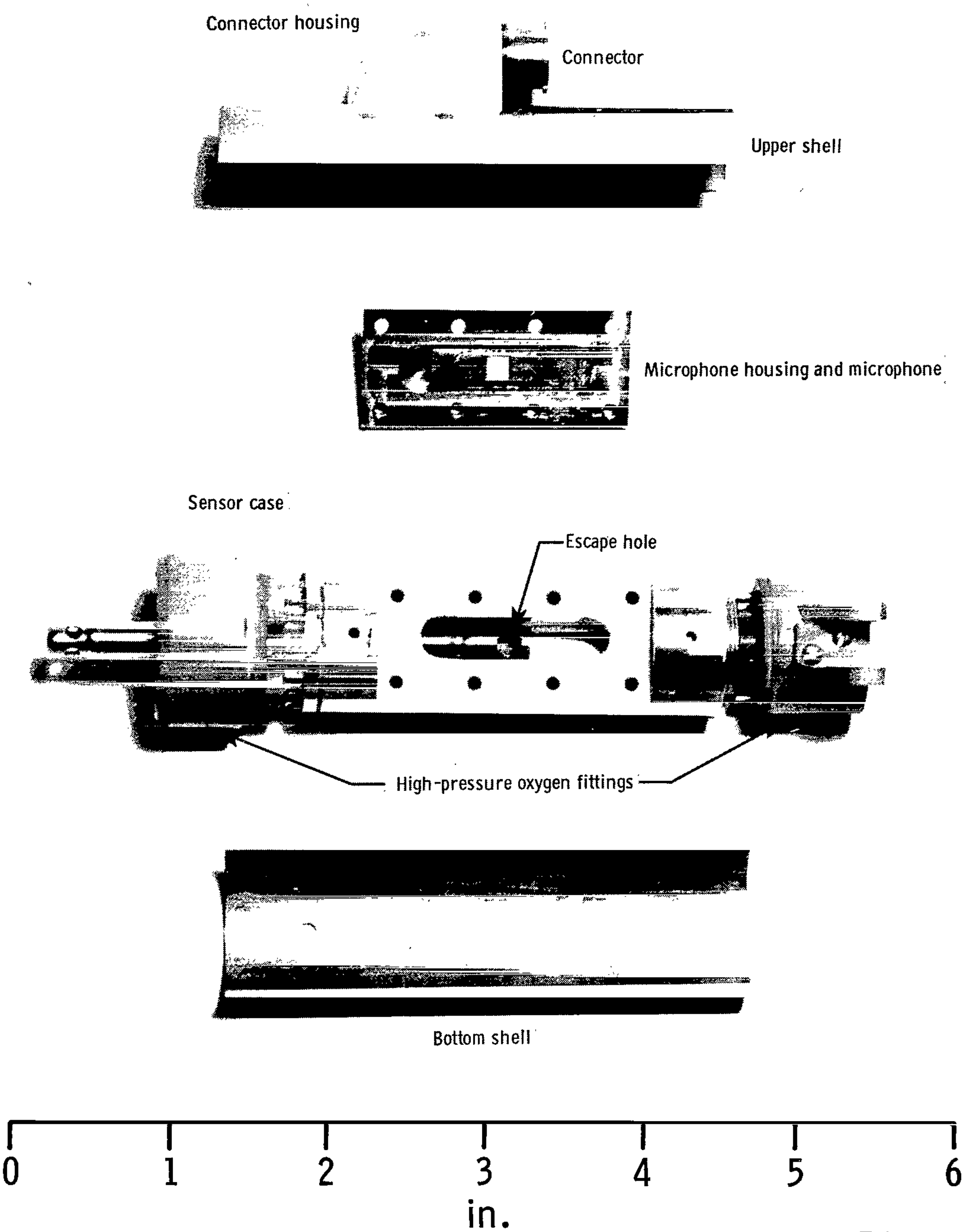

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Figure 8.— Disassembled experimental model of the high-pressure pneumotachometer.

the escape hole. The microphone housing was fabricated by cutting a slice from a cylindrical aluminum rod; the rod was the same diameter as the sensor body. The thickness of the slice was approximately the same as that of a section removed from the sensor body. An area was then milled from the top to provide room for the ceramic microphone. A Teflon gasket was fabricated to provide a good seal between the body of the sensor and the top of the microphone. The top assembly was mounted to the sensor body by means of eight 4-40 screws.

The microphone was installed in the microphone housing on top of a thin layer of Neoprene cement. The Neoprene cement provided a shock mount for the microphone and was compatible with the oxygen environment. The microphone leads were routed through two small lead holes to the exterior of the sensor, and the holes were sealed with epoxy. The electrical connector was attached to a half-cylindrical shell. After the microphone leads were connected to the connector, the shell was mounted to the sensor body. Another half-cylindrical shell was mounted on the bottom portion of the sensor body. A photograph of the assembled experimental model is shown in figure 9.

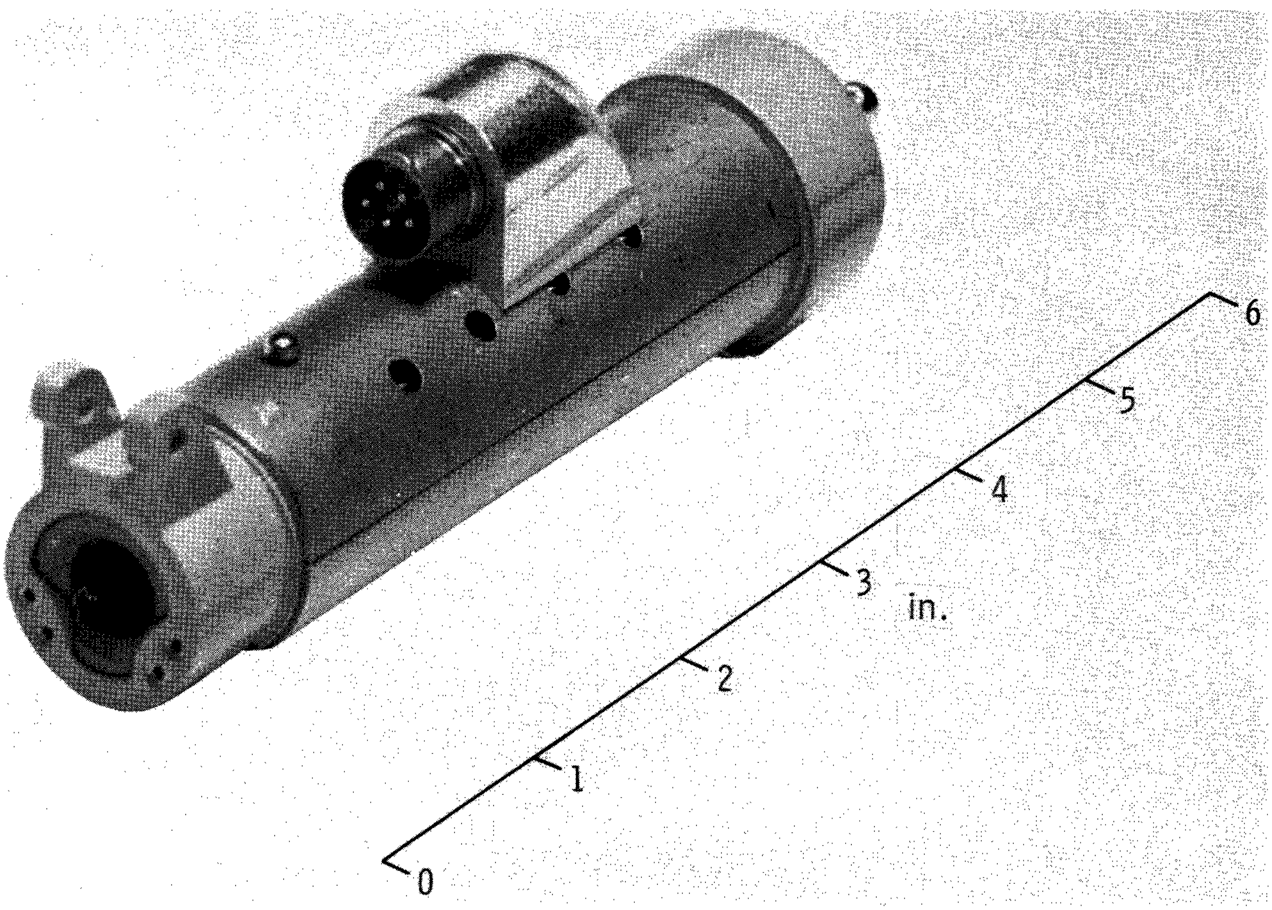

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Figure 9.– Experimental model of assembled high-pressure pneumotachometer.

Preliminary testing. – A high-pressure air source was connected to the inlet port of the experimental model, and an air regulator was connected to the outlet port. The output of the air regulator was connected to the Wedge spirometer. The high-pressure source was set to 75 pounds per square inch of air pressure. The airflow through the experimental model was varied from 0.1 liter per second to 1 liter per second. The flow values were established by the spirometer. The predominant frequency of the microphone signal was approximately 3 kilohertz for these values of airflow. The amplitude of the microphone signal was logarithmic and varied from approximately 20 millivolts peak to peak to 100 millivolts peak to peak as the airflow increased from 0.1 liter per second to 1 liter per second, respectively.

Signal conditioning. – Signal conditioner requirements for the high-pressure sensor were virtually the same as for the low-pressure pneumotachometer.

Prototype Sensor

Construction. – A high-pressure prototype pneumotachometer was constructed so that flight testing could be performed. The configuration used for the prototype sensor was varied from that of the experimental model in order to shorten the overall length.

Figure 10 shows the disassembled high-pressure pneumotachometer. The sensor body and top were fabricated from aluminum. The high-pressure oxygen fittings were

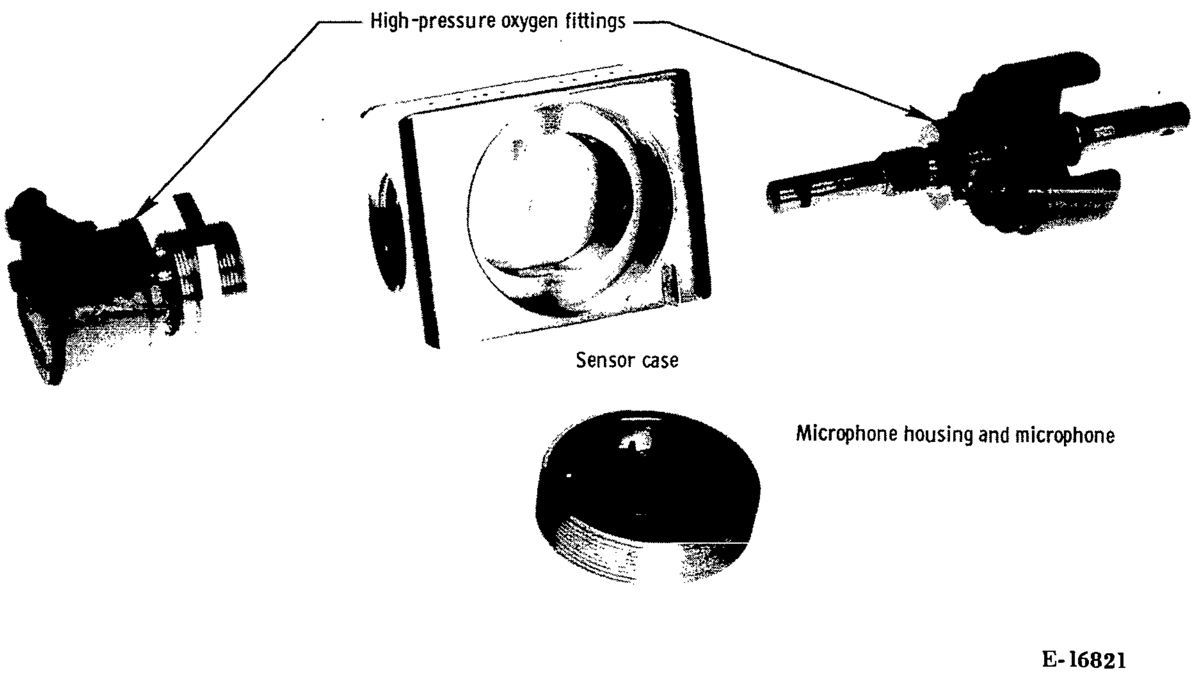

Figure 10.– Exploded view of prototype high-pressure pneumotachometer.

basically the same types as those used in the experimental model. In order to reduce the overall length of the sensor, the sensor body was made rectangular. The chamber was then formed by drilling, rather than milling, a large hole in the side of the sensor body. Figure 11 shows the assembled prototype. In the aircraft with the high-pressure oxygen system, electrical connections between the pilot's microphone and the aircraft radio were routed as a part of the oxygen hose. Consequently, the electrical wires on the pneumotachometer (fig. 11) were necessary to provide continuity between oxygen fittings.

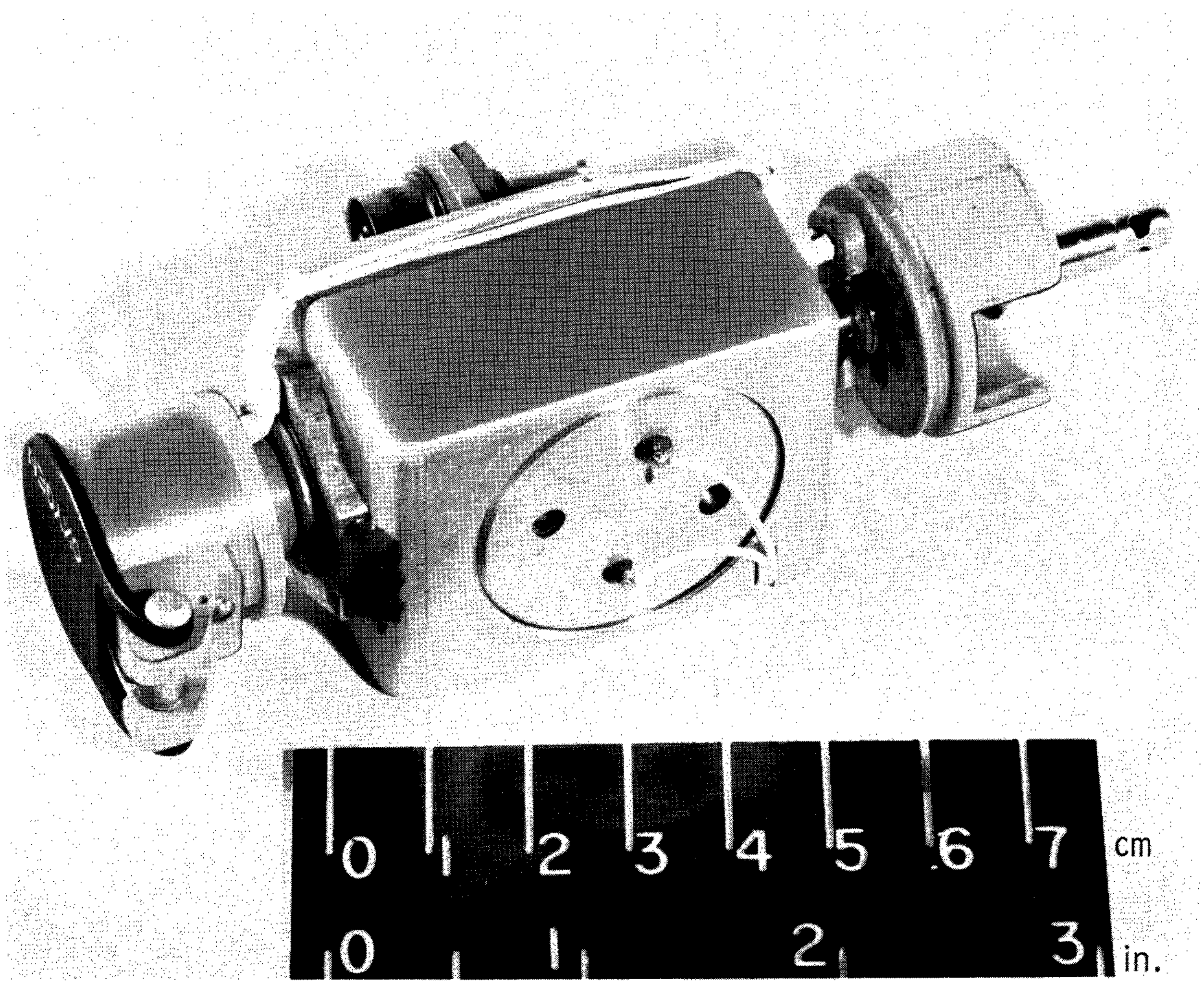

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Figure 11.– Assembled high-pressure pneumotachometer prototype.

Figure 12 shows the pneumotachometer after potting.

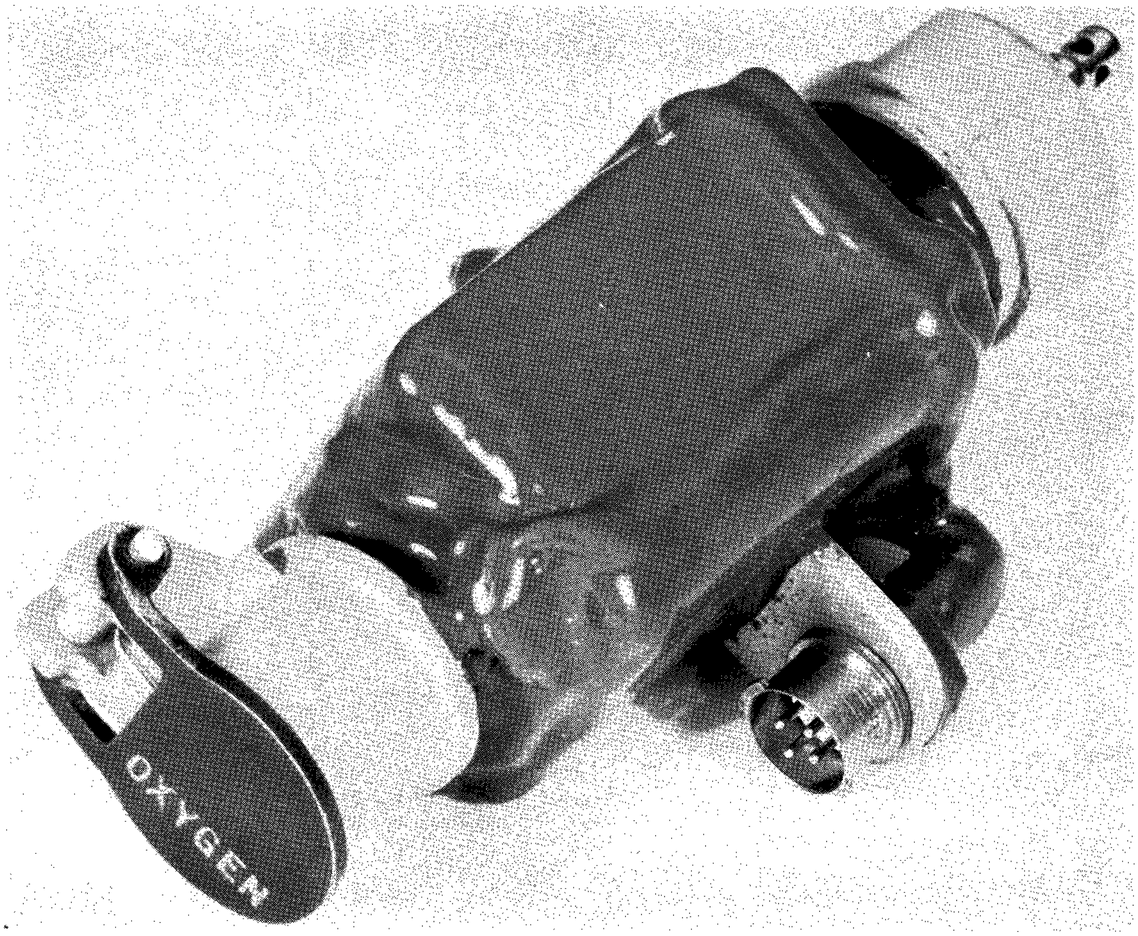

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Figure 12.– Potted high-pressure pneumotachometer prototype.

Test data. – The high-pressure pneumotachometer was subjected to a high audio-noise environment. Test results indicated that the high-pressure sensor had the same degree of noise insensitivity as the low-pressure sensor.

Laboratory test data, shown in figure 13, were recorded while a subject breathed normally from an oxygen mask that was connected to the high-pressure pneumotachometer.

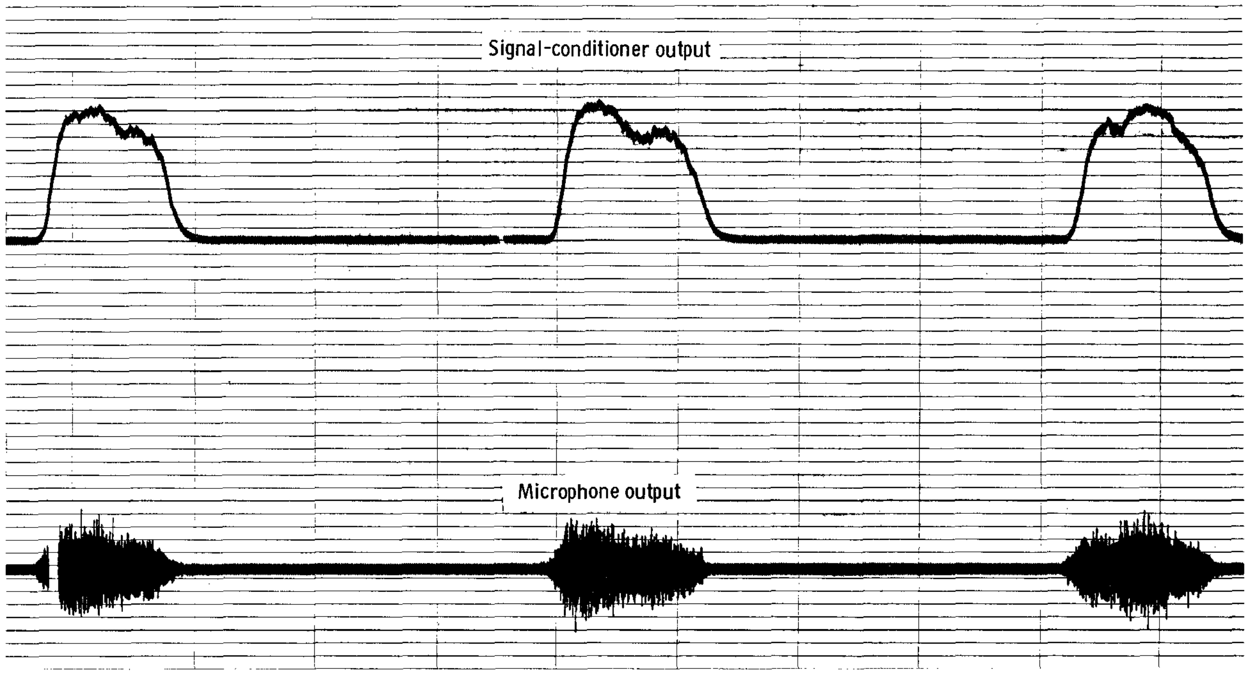

Figure 13.— Laboratory oscillogram showing microphone and signal-conditioner output signals from the high-pressure pneumotachometer.

Figure 14 shows a test pilot installing the high-pressure sensor before making a test flight to evaluate the pneumotachometer. A number of flights were made on which the high-pressure pneumotachometer was used. Test data from three flights are

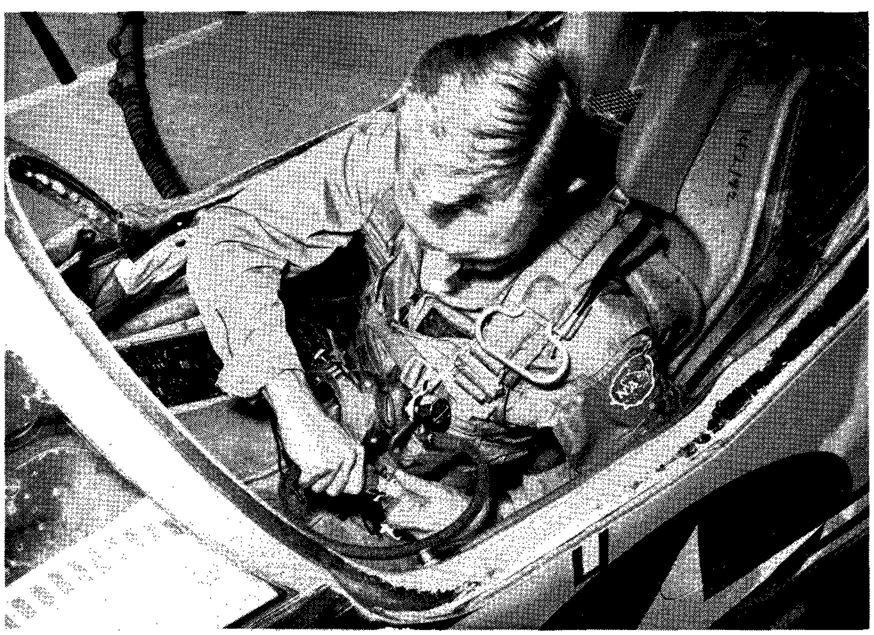

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Figure 14.— Pilot preparing to flight test high-pressure pneumotachometer.

shown in figure 15 to illustrate the excellent results obtained with the high-pressure pneumotachometer.

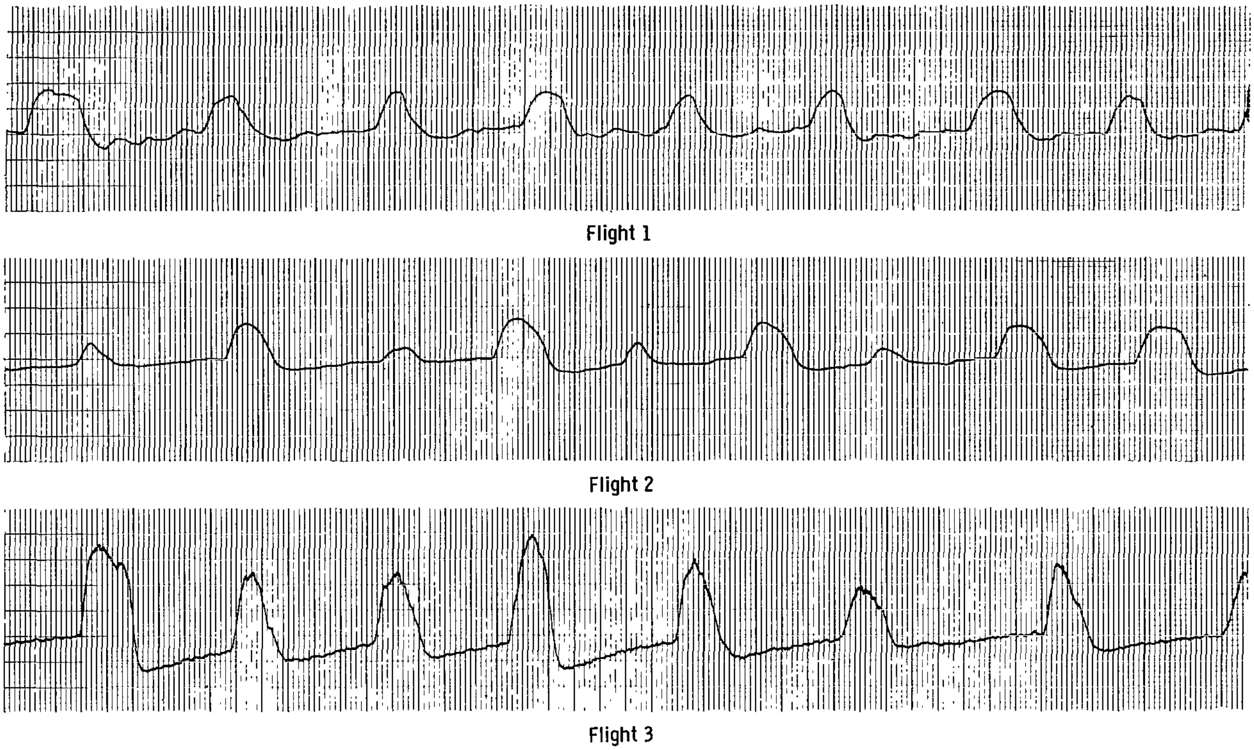

Figure 15.— Oscillograms from midflight segments of three flight tests on which the high-pressure pneumotachometer was used.

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National Aeronautics and Space Administration,
Edwards, Calif., August 22, 1967,
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