A MINIATURE RESPIRATORY MINUTE VOLUME SENSOR FOR THE FLIGHT ENVIRONMENT

(Flight Research Program XVII)

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Abstract. A miniature respiratory rate and volume sensor has been developed and flight qualified at the Flight Research Center. This device weighs only 172 grams, is sufficiently rugged to perform in the flight environment, and small enough to be worn as an integral part of the pilot's personal equipment. The safe operation of this system in an hyperbaric, pure oxygen atmosphere, is demonstrated. Details for the fabrication of the system are described. Operational experience over a two year period is reported.

1. Introduction

The understanding of dynamic respiratory physiology is dependent upon accurate measurement of respiratory minute volume, a function of tidal volume and respiratory rate. The measurement of minute volume in the laboratory is routine but is characterized by the use of large instruments, such as bell spirometers or Douglas bags, entirely impractical for use in the flight environment because of size and sensitivity to vibration, pressure, and temperature induced errors.

At the National Aeronautics and Space Administration (NASA), Flight Research Center (FRC), a continuing program to study cardiorespiratory stresses in the flight environment has led to the development of a series of flight-rated biosensors and associated data storage and retrieval equipment (Roman, 1965, 1966; Roman and Brigden, 1966; Patten *et al.*, 1966; McDonald and Roman, 1967; Carpenter and Roman, 1968a, b; Roman and Figarola, 1968), included were a variety of respiratory rate sensors (McDonald and Roman, 1967) which were used to estimate respiratory function in flight prior to qualification of the instrument reported here.

In situations where the subject is relatively inactive, respiratory rate is often a satisfactory estimation of respiratory function. However, in-flight, because of the effect of voluntary breath holding, pressure breathing, and the operation of *g*-suits on both respiration rate and volume, the measurement of rate alone becomes unacceptably inaccurate. Thus, the need for a miniature flight-qualified biosensor capable of accurately measuring respiratory minute volume was apparent and a program to develop such a device in-house was established at the NASA Flight Research Center.

The search for suitable sensors led to the Wright Spirometer, a small laboratory

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volume sensor which is unsuitable for use in flight because readout is accomplished from dials and because the device is nonlinear at low and high flow rates. In spite of these objections, its small size, rugged design and demonstrated high reliability suggested that a suitable modification might make the Wright Spirometer a valuable flight instrument.

Modifications were accomplished in two phases. In Phase I, fabrication and calibration of the laboratory prototype were completed during the summer of 1967, and have been previously reported (Roman and Sato, 1967). Phase II, redesign of the prototype sensor, design and packaging of the signal conditioner, and the refinement and flight-qualification of the resulting system was completed in the fall of 1967. This report reviews Phase I and discusses Phase II in detail, including a complete report of the operational experience to date with the flight-qualified device.

2. The Basic Instrument

The Wright Spirometer is a miniature gas volume detector (Figure 1) designed for laboratory use. A detailed description of its internal configuration and method of

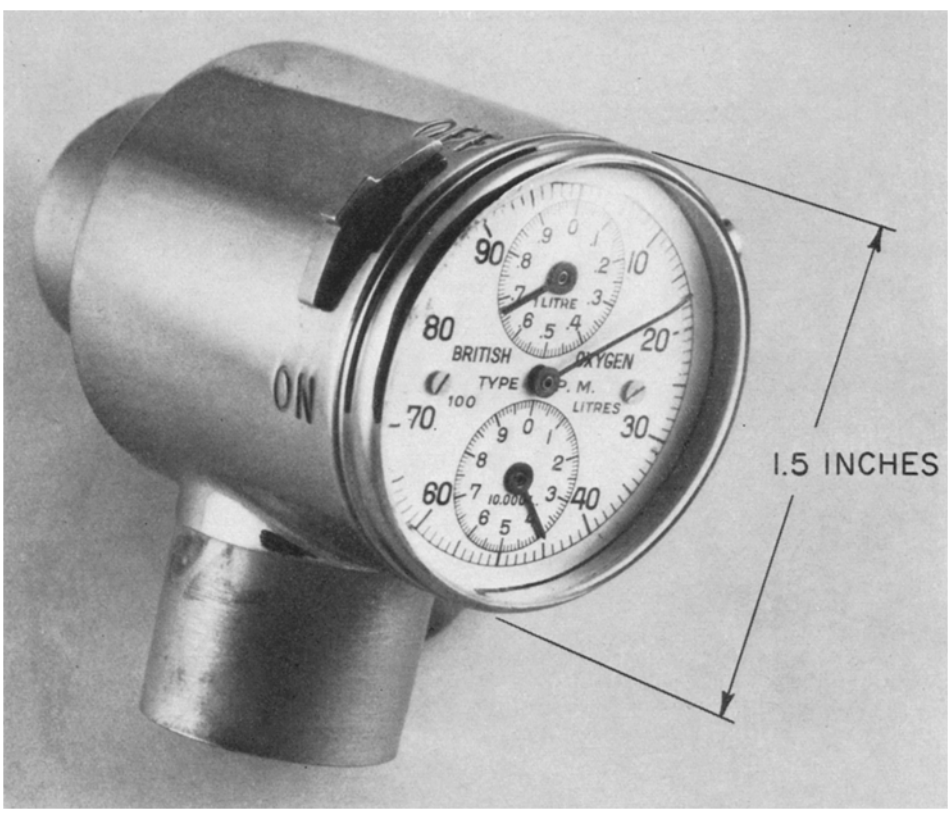

Fig. 1. The unmodified Wright Spirometer.

operation is described by Roman and Sato (1967). Gas entering the instrument impinges on a very light turbine blade causing its rotation. This rotation is carried through a gear train to the face of the device where accumulated volume is read out on a series of dials. All components of this instrument are designed to minimize angular moments of inertia. The angular rotation of the turbine is approximately proportional to the volume flow through the instrument.

3. The Laboratory Prototype

To convert this visual readout device to an electronic output and improve dynamic response, all unnecessary pointers, gears, and indicator shafts were removed. The one liter per revolution shaft was left, its pointer replaced with a spoked wheel. A miniature lamp and a miniature photo sensor were added and arranged so that the spokes of the wheel interrupt the light path between the lamp and photo sensor (Figure 2). Signal conditioning was designed to produce one square pulse for each one-tenth liter of gas passing through the instrument. Residual angular inertia and mechanical linkage errors were found to accumulate during any acceleration mode in spite of the very light, low friction design. To compensate, the laboratory prototype was very carefully calibrated at various rates of steady flow, and from zero to very high flow

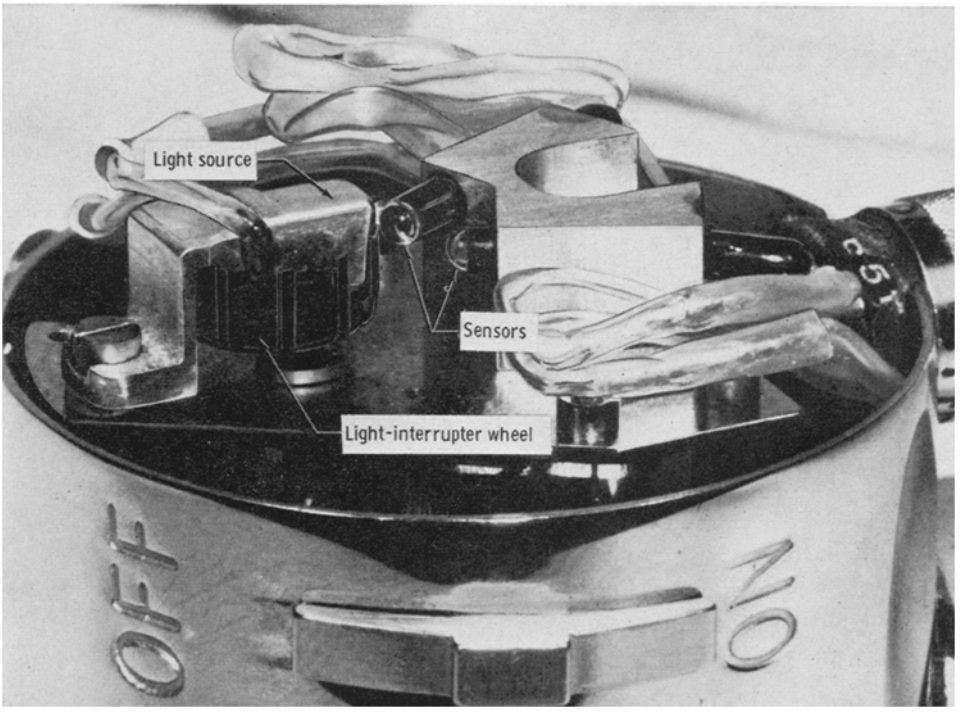

Fig. 2. Sensor readout modification – laboratory prototype.

rates during sudden acceleration (Figure 3), and the results incorporated into a computer program that provides automatic reduction of subsequent flight data. The details of this procedure were reported by Roman and Sato (1967).

4. The Flight Prototype

Encouraging performance of the laboratory prototype (Figure 4) led to the decision to fabricate a flight prototype. The rigorous demands of the flight environment required that such a prototype be developed to fulfill the following design criteria:

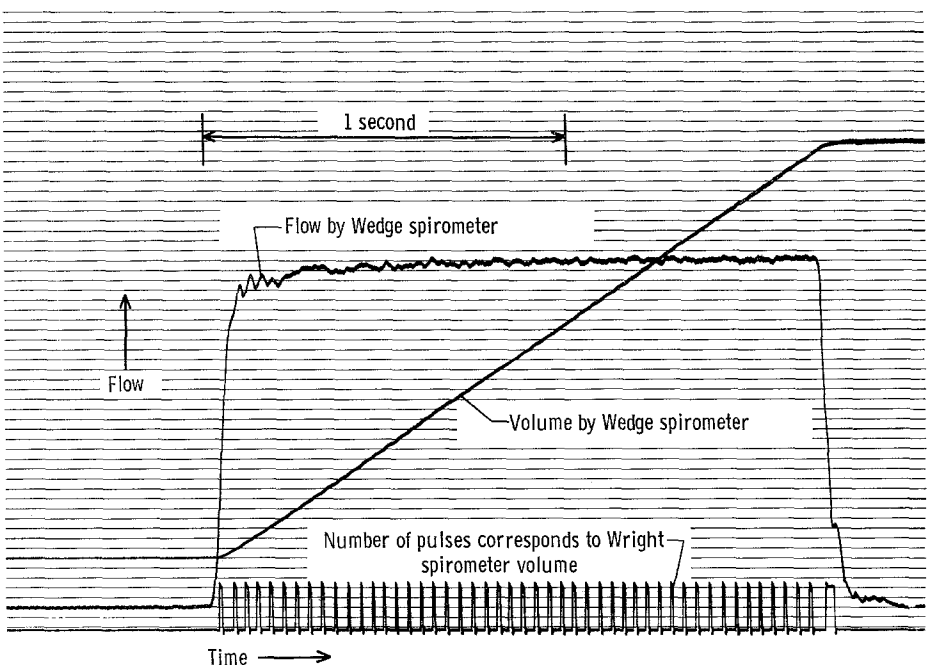

Fig. 3. Typical calibration data.

(1) Small size.
(2) Sufficient ruggedness to operate in the flight environment.
(3) Remote electrical readout.
(4) Must be safe for use in enriched oxygen environments.
(5) Must produce negligible restriction to flow of gas.
(6) Must not encumber pilot (or subject) in any way.

To meet these criteria, the laboratory prototype required two major improvements. First, to enable the signal conditioning electronics to function in the cockpit environment, a discrete component solid-state circuit (Figure 5) was developed, vacuum encapsulated, tested, and flight-qualified (Figures 6 and 7). Suitable adapters and moun-

ting brackets were designed to enable interfacing with military oxygen equipment. For the United States Air Force type breathing oxygen equipment in use at the FRC, the light weight and solidarity of the spirometer design prompted replacement of the standard T-block (Figure 8) with the combination connector adapter and mounting plate shown in Figure 9, complete with Wright Spirometer installed.

The sensor itself required more careful consideration since the turbine shaft bearing could not be completely leak sealed without introducing prohibitively large errors due to shaft friction. During high altitude flights, pressure breathing causes pressure differentials that tend to force oxygen around the turbine shaft into the

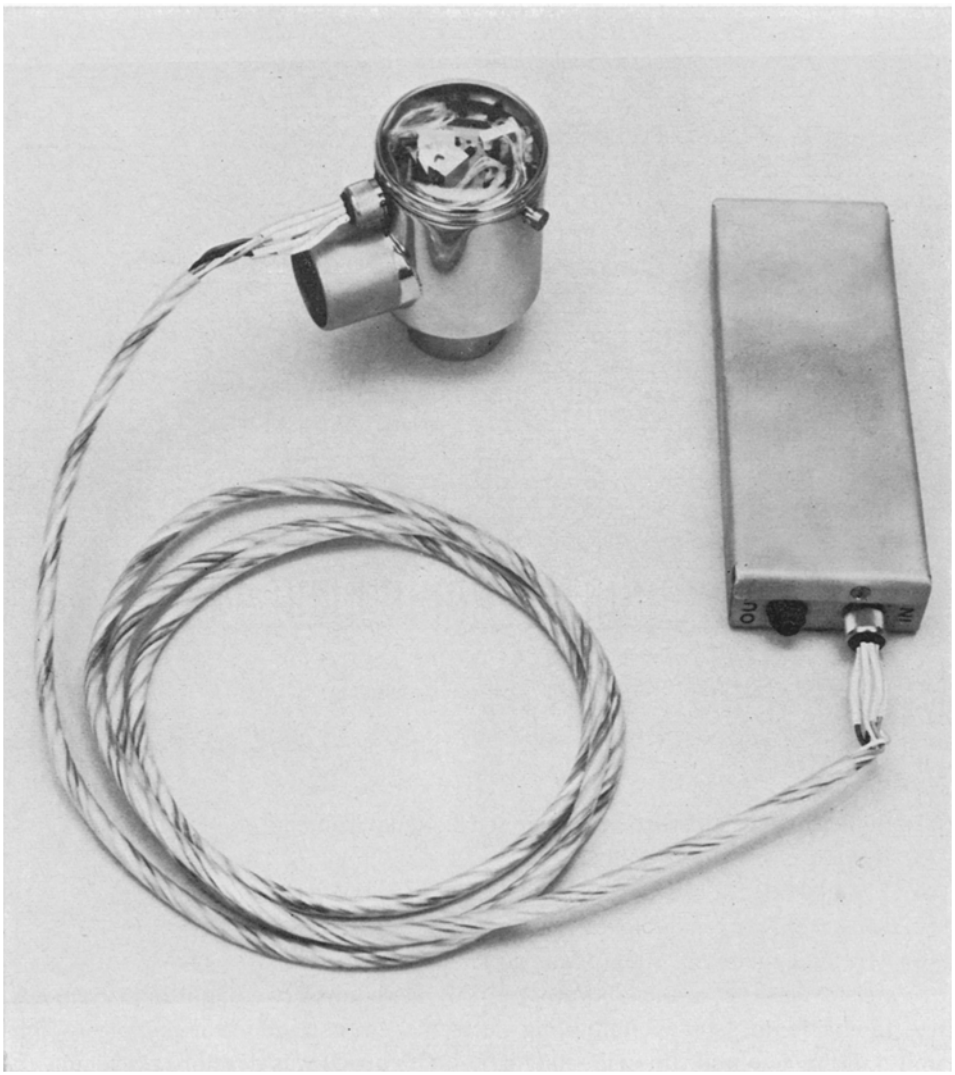

Fig. 4. Laboratory prototype with signal conditioner.

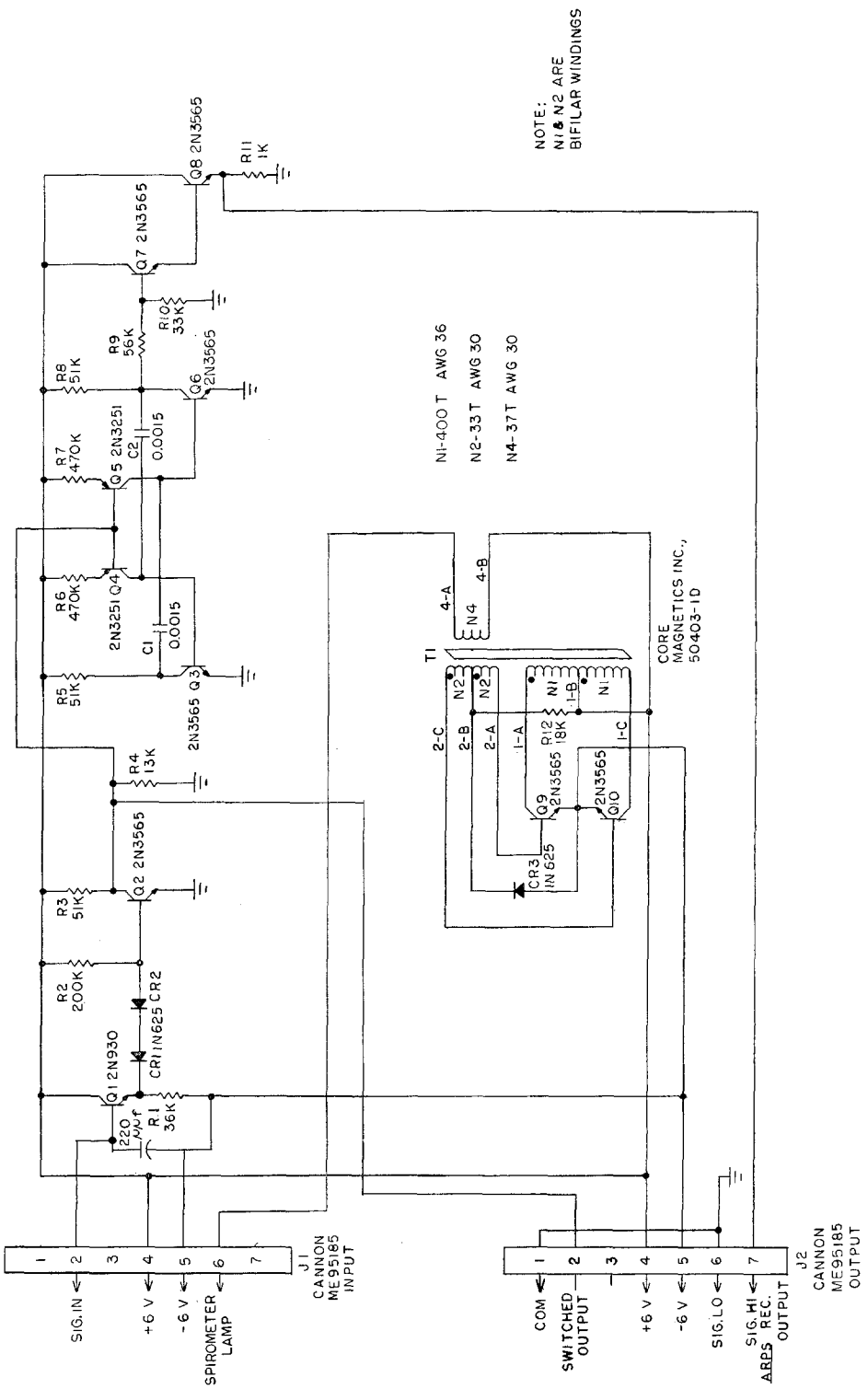

Fig. 5. Signal conditioner schematic.

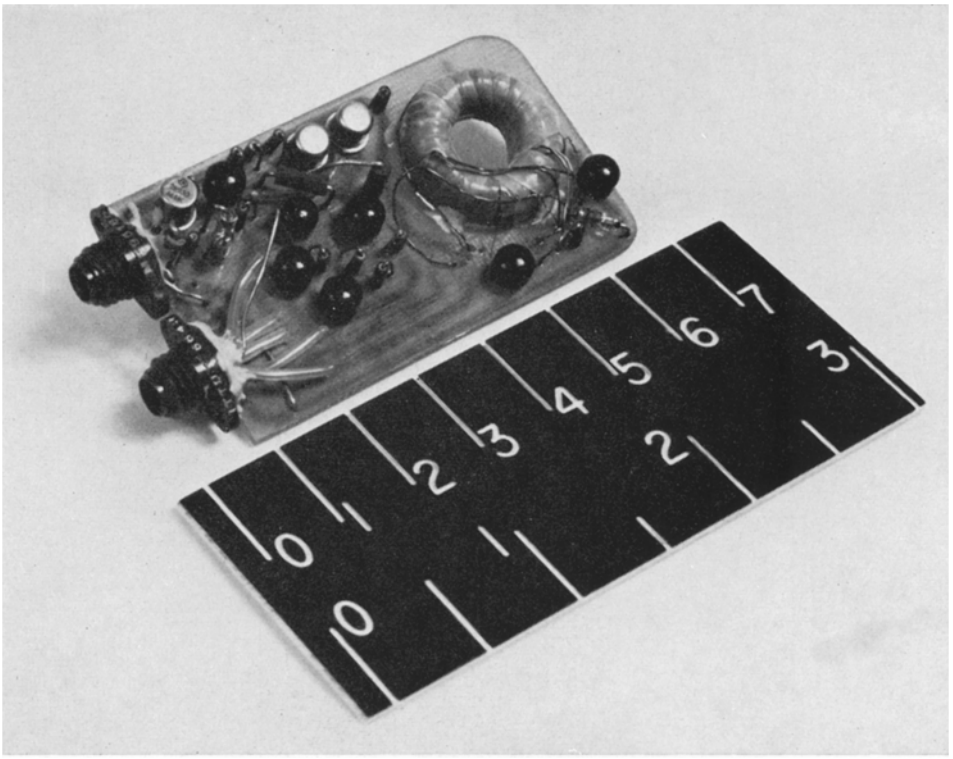

Fig. 6. Flight signal conditioner before encapsulation.

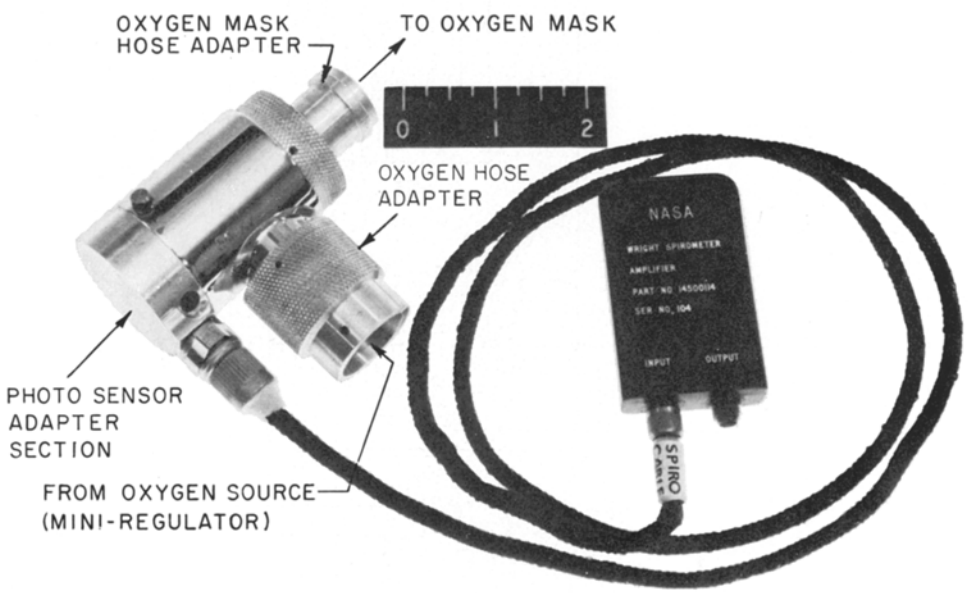

Fig. 7. Completed flight-qualified spirometer and signal conditioner.

Fig. 8. Standard T-block.

Fig. 9. The modified spirometer in place on parachute harness.

photoelectric adapter section. To circumvent the potentially hazardous condition which might result, should the lamp or sensor crack during operation, both the lamp and photosensors were placed remote to the light interruptor wheel. This was accomplished using Lucite light pipes to transmit the light from the lamp through the encapsulating material, past the interrupter wheel, and back to the photosensor (Figure 10). With this module aligned, tested and encapsulated, oxygen could not enter the immediate vicinity of the lamp or photosensor. Sealing this electric adapter section to the modified spirometer housing prevented leakage of oxygen into the photoelectric adapter section without friction loading the turbine shaft. Finally, only the lamp and photosensors were packaged into the adapter section, all other electronics were located in the signal conditioner.

5. Laboratory Testing

Since flight safety is of paramount importance, the sensor assembly was tested for safe operation in pure oxygen with particular regard for the possibility of an enriched O_2 fire. Three conditions are necessary for the occurrence of fire:

(1) Oxygen must be present.

(2) Flammable materials must be present.

(3) Ignition temperatures must be generated.

The photosensor adapter was specifically designed to minimize the second condition and to eliminate the first and third.

The normal operation of the entire system in pure oxygen at 2 atmospheres (25 PSIA) was established in a small chamber capable of withstanding up to 50 PSIA. To

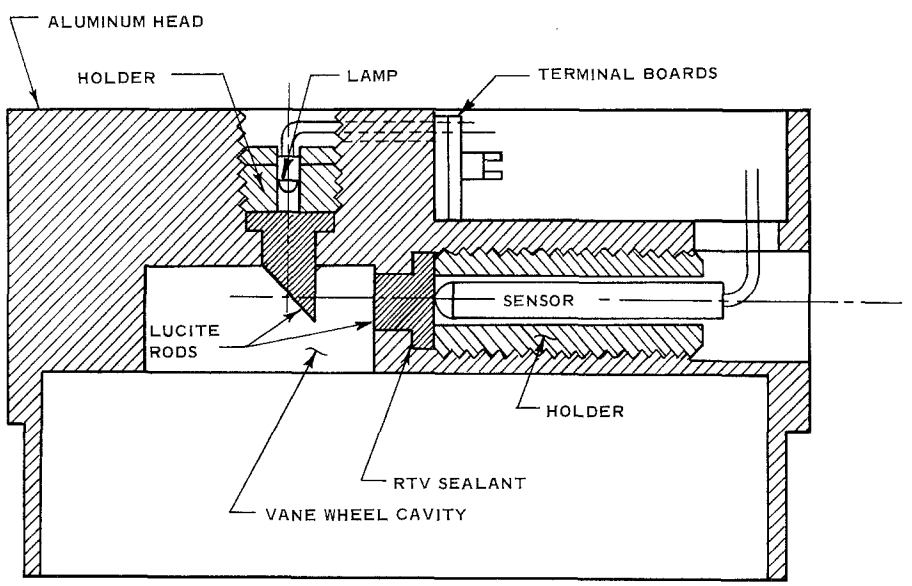

Fig. 10. Photo sensor adapter section.

test the assumption that a fire could not occur even with catastrophic failure of the component in the photosensor adapter section, the following tests were performed:

(1) With the unit operating normally, first the lamp and then the photosensor were broken during operation in pure oxygen at 25 PSIA using a special adapter section containing a solenoid actuated plunger to remotely break either the lamp or photosensor.

(2) Following this, all possible combinations of over voltages (up to 50 volts DC) and shorting of any two of the four connections into the adapter section were accomplished without the production of fire or any surface or core temperature changes as measured by a calibrated thermocouple array.

6. Flight Qualification

Use in pure oxygen necessitates that no hydrocarbon lubricants be used on this device, however, most of the movement is set in jeweled bearings and requires no oil. Prior to flight, each unit is thoroughly cleaned and inspected to assure removal of all toxic materials and organic matter which may be hazardous in pure oxygen. Testing for residue was accomplished using the CEC Model 24-120B Leak Tester. Each unit was then packaged in a clean polyethylene bag and sealed while awaiting flight use.

Five flight units were subjected to a complete preflight calibration developed during testing of the laboratory prototype (Roman and Sato, 1967). Initially, calibration was accomplished before and after each flight; subsequently, this cycle was extended to a one-month interval. After 2 one-hour flights, each unit was completely disassembled, inspected, and a standardized maintenance accomplished, followed by preflight cleaning and packaging.

During twenty hours of initial flight-qualification tests, no failures were observed and no changes noted in the instrument's calibration. There were no effects on crew performance nor were unfavorable comments received from any of the pilots.

7. Operational Experience

Following flight-qualification, the first major use of the modified spirometer was a field monitoring effort involving 75 student naval aviators during their first arrested landings and catapult launches on an aircraft carrier at sea. During this field trial, maintenance was not available for one month and none of the four units were serviced. All units were calibrated prior to deployment and subsequent to return to the FRC. During this study, daily postflight data samples were examined to determine that none of the units had failed overtly.

The protocol for this experiment included practice landings by the students at a field remote from the Naval Air Station (NAS), Pensacola, Florida, the home base. An instrumentation package was attached to the student by an FRC technician and carried by the students during the flight to the remote field. At the field, the students themselves removed the equipment between flights and, subsequently, reinstalled it for

use during practice landings at the field and for return flight to NAS, Pensacola. Since skilled technical help was not available during these flights and the instruments were subjected to considerable rough handling, this operational test was considered extreme.

After return to the FRC, recalibration revealed that one of the four sensors had experienced a baseline change of less than five percent full scale. This was traced to a bent turbine shaft, presumably damaged by rough handling in the field. With the exception of this single correctable incident, operation of the modified Wright Spirometer throughout this experiment was completely free of failures. A sample of the data collected is shown in Figure 11.

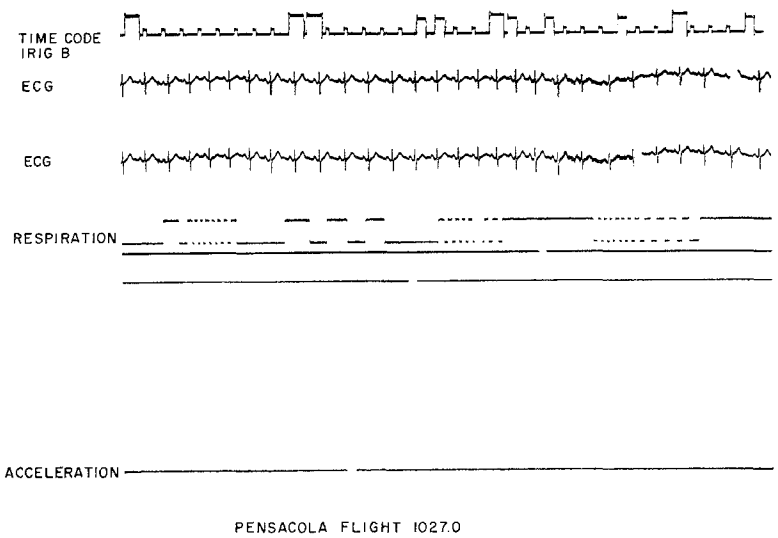

Fig. 11. Sample of flight data showing typical spirometer output (center trace).

During the summer and fall of 1968, a local flight monitoring project called 'Cyclops I' was accomplished using this sensor system as part of the biomedical instrumentation. In this study, the cardiorespiratory stresses associated with the acute loss of vision in one eye were measured. This experiment extended over several months with the sensors subjected to a routine one month calibration and maintenance cycle. There were no failures observed during this six-month experiment.

8. Conclusions

A miniature respiratory rate and volume sensor is described that weighs only 172 grams and is sufficiently rugged to perform in the flight environment. The safe operation of this device as an integral part of both Air Force and Navy pilots' breathing oxygen systems is demonstrated. Only simple modifications are required to the basic instrument that can be accomplished in any well equipped instrumentation laboratory.

Finally, the measurement of respiration minute volume in flight is demonstrated.

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