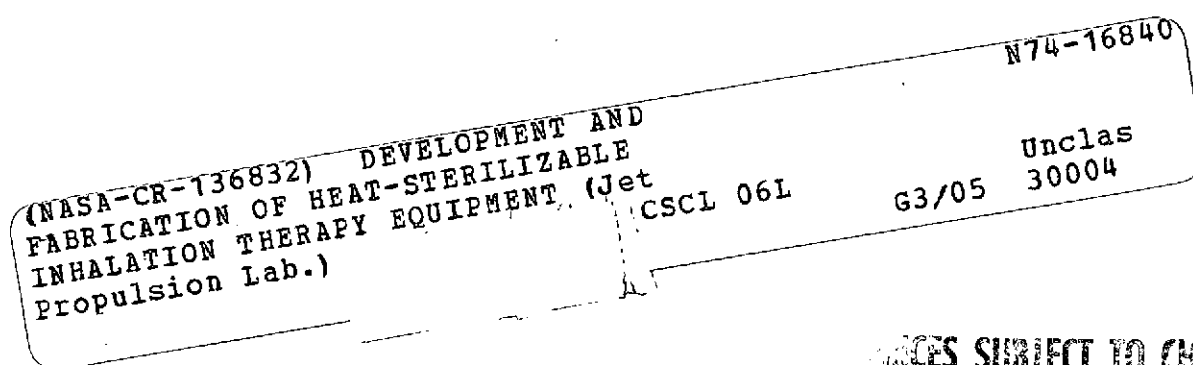NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Memorandum 33-670

Development and Fabrication of Heat-Sterilizable Inhalation Therapy Equipment

A. S. Irons

JET PROPULSION LABORATORY

CALIFORNIA INSTITUTE OF TECHNOLOGY

PASADENA, CALIFORNIA
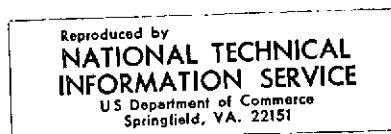
January 15, 1974

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PREFACE

The work described in this report was performed by the Project Engineering Division of the Jet Propulsion Laboratory.

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FOREWORD

In recent years the Jet Propulsion Laboratory has been encouraged by its sponsoring agency, the National Aeronautics and Space Administration, to apply a portion of its knowledge and abilities to important civil problems. In such efforts, JPL works closely with members of relevant professions, representatives of the public agencies, and, under special circumstances, industrial organizations affected by the problems. When a feasible solution has been demonstrated, the transfer of technology from the research and development setting to the commercial marketplace is encouraged.

The development effort described herein exemplifies this approach. In the medical field, it has been known for some time that certain devices used in patient care are not sterilizable in all cases and that their use consequently entails a hazard of infection. One such piece of equipment is the intermittent positive pressure breathing (IPPB) ventilator. In the effort described in the present document, JPL, utilizing specialized materials and techniques developed for spacecraft sterilization, modified the design and materials of construction of a widely used model of the IPPB so as to render it 100% heat sterilizable. The manufacturer, the Bird Corporation, cooperated with JPL throughout the effort, providing essential information, equipment, and services. The Bird Corporation has now adopted dry heat sterilization as a major design criterion for all its products wherever feasible. JPL, pursuant to its obligation to make information concerning this technology generally available to manufacturers of medical equipment, has prepared this document.

ACKNOWLEDGMENTS

SUMMARY AND CONCLUSIONS

Hospital-associated infections rank as a major cause of illness in the United States. Over 3.5 million patients, it is reported, are afflicted annually. The overall economic cost approaches 10.5 billion dollars per year.

JPL has conducted an investigation under NASA Applications Technology Office sponsorship into hospital-acquired infections and the possibility of reducing the number of such infections and the consequent cost by the application of NASA-developed materials, design, sterilization, and environmental control techniques. The study revealed that a major contribution to the dissemination of infectious organisms was being made by inhalation therapy equipment which could not be reliably sterilized. This type of equipment, because of its design and materials of construction, could not be sterilized by heat but instead had to be decontaminated by less efficient methods which utilized chemical or gaseous disinfectant or decontaminating agents.

As a result of the initial phase of this study, it was decided by JPL and NASA to attempt to develop a completely heat-sterilizable intermittent positive pressure breathing (IPPB) ventilator in an effort to reduce the number of hospital-acquired infections.

The task of developing and producing a heat-sterilizable IPPB machine employed a coordinated team effort approach. To maintain maximal technical support in all desired areas, a working triad was formed to define the medical, manufacturing, material, and design problems involved in producing such a ventilator. The teams consisted of medical doctors who specialize in inhalation therapy; design and engineering personnel from a manufacturer of inhalation therapy equipment; and JPL sterilization, materials, and design personnel.

After appropriate changes in materials and design were made, six prototype units were fabricated and were successfully field tested in local hospitals.

Most components of the modified ventilators are compatible with existing machines. In all but a few instances, such as installation of bacteria-retentive filters and a modified venturi, the changeover from non-heat-sterilizable to sterilizable units was accomplished by replacement of heat-labile materials with heat-stable materials.

The results of this project have shown that, by the use of alternative materials and concomitant modification of design, it is possible to convert an important non-heat-sterilizable medical device to one that is completely heat sterilizable, thus permitting elimination of a potential source of hospital infections. Information gained from this study indicates that application of the same technologies successfully used to produce a heat-sterilizable IPPB unit could permit the development and fabrication of other heat-sterilizable medical equipment to replace heat-labile apparatus now in use.

As a direct consequence of this task and the practical application of relevant NASA-developed spacecraft sterilization technologies to the medical device field, the Bird Corporation, manufacturer of the patient ventilators chosen for study and redesign, has been thoroughly convinced* that the dry heat method of sterilization is far superior to any other method or methods currently available and in use for their equipment. Consequently, the Bird Corporation intends to incorporate dry heat sterilization capability as a major design criterion in all of its products wherever possible. Because of the enthusiasm generated by JPL for the heat sterilization concept, the Bird Corporation has initiated a parallel project. This consisted of converting a smaller, less complex (Mark I) ventilator design to heat sterilizable materials. It is planned to produce several hundred of these smaller units and to introduce them to the medical field on a large scale for evaluation. Bird has expressed confidence in dry heat sterilization as the most efficient and effective method for sterilization of not only inhalation devices but most other hospital equipment as well.

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*See letter, Appendix A.

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ABSTRACT

More than 3.5 million patients in the United States are reported to be afflicted with hospital-associated infections each year, resulting in an overall cost approaching 10.5 billion dollars per year. A considerable amount of medical apparatus, because of its incompatibility with reliable sterilization methods, is implicated in the transmission of disease-producing microorganisms. One such device, an intermittent positive pressure breathing (IPPB) apparatus, was modified in conjunction with a manufacturer to demonstrate the feasibility of converting an existing apparatus to one which is compatible with dry heat sterilization. This sterilization method has been proven to be capable of highly efficient, consistent, reliable, total destruction of all bacterial and viral forms of life.

NASA-developed material, design, and sterilization technologies were utilized to effect the appropriate modifications to this apparatus. Prototype units produced are capable of withstanding repeated sterilization cycles at 125°C. The results of hospital field testing substantiated the effectiveness of this effort.

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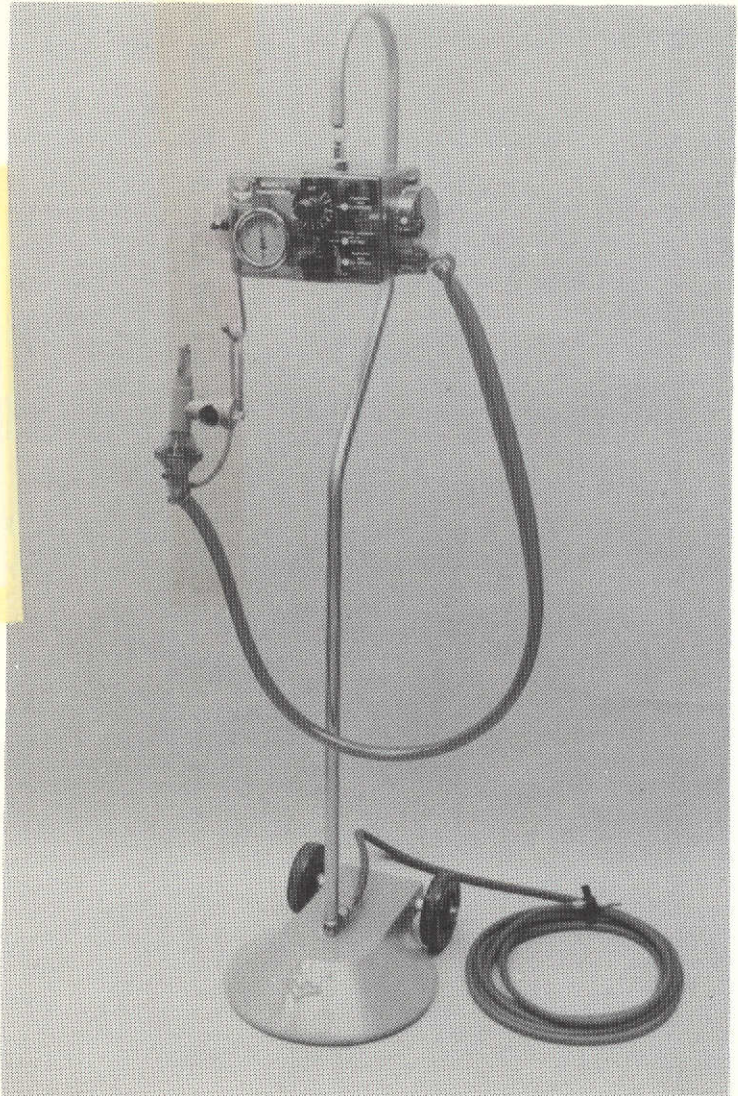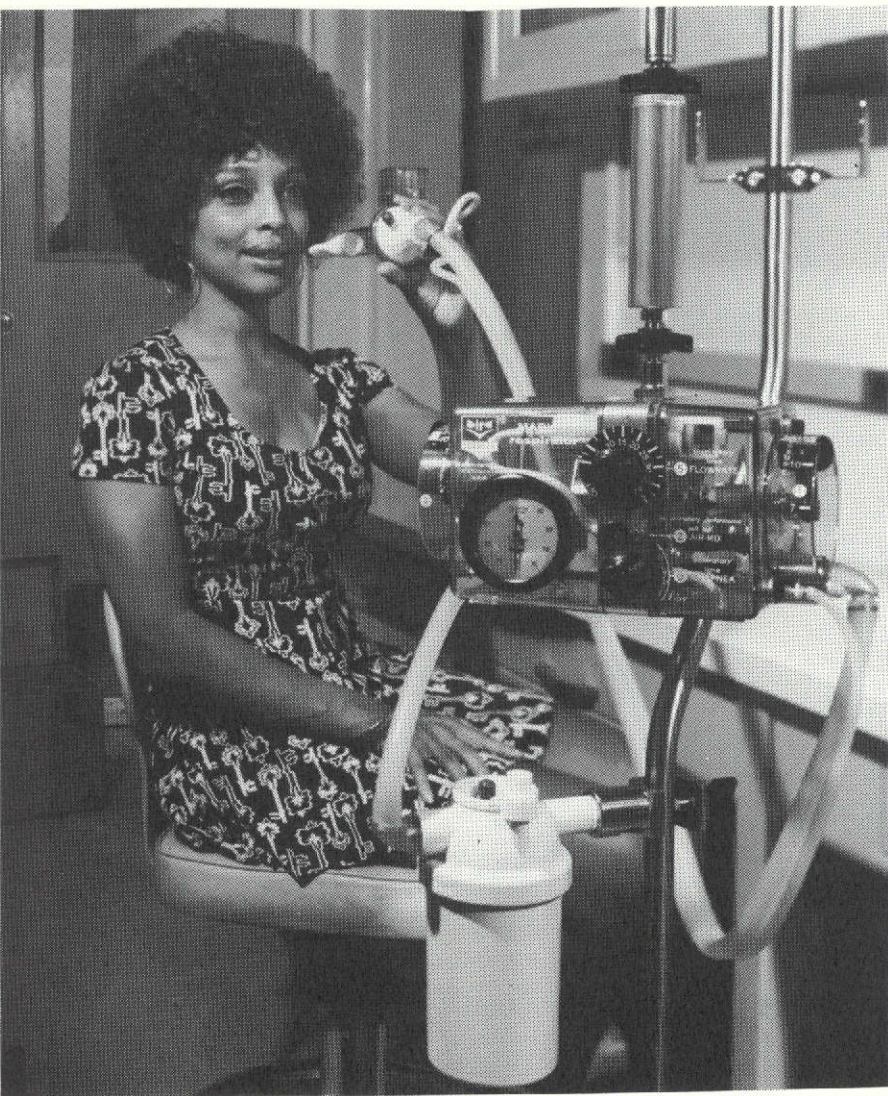
Frontispiece.   Original design (left) and final design (right)

SECTION I

STATEMENT OF THE PROBLEM

It has been reported that more than 3.5 million patients in the United States are afflicted with hospital-associated infections each year, resulting in an overall cost approaching 10.5 billion dollars per year (Ref. 1).

Constant awareness of the modes of dissemination and transmission of disease-producing organisms in health care facilities, and a continuing search for methods to prevent their spread, are prerequisite to reducing this infection rate and planning a defense against the spread of infectious agents from one person to another within these facilities.

Prior to the work reported here, studies had been conducted to investigate the newest concepts of medical-facility-induced infections and the relationship between infection rate and microbial contamination in the environment (Ref. 2). These studies revealed the existence of a major factor in the dissemination and transmission of infectious organisms. This factor is non-heat-sterilizable medical equipment, and is of great concern to medical personnel. In many types of induced infections, it has been implicated as the primary transmitter of infectious organisms. Such equipment, which is rendered non-heat-sterilizable by virtue of materials of construction or design of the equipment, must be decontaminated by chemical agents. Chemical agents cannot always be relied upon to sterilize because of such things as physical complexity of the equipment (which may prevent decontamination of all parts), the types and numbers of microorganisms present, or other conditions which may exist at the time of sterilization is attempted. Medical apparatus which have been implicated in the spread of infectious organisms include respiratory, inhalation therapy, and anesthesia equipment (including the ancillary humidifying apparatus); incubators; nebulization equipment; and mist therapy units. Cystoscopes, suction equipment, and air compressors have also been implicated but not to such a high degree.

A definitive examination of the medical literature pertaining to non-heat-sterilizable, infection-implicated instruments revealed that the most culpable

class of instruments was inhalation therapy and anesthesia equipment and within this class, more specifically, Intermittent Positive Pressure Breathing (IPPB) apparatus (Refs. 3-7). It was also determined that a large proportion of the medical professionals knowledgeable in inhalation therapy consider nonsterile IPPB apparatus to be a major contributor to, and source of, infection. Many of these experts believe that this apparatus is involved primarily because it is incompatible with reliable sterilization processes and this incompability prevents complete removal or inactivation of infectious microorganisms associated with the equipment (Tables 1 and 2). Evidence derived from microbiological studies also indicates that the remaining viable organisms can multiply rapidly in a high humidity environment such as that present in the machine (Ref. 8).

Intermittent positive pressure breathing devices are used to treat asthma, emphysema, obstructive pulmonary disease, and some cases of respiratory failure. They can breathe for a patient or be used to introduce oxygen, air, or medication into the lungs. They are required in many cases to ventilate critically ill patients with an indwelling endotracheal tube or tracheostomy, or postoperative patients with respiratory problems.

These devices can be adjusted to assist or control the rate and depth of pulmonary ventilation. Both the inspiratory and expiratory phases of spontaneous respiration can be mechanically assisted by this device to increase the gas volume during inspiration and enhance the outward flow of gases from the lungs during expiration. When a spontaneous respiratory pattern ceases to exist the patient may have both the rate and depth of pulmonary ventilation controlled mechanically by the unit. The difference between normal respiration and that produced by the machine can be seen in Fig. 1.

The ventilator is actuated by differential gas pressure and needs no other power source; therefore, it is safe to use in the presence of anesthetic gases. The pattern of gas flow which actuates the machine can be seen in Figs. 2 and 3. A detailed functional diagram appears in Fig. 4.

Table 1. Methods used by cooperating hospitals to clean and decontaminate IPPB apparatus

Hospital Code Number	Number of of Therapists	Number of Procedures Per Month	Types of Equipment Used	Types of Equipment Sampled	Basic Cleaning Procedure	Disinfectant Used to Decontaminate	Was Ethylene Oxide Used to Sterilize After Decontamination?	How Equipment Was Packaged for Storage
1	30	7000	Bird Bennett	Bennett	Disassemble equipment and soak in Cidex 10-15 min. Wash in detergent, rinse and drip dry.	Cidex	No	No packaging
2	9	1600	Bennett	Bennett	Soak and wash in Micro-Quat. Soak in Cidex and rinse in cold running water.	Micro-Quat Cidex	Yes	No packaging
3	2 Therapists 8 Technicians	1600	Bird Bennett	Bird	Soak in detergent and Cidex and wash manually. Put equipment in dishwasher, add Cascade detergent, and wash full cycle at 60°C. Air dry with compressed air. Place in bags.	(Data missing)	Yes	Plastic bags
4	3	475	Bird Bennett	Bird	3 Tub Cleaning Procedure: 1st Tub - Soak 10 min in 15% Cl_2, rinse in H_2O for 15 min; 2nd Tub - Soak for 2 min in 15% Cl_2 and rinse; 3rd Tub - Rinse in 1:1000 Zepheran and air dry.	Chlorine Zepheran	No	Plastic bags
5	12	425	Bird Bennett	Bird	Wash in hot Dreft solution, rinse in tap water, force air dry and steam or gas sterilize.	Dreft	Yes	Plastic heat-sealed bags and Tupperware boxes
6	(Data missing)	(Data missing)	Bird Bennett	Bird	Manual prewash; mechanical wash and rinse.	(Data missing)	Yes	Polyethelene bags

[*] These data on IPPB apparatus were the result of studies conducted by the American Public Health Association in conjunction with the United States Public Health Service.

Table 1. (Contd)

Hospital Code Number	Number of of Therapists	Number of Procedures Per Month	Types of Equipment Used	Types of Equipment Sampled	Basic Cleaning Procedure	Disinfectant Used to Decontaminate	Was Ethylene Oxide Used to Sterilize After Decontamination?	How Equipment Was Packaged for Storage
7	14	1400	Bennett II Bird Emerson	Bennett	Soak 24 hours in Cidex, 10 min. in Instra-San, scrub, rinse in H_2O, soak in Cidex 10-20 min., soak in Instra-San 10 min., rinse in H_2O, and dry by hot air.	Instra-San Cidex	No	Plastic bags
8	12	1800	Bennett Bird Air Shields Ohio	Bennett	Wash in ultrasonic cleaner for 7 min, soak in Cidex 60 min., rinse, and air dry.	Cidex Morcept	Yes	Plastic bags and plastic boxes
9	(Data missing)	240	Bennett	Bennett	Soak 30 min. in Micro-Quat, brush, rinse in hot H_2O, and air dry.	Micro-Quat	Yes	Plastic wrapped

Table 2.   Types of organisms isolated from IPPB units after cleaning and decontaminating

Hosp. No.	Types of Part Assayed and Results									Types of Organisms Isolated
	Main Line Tubing			Nebulizers			Manifold			
	Number Tested	% of Parts Positive	Number of Org. Per Sample*	Number Tested	% of Parts Positive	Number of Org. Per Sample*	Number Tested	% of Parts Positive	Number of Org. Per Sample*	
1	23	52	0-200	23	48	0-100	23	26	0-125	Staphylococcus epidermidis, Bacillus, Actinomyces, Micrococcus, and Alcaligenes species
2	20	50	0-7350	14	50	0-50,000	20	80	0-25	Klebsiella-Enterobacter group, E. coli, Staph. aureus, Bacillus, Gaffkya, and Pseudomonas species and diphtheroids
3	25	16	0-1000	25	32	0-2600	25	40	0-500	Staph. epidermidis, Klebsiella-Aerobacter group, Bacillus, Corynebacterium, Streptococcus, and Pseudomonas species
4	(Data not reported as requested)									
5	(Data not reported as requested)									
6	21	(Data missing)	0-10	(Data missing)	(Data missing)	0-500	(Data missing)	(Data missing)	0	Staph. albus, Klebsiella group, Bacillus, and Enterobacter species
7	19	53	0-14,080	20	50	0-60,000	20	55	0-14,400	Staph. epidermidis, Alcaligenes fecalis, Enterobacter cloacae, and Bacillus species
8	27	4	1400	27	40	0-100	27	22	0-40	Strep. viridans, Gaffkya tetragena, Bacillus megaterium, Corynebacterium Hoffmannii, Staph. albus, Pseudomonas, and Flavobacterium species
9	10	10	0-680	(Data missing)					(Data missing)	Staphylococcus species

*This is not to be construed as total present per part tested.

Fig. 1. Normal respiration vs. IPPB pressure cycles
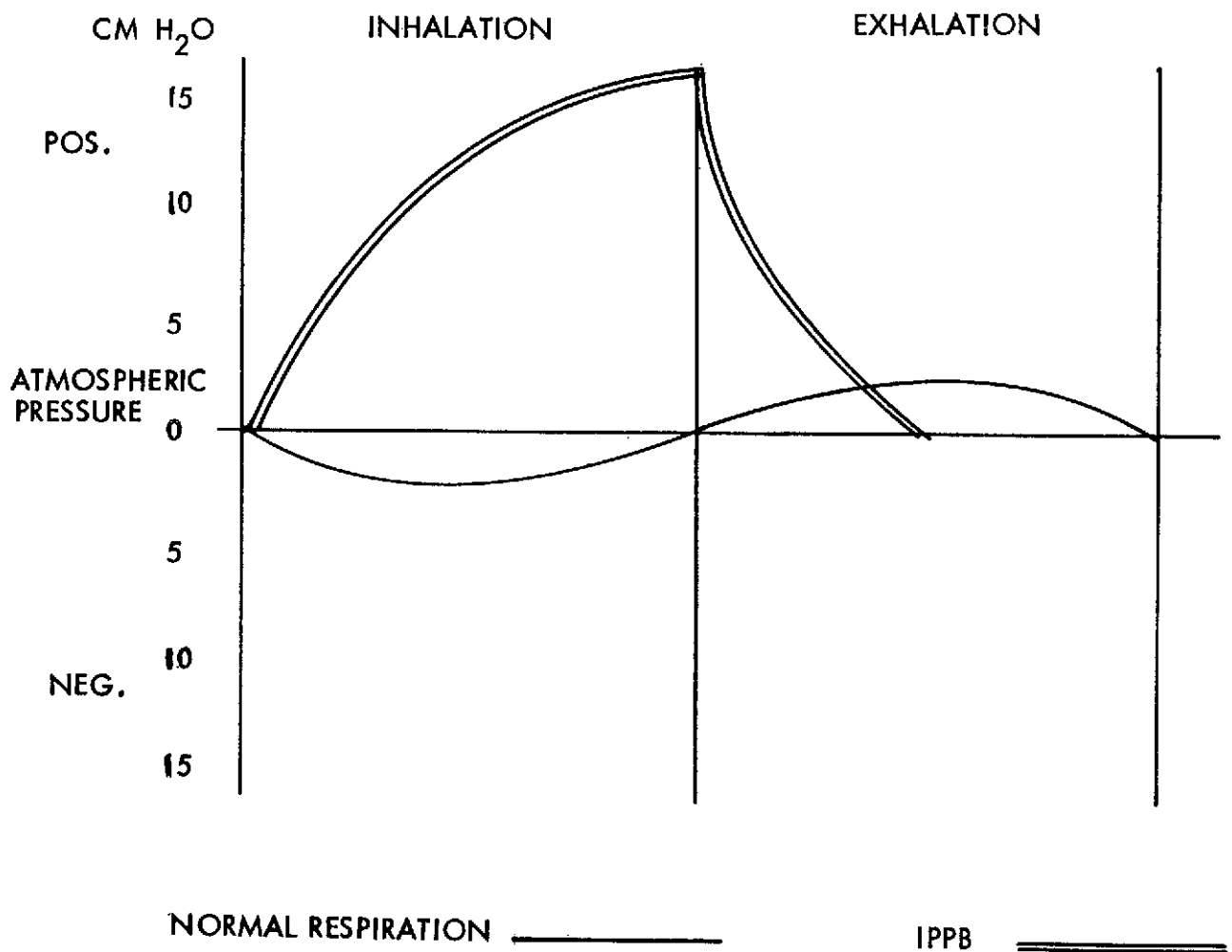
During use of IPPB the pressure within the chest's airways is positive during both inhalation and exhalation.

During normal respiration a negative pressure within the airways of the chest is normal during inhalation, becoming positive during exhalation.

AMBIENT AIR

WATER

INHALATION

EXHALATION
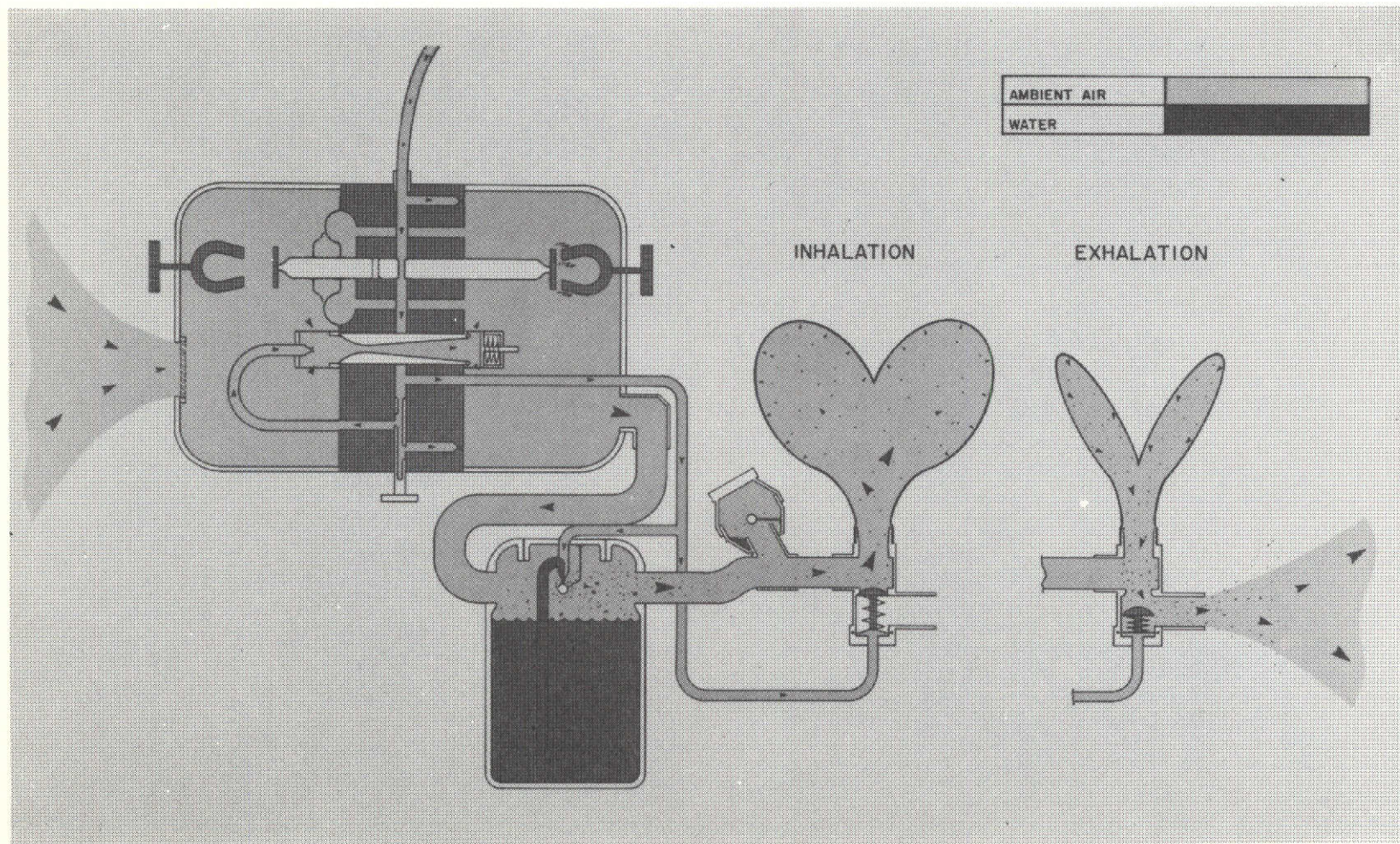
Fig. 2. Existing configuration
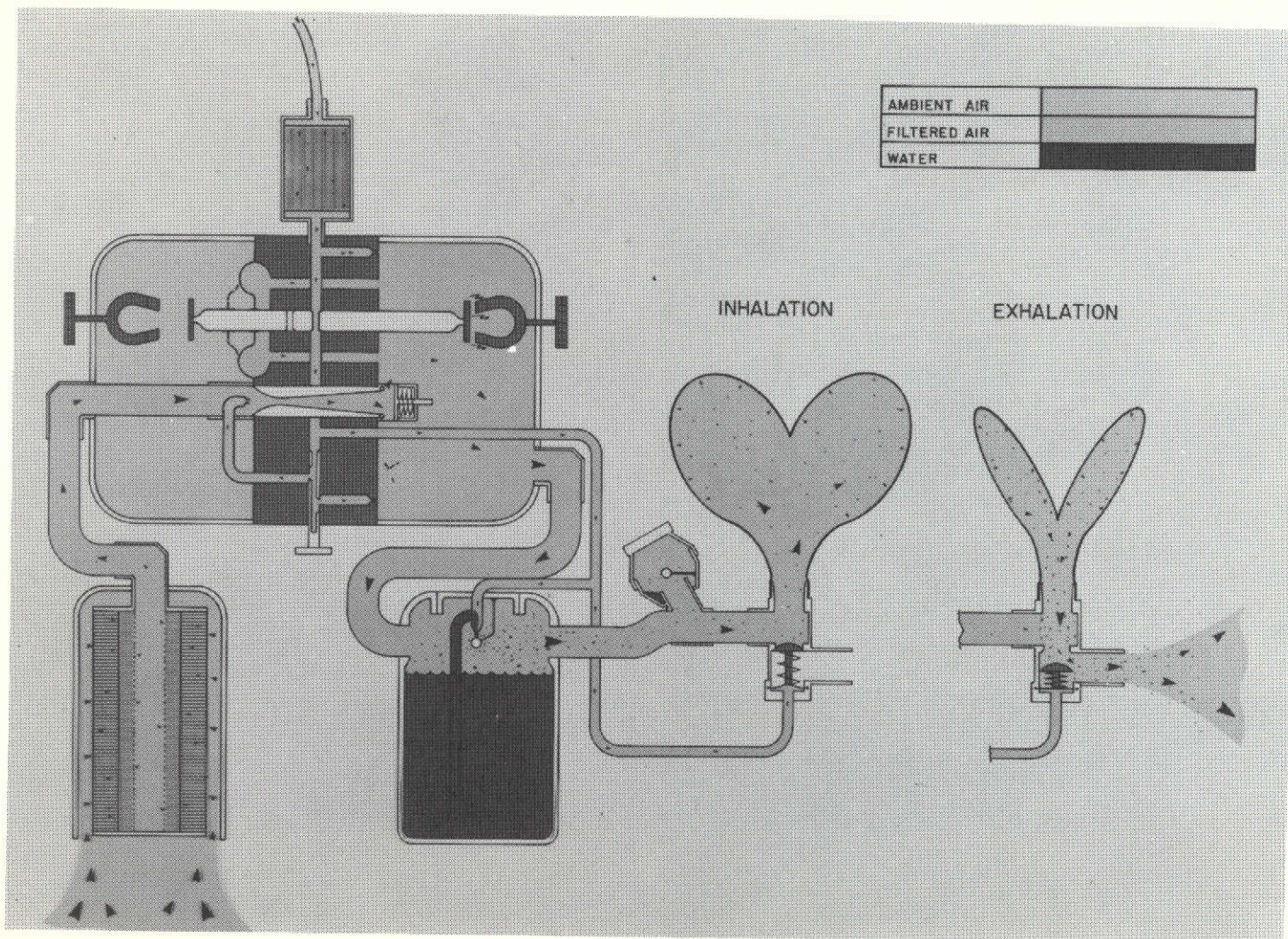
Fig. 3. Modified configuration
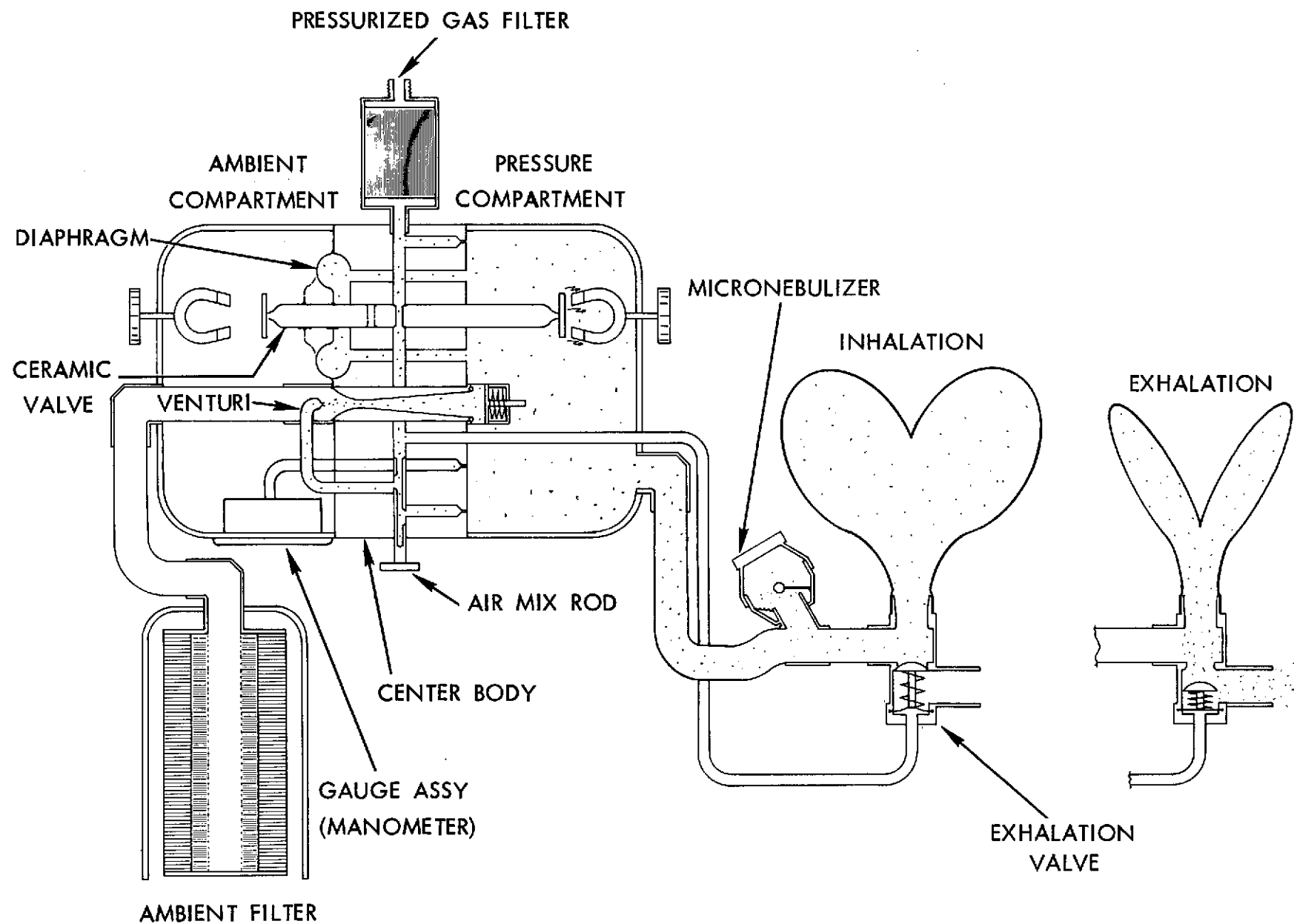
Fig. 4.   Detailed diagram of modified unit showing
ambient filter, pressurized filter, and
modified (sealed) venturi

SECTION II

TASK OBJECTIVE AND APPROACH

A. OBJECTIVE

The objective of this task was to design and produce a completely heat-sterilizable IPPB apparatus made up of NASA-proven dry-heat-sterilizable materials.

B. OVERALL TASK APPROACH

To meet this objective, it was deemed necessary to examine existing ventilators in order to identify those parts which were not compatible with either steam under pressure or dry heat; to determine the reasons for incompatibility; to propose changes in materials and design as required; to complete a preliminary design incorporating the proposed changes; and, finally, to build and field test a prototype unit incorporating all the suggested changes. An additional step was to define and prove out a heat-sterilization time and temperature that would not damage the apparatus and would produce rapid, consistent sterilization.

For the task of developing and producing a heat-sterilizable IPPB machine, a coordinated team effort approach was employed. To maintain maximal technical support in all desired areas, a working triad was formed to define the medical, manufacturing, material, and design problems involved in producing such a ventilator. The teams consisted of medical doctors who specialize in inhalation therapy; design and engineering personnel from a manufacturer of inhalation therapy equipment; and JPL sterilization, materials, and design personnel. JPL has had extensive experience in developing sterilization methods and requirements, as well as in determining materials compatibility (Refs. 9, 10). This, combined with a knowledge of the design requirements of complex sterilizable space hardware, provided the background of information and experience required to make a definitive study of such a complex equipment as an IPPB apparatus and to determine the feasibility of making it heat sterilizable.

A review of the design of the apparatus by JPL materials and design personnel indicated that the device could probably be made dry heat sterilizable by certain design changes and the use of existing materials, proven by JPL's Materials Section to be capable of withstanding sterilization temperatures for long periods without degradation or production of toxic by-products.

The manufacturer of the equipment used in this study furnished all the machines, parts, and technical assistance required, on a no-cost to JPL basis, and agreed to build prototype units based on JPL's suggested modifications. He also made a positive commitment to explore the commercial feasibility of using the concepts and approaches developed by the team and to permit the development reports to appear in the open literature so that other manufacturers of this type of equipment could benefit from the study. In addition, the manufacturer provided a complete set of drawings of his equipment, and gave the reasons for his choices of materials and his design rationale.

C. OVERALL TASK DISCUSSION

1. Task Structure

This task was structured to include and give consideration to the following actions:

1) Enlist the aid of medical personnal and gain their support.
2) Gain the support of medical equipment manufacturers.
3) Form working groups of medical, industrial, and JPL personnel.
4) Identify the major elements of work to be performed.
5) Determine and designate the responsibilities of the working teams and team members.

2. Medical Team Personnel and Responsibilities

After it was established that the medical equipment to be worked with would be an IPPB apparatus, it was necessary to contact inhalation therapy personnel at various hospitals to enlist their aid in defining their needs and requirements. Four inhalation therapy departments of hospitals in the Los Angeles

area were visited and discussions were held with inhalation therapists, as well as directors of the departments. A team composed of the directors of inhalation therapy from each of the four hospitals was formed and they agreed to assume the following responsibilities:

1) Render technical assistance to the JPL team by demonstrating how the machines are used, disassembled, cleaned, decontaminated, reassembled, and put back into use.

2) Indicate the most acute problem areas in terms of contamination levels within the machine, difficulty in cleaning, and prevention of contamination of "clean" machines by patients and personnel.

3) Point out areas of most intimate contact between patient and machine that appear to present the greatest potential hazard for recontamination of the apparatus.

4) Make equipment available to the JPL team as required for non-destructive examination and experimentation.

5) Give professional advice and guidance as required.

6) Render judgment as to the usefulness and applicability of new materials and designs as developed.

3. Considerations Involved in Determining Manufacturers' Acceptability

Based on discussions with the above and other medical personnel about the type of equipment used in their facilities, a list of IPPB apparatus manufacturers was prepared.

Before the manufacturers of this type of ventilating equipment were approached, criteria were developed to determine which companies would be most acceptable to JPL and the medical team. The criteria used to establish preference were as follows:

1) Medical team's experience with company and equipment.

   a) Performance of equipment under conditions of use, i.e., whether the device adequately and easily does what it is supposed to do.

b) Reliability of apparatus and company.

c) Impressions of company personnel (capabilities and cooperativeness).

d) Personal contacts - ease of working with company personnel and satisfaction with their response to hospital and medical personnel demands.

2) Geographical location of manufacturing facility (proximity to JPL).

3) Ease of demonstration (device easy to work with - not complex).

4) Percent of market (number of machines in use).

5) Degree of commitment of manufacturer - willingness to cooperate in new developments, as determined from prior activities.

On the basis of the above criteria, four companies were considered and contacted; however, it was subsequently decided to work with only one company. The decision to choose only one manufacturer was based on the following rationale:

1) IPPB devices made by different manufacturers are not made of the same materials and are of different designs, thus making it complex and costly to work with more than one manufacturer's apparatus.

2) JPL manpower and travel costs would be prohibitive if several companies, widely separated geographically, were involved in the study. Two manufacturers of IPPB apparatus are located in California. Both were contacted. One agreed to the JPL terms and conditions; the other was not interested in cooperating in the study under the terms and conditions stipulated by JPL.

3) The "triad concept," in which JPL, doctors, and manufacturers' personnel teams would work closely together, would be almost impossible to attain because of the scheduling difficulties that would arise when attempting to conduct meetings and seminars to be attended by team members from several companies located in widely scattered geographical areas.

4) A manufacturer could not be expected to expend large sums of money and time traveling from widely separated geographical areas to Southern California to attend the all-important meetings of the working group.

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5)   If too many individuals with vested interests were involved, the spirit of cooperation and team rapport might be severely diluted.

On the basis of the above criteria and rationale the Bird Corporation, Palm Springs, California, was chosen.

4.   Why Bird Corporation?

1)   Our survey indicated that the majority of IPPB apparatus used in health care facilities and teaching institutions in the Los Angeles area is manufactured by this one company. Thus, it follows that the greatest number of patients would benefit from this task if this company's apparatus was studied and made heat sterilizable. By working with this one organization, a completely successful program could mean the greatest potential for <u>reduction in infections</u> caused by contaminated IPPB apparatus. It was concluded that the maximum technology transfer impact per dollar would be realized by this working arrangement.

2)   The manufacturer is located in Southern California in close proximity to JPL and members of the medical team, thus simplifying working arrangements.

3)   A minimum of time and money would be required for travel and transportation of equipment to and from JPL.

4)   All members of the medical team or their staffs involved in this study are fully acquainted with the construction and function of this equipment and most are able to disassemble, repair, and reassemble the equipment as required, thus aiding in the evaluation of proposed changes in the apparatus in relation to probable effects on patient response.

5)   A firm commitment was received from Bird Corporation to work under the following terms and conditions stipulated by JPL.

The manufacturer agreed to work with JPL on a no-cost-to-JPL basis and:

1)   Furnish all the required IPPB apparatus free of charge for JPL use.

2) Give a positive commitment to explore the commercial feasibility of using the concepts and approaches developed by the JPL team and to issue a product development report.

3) Furnish a complete set of working drawings.

4) Give reasons for choice of materials.

5) Give the design rationale.

6) Permit unlimited consultation with the company's designers.

7) Furnish information on cost analysis and marketing methods if and as required.

8) Permit public information release of any new technology developed as a result of the study.

In addition to the above, the following specific responsibilities of the manufacturer's team were developed during meetings between JPL and their engineering, design and fabrication personnel. They agreed:

1) To render technical assistance to the JPL team by furnishing equipment needed for experimentation and engineering assistance as and when required by JPL material and design personnel.

2) To furnish information on the physical and chemical properties of the materials used in present as well as future or proposed designs if not of a proprietary nature and if release of such information did not constitute a patent infringement.

3) To render opinions as to the usefulness, applicability, and impact on cost of proposed materials and designs.

The JPL team consisted of one materials engineer, one design engineer, and one life science engineer (microbiologist) serving as overall task manager. The team's responsibilities were to

1) Examine existing equipment and, with the aid of the other team, identify those parts which were not heat sterilizable and the reasons for sterilization incompatibility.

2) Identify the changes necessary to make those parts heat sterilizable.

3) Determine alteration feasibility and identify materials which are heat sterilizable and which could be substituted for existing heat-labile materials.

4) Suggest changes in design which are necessary to produce a heat-sterilizable machine.

5) Define new material and fabrication approaches.

6) Establish a dry heat sterilization cycle capable of achieving consistent sterility of the equipment.

7) Generate a list of heat-sterilizable components which were not previously heat sterilizable.

8) Present all recommendations, materials, and methods to the medical profession and manufacturing teams for their use.

As a result of this team effort, it was established that the medical profession and the manufacturers of IPPB devices would be receiving the benefit of JPL's experience in the development of heat-sterilizable materials, the design of heat-sterilizable spacecraft, and the development of improved sterilization methods. In addition, they would have access to the large amount of information already in existence at JPL on polymeric materials in common use in the aerospace industry that have been tested and found to be able to withstand thousands of hours at the suggested sterilization temperature without alteration of physical properties.

SECTION III

MICROBIOLOGICAL PROCEDURES AND RESULTS

The temperature needed to achieve consistent sterilization of any equipment, especially within a reasonable period of time, directly affects its material and design requirements. Therefore, to determine the equipment requirements, it was necessary to first define the approximate sterilization cycle. Initial determinations of the times and temperatures required to sterilize IPPB apparatus were based on the death rates of organisms isolated from "patient used", contaminated current-model breathing head assemblies obtained from one of the hospitals cooperating in the study.

The death rate or D value of an organism is the time in minutes at a constant temperature necessary to destroy 90% of the organisms present. On semilog paper, the number of organisms is plotted on the logarithmic scale against time in minutes on the linear scale, and the best straight line is drawn through them. The D value is the time in minutes required for this curve to traverse one logarithmic cycle. A subscript denotes the temperature to which D relates. For example, D_{100} refers to the death rate at 100°C, while D_{125} refers to the death rate at 125°C.

A.   PROCEDURES USED FOR MICROBIOLOGICAL ASSAY OF INTERMITTENT POSITIVE PRESSURE BREATHING APPARATUS

Ten current-model units, with the configuration shown in Fig. 5, were obtained from a local hospital. The units were picked up from the ward where they had been used, placed in sterile plastic bags, and sealed to prevent further contamination. The units were then transported to JPL for microbiological assay.

Once in the laboratory, the bags were opened aseptically and the units were disassembled into their component parts. Each individual part which was to be sampled was placed in a thin-walled beaker and immersed in a sterile phosphate buffer solution. The buffer solution consisted of distilled water,

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TRACH TUBE ADAPTER

EXHALATION VALVE AND "T"

SMALL TUBE OFF MICRONEBULIZER

ELBOW

SMALL TUBE (GAS)

CLOUDY   CLEAR

500 CC IN-LINE NEBULIZER

LARGE TUBE

MICRONEBULIZER

PREMOUTH TUBING

MOUTHPIECE
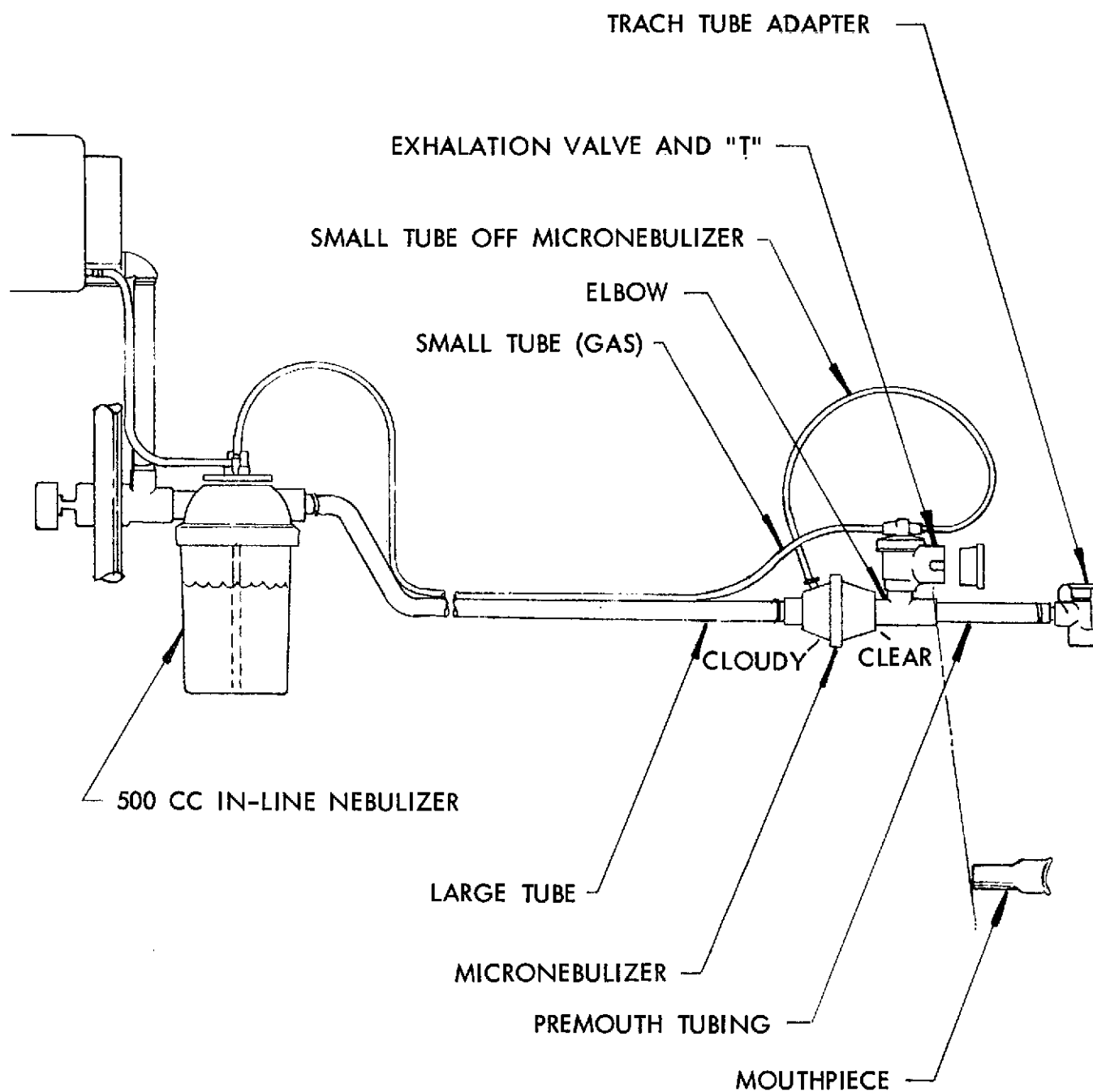
Fig. 5. Intermittent positive pressure breathing apparatus

potassium dihydrogen phosphate, and 0.02% v/v Tween 80. The pH was adjusted to 7.2 ± 0.1 through the use of sodium hydroxide.

The beakers containing the parts and buffer solution were then insonated at 25 kHz in a tank containing an aqueous solution of 0.3% v/v Tween 80. The sonicated fluid from the beakers was then passed through a 0.45-micron cellulose filter after which the filters were plated on Eugon agar and incubated for 72 hours at 37°C.

The burden for each part is shown in Table 3. The note for each unit reflects the number and duration of sonications which each part underwent. The units were processed in sets of five. It was noted in assaying the first five units that most of the samples had extremely high counts in the mouthpiece, trach-tube adapter, and premouth tubing parts. Therefore, it was decided to do a 10-fold serial dilution on the fluid obtained from these parts in order to be able to more accurately count the colony centers on the filters. Samples designated with three asterisks (***) have had their burden derived from these dilutions. The double asterisk (**) indicates that an extrapolation factor was incorporated in the total burden determination on that part. For each type of tubing a 3-inch (76.2-mm) section was sampled and the burden was extrapolated to the total length of tubing. One hundred milliliters of liquid was taken from each 500 ml inline nebulizer and filtered. The burden was then extrapolated to reflect the total volume of the nebulizer at the time it was sampled.

B.   PROCEDURES FOR THE SELECTION, PURIFICATION, AND DRY HEAT TESTING OF IPPB ISOLATES

Three isolates were recovered from each of the 10 apparatus tested and, where possible, from different parts on the apparatus. Isolates were picked on the basis of their gross colonial morphology and ease of recovering a pure colony.

The isolates were recovered from the filters using a sterile loop. The selected isolates were purified on prepoured Eugon agar plates using the quadrant streak method and then incubated at 37°C for 48 hours.

Table 3. Total bacterial burden on individual parts*

Unit	Mouth Piece	Tracheal Tube Adapter	Pre-Mouth Tubing**	Exhalation Valve and "T"	Micro-Neb. (Clear)	Micro-Neb. (Cloudy)	Elbow	Small Tube Off Micro-Neb. **	Small Tube (Gas)**	Large Tube**	Nebulizer Fluid**
1[a]	TNTC	NS	6000	900	7	619	400	6	NS	312	NS
2[b]	NS	NS	1920	750	216	178	12	NS	NS	51,600	24
3[c]	NS	TNTC	TNTC	TNTC	TNTC	TNTC	TNTC	5400	NS	TNTC	4
4[c]	NS	NS	TNTC	34	99	960	103	228	NS	6072	NS
5[c]	NS	TNTC	TNTC	15	TNTC	26	NS	NS	NS	1464	8
6[c]	NS	NS	1020	3	22	11	1400	138	NS	1896	0
7[c]	NS	NS	77	2	144	15	1	72	NS	1800	0
8[c]	18,000***	NS	1920	1	TNTC	32	TNTC	NS	720	1296	14
9[c]	102,000***	NS	3120*	0	33	52	NS	234	NS	1392	0
10[c]	37,500***	NS	864	14	TNTC	TNTC	5	3120	NS	1680	0
Average	52,500	---	2131	215	86	236	320	1314	720	7501	6

Notes:

[a] Three 2-minute sonications at 25 kHz.

[b] One 2-minute sonication at 25 kHz.

[c] One 12-minute sonication at 25 kHz.

NS = not sampled.
TNTC = too numerous to count.

*See Fig. 5 for parts identification.

**Total burden determined by extrapolation.

***Count determined by dilution plate.

After purification, a final streak was made for the purpose of taking notes on the gross colonial morphology. The material for streaking was obtained from a broth culture which had been incubated at 37°C for 24 hours. Then 0.2 ml of the broth suspension was transferred to sterile Eugon agar slants, incubated at 37°C for 48 hours, and stored at 4°C for later use.

When needed for dry-heat testing, the isolates were washed off the slants with Eugon broth. Lawns were made on prepoured Eugon agar plates. The 48-hour lawns were harvested on the day of the test. The isolates were washed off the plates with 20 ml of cold sterile distilled water. The resulting suspension was centrifuged for 10 minutes at 9750 relative centrifugal force. The washing-centrifugation procedure was performed four times.

The bacterial concentration of the suspension was obtained by spectro-photometric means, utilizing the Spectronic 20. A sample of the washed suspension was added to a cuvette containing 4 ml of distilled water to obtain an absorbance value of 0.50. This produced a titer of between 10^6 and 10^7 organisms/ml. An Eppendorf pipet was used to deposit approximately 10^5 organisms on sterile 25 x 50 mm stainless steel coupons. The inoculated coupons were allowed to air dry for approximately 30 minutes before being placed in a dry heat oven which was set at 100°C. Pull times were zero time (non-heat-treated), 5, 8, 12, and 16 minutes, respectively. After being removed from the oven the coupons were placed in flasks containing 20 ml of a 1% peptone solution and sonicated for 2 minutes. Following sonication, appropriate 10-fold serial dilutions were made and plated out with Eugon agar. After incubating the plates at 37°C for 48 hours, colony-forming units were counted.

Linear regression analysis was performed with the results shown on Table 4. The results show that most IPPB cocci tested were rendered non-viable within the first 10 minutes at 100°C. Some sporeforming and nonspore-forming rods were also tested. For three of the sporeformers the $D_{100°C}$ values are not shown in Table 4 because, at the time of testing, they were mostly in the spore state as a result of the culturing techniques used; it was thought that on the apparatus itself the conditions required for sporulation would probably not be present. In the two cases where nonsporeforming rods were tested, they died off in less than 5 minutes at 100°C, as shown in Table 4.

Table 4. $D_{100°C}$ values of selected IPPB isolates

Organism	Apparatus/ Part Code*	Type	Gram Stain	$D_{100°C}$ (min)
1	1-MP**	Yeast	+	5
2	1-MP	Rod	-	5
4	2-NF	Yeast	+	7
6	2-LT	Coccus	±	6
7	2-LT	Rod	-	Not tested
8	3-TTA	Rod	-	<5
9	4-E	Rod	-	Not tested
10	6-STM	Coccus	+	6
11	6-STM	Coccus	±	5
12	6-STM	Rod	+	Not tested
13	8-MP(1)	Coccus	+	7
14	8-PMT	Coccus	+	11
15	8-STG	Coccus	+	8
16	9-MP	Coccus	±	8
17	9-MP	Coccus	+	5
18	10-MP(1)	Coccus	+	24
19	10-PMT	Coccus	+	5

*Numbers in front of letters code correspond to apparatus numbers

**The letter codes are as follows: E - elbow, LT- large tube,
MP - mouthpiece, NF - nebulizer fluid, PMT - premouth tube,
STM - small tube micronebulizer, STG - small tube (gas),
TTA - tracheal tube adapter.

"(1)" indicates first dilution.

An attempt was made to establish D values for the isolates at 110°C as well as 125°C, but the organisms died off too rapidly to permit a determination at the higher temperature.

In any event, the primary purpose of establishing the D values of the isolates was to initially define the approximate dry-heat cycle which would have to be used to sterilize IPPB apparatus. It was decided that the actual sterilization cycle would have to be determined by exposing naturally occurring organisms, found on patient-used apparatus, directly to the predicted sterilization cycle. It was further decided that, even though the likelihood of spores being present was rather remote, they too would be included, in the form of spore strips, and exposed to the sterilization cycle along with patient-contaminated assemblies.

C.   DETERMINATION OF THE DRY-HEAT-STERILIZATION CYCLE
FOR IPPB APPARATUS

An evaluation of the data on the types of organisms isolated from conventional apparatus and their dry-heat resistance indicated that the most heat-resistant organism had a D_{100} value of less than 30 minutes. D values at higher temperatures could not be determined due to the heat sensitivity of the organisms. The number of organisms obtained from the individual parts assayed was then extrapolated to a complete unit in order to determine the total number of organisms present. In the "worst case" condition the number of organisms on a complete unit was 1×10^7.

On the basis of a D value of 30 minutes at 100°C, the number of organisms present on each unit, and the time required for the most slow-heating part of the unit to reach oven temperature, it was estimated that a total cycle time of 6 hours at 125°C should be more than adequate to sterilize the units.

Studies were then initiated utilizing the new dry-heat-sterilizable units. Since naturally occurring microorganisms are generally more difficult to kill than cultured organisms, it was decided to expose patient-contaminated heat-compatible breathing head assemblies (the most contaminated part of the unit) to the proposed sterilization cycles and then culture the entire assemblies to check for sterility.

Six prototype control units and 36 breathing circuits, which included all tubing and breathing-head components, were fabricated by Bird Corporation according to JPL's suggested materials and design modifications.

These units were initially sterilized for 8 hours at 125°C in a forced-circulation dry-heat oven using a drive temperature of 127°C. The units were sterilized in sealed bags and delivered to the cooperating hospitals. Each of 2 hospitals received 3 units and 18 breathing heads. Once a week the control units and breathing-circuit components were brought back to JPL for processing as follows:

1) The control units were examined for defects in construction or function and adjustments made if required.

2) The control units were sealed in bags and sterilized at 125°C for 6 hours and returned to the hospitals along with sterile breathing heads.

3) The contaminated breathing head assemblies were placed in bags and sealed. They were then exposed to a sterilization cycle of either 2, 4, or 6 hours at 125°C.

4) After exposure to the above cycles the heads were disassembled without opening the bags, then the parts were removed from the bags aseptically, in a laminar flow hood, and placed in half-gallon screw-cap bottles containing Trypticase Soy Broth (TSB).

5) The parts were incubated at 37°C for 5 days and examined for growth.

6) After 5 days the parts and broth were autoclaved for at least 1/2 hour at 121°C before removal of the parts and subsequent washing.

7) After washing and drying, the parts were assembled and the breathing head assemblies were bagged, sterilized for 6 hours, and returned to the hospitals.

8) Some contaminated units were placed directly into the broth to be used as positive controls to check the culture medium.

9) Some units which had not been sent to the hospitals but had been sterilized in the same manner as contaminated units, were used as controls to verify the techniques being used to make sure that the manipulations were not introducing contamination.

10) In addition to the above component controls, commercially available spore strips were placed in the oven along with the contaminated parts, to determine if the cycle was adequate to kill spores, which are much more difficult to destroy than the vegetative cells   that make up the greater proportion of the bacterial population found on the ventilators.

The above process was repeated for the duration of the testing period of 2 months with exception of the 2-hour cycle, which was deleted because it failed to sterilize.

The results of these studies (Table 5) indicate that a 4-hour cycle at 125°C is adequate to sterilize the modified IPPB units; however, to increase the probability of sterility and to take care of the "unusual" case, it is recommended that the sterilization cycle be 6 hours at 125°C. In JPL's oven, fully loaded with 6 complete units and 16 extra breathing-head assemblies, all individually sealed in plastic bags, it took 1 hour for the coldest part of the units to reach temperature. Thus, the total length of time in the oven was 7 hours.

D.   AMBIENT AIR AND PRESSURIZED GAS FILTRATION REQUIREMENTS

To prevent contamination of the sterilization unit and the patient by microorganisms contained in the ambient air or in the pressurized gases used to operate the ventilator, a bacteria-retentive filter system (Fig. 3) was installed.

The operating characteristics of the IPPB unit demanded a high efficiency, high flow rate, low resistance filter in the ambient air stream. For the pressurized gas filter, the primary requirement was high efficiency filtration; flow rate and resistance requirements were of secondary importance.

Extensive research by JPL in the microbiological evaluation of high-efficiency filters for liquids and gases (Refs. 11, 12) and a thorough literature search in this area, furnished information on which to base the fabrication of a dry-heat-sterilizable filter having the needed characteristics.

Table 5. Time required to sterilize patient-contaminated respirator breathing-head assemblies using dry heat at 125°C

Test No.	Hours Exposure at 125°C	Number Exposed	Number Sterile	Percent Sterile	Spore Strip Controls*		
					Number Exposed	Number Sterile	Percent Sterile
1	0**	2	0	0			
	2	2	0	0			
	4	2	2	100			
	6	2	2	100			
2	0	2	0	0			
	2	2	0	0			
	4	2	2	100			
	6	2	2	100			
3	0	2	0	0	2	0	0
	2***						
	4	8	8	100	2	2	100
	6	9	9	100	2	2	100
4	0				2	0	0
	4	9	9	100	6	6	100
	6	9	9	100	6	6	100
5	0						
	4	9	9	100			
	6	9	9	100			
6	0				2	1	50
	4	9	9	100	2	2	100
	6	9	9	100	2	2	100
7	0				4	0	0
	4	9	9	100	6	6	100
	6	9	9	100	4	4	100
Totals	0	6	0	0	10	1	10
	2	4	0	0			
	4	48	48	100	16	16	100
	6	49	49	100	14	14	100

*Spore strip controls used: Bacillus subtilis, Bacillus stearothermophilus.
**Time 0 exposed assemblies and spore strips were positive controls.
***Two-hour exposure was deleted at this point because of previously determined inability to sterilize.

Both the ambient and pressurized gas filters are compound filters made up of layers of urethane foam and fiberglass filter material. The type of fiberglass filter material used has had extensive use as an air filter medium for germ-free animal isolators (Ref. 13) and for the removal of bacteria from oxygen used

clinically (Ref. 14). The urethane prefilter is used to prevent premature plug-
ging of the fiberglass filter medium; the post filter is used to prevent any possible
migration of filter particles into the ventilator.

After fabrication the filters were tested under the same conditions of
differential pressure and gas flow volume as would be encountered in actual use.
The gases were permitted to flow through the filters for several hours in an
attempt to collect any particles of fiberglass which were present; 0.45-micron
black, gridded membrane filters were used. The counting was done with a
microscope at 150 power. The results obtained from counting six ambient and
six pressure filters indicated that no particles of fiberglass were present on any
of the membrane filters.

The filters were not challenged with bacterial aerosols because the data
available in the literature indicates that the fiberglass filter material used in
this application — and used in this same or similar configuration — is indeed an
absolute filter, capable of removing 100% of the bacteria which may be present
in an air or gas stream (Refs. 13, 14).

SECTION IV

MATERIALS

A.   DEFINITION OF REQUIREMENTS, PROBLEMS, AND APPROACHES

An initial assessment of the various functional requirements for operation of Bird Mark 7 IPPB units at the manufacturing and at the user level was conducted. This assessment aided initial identification of potential problem areas and also provided a preliminary definition of constraints under which design and material modifications could be made.

1.   Hospital Visits

Inhalation therapy departments at several Los Angeles University-affiliated hospitals were visited to discuss and observe the hospitals' operating and handling of IPPB ventilators and thus obtain information on the operational conditions to be met. The sterilization techniques currently in use were discussed in detail in order to permit assessment of the impact of heat sterilization on hospital operations. It does not appear that implementation of dry-heat sterilization will create major problems except, in some instances, where there may be a shortage of suitable dry-heat-sterilization equipment. This is a situation that can be easily and cheaply rectified. The operational advantages of dry-heat sterilization, compared to currently employed chemical-decontamination and gas-sterilization methods, are many. Heat sterilization will permit a reduction in the man-hours necessary to sterilize the units. In addition, as compared to gas sterilization, it will reduce equipment "downtime", since no time will be needed for toxic gas to leach out of the equipment. Various operating modes were identified, the particular mode used to be dependent upon the type of accessory equipment used. Hospital personnel emphasized the need for operational flexibility and ease of adjustment of the units. The requirement to sterilize both ambient incoming air and pressurized gas had been identified in Phase 0 of the program but was re-emphasized during hospital visits.

2.   Manufacturer Visits

The Bird Corporation in Palm Springs was visited to discuss design
rationale of the equipment and its component parts. These discussions were
essential to the development of an understanding of the functional requirements
and economics of manufacturing, i.e., the factors which led the manufacturer
to his selection of materials as well as the configuration and fabrication of the
equipment for the Mark 7 design. Although material and fabrication costs were
not a prime criteria for the prototype heat-sterilizable units, it was essential
that, for the program to be of practical value, the ultimate manufacturing costs
of a redesigned unit be considered. The functional requirements of the major
elements of the assembly and the experience of the manufacturer in design evolu-
tion were discussed in detail. These discussions continued throughout the program
in order to make maximum use of the manufacturer's experience and expertise.

3.   Data Review

Available information from prior JPL equipment-sterilization programs
was reviewed as an initial step in identification of potential problem areas, ap-
proaches, and fabrication materials which might be applicable to a modified de-
sign. A file of sterilization reports and of related materials technical data, app-
licable to dry-heat sterilization, was established for use throughout the program.

B.   PRELIMINARY STERILIZATION COMPATIBILITY ASSESSMENT

Drawings and materials lists received from the manufacturer were reviewed
simultaneously with disassembly and examination of units. A principal product
of this assessment was identification of materials in the design which, based on
previous experience, were not expected to be suitable for heat sterilization.
The materials and assemblies in the unit were categorized as (1) problems,
(2) possible problems, (3) probably acceptable, and (4) unknown. One or more
candidate replacement materials was identified for each material and/or part
which was expected to require replacement or modification.

The physical, chemical, mechanical, and thermal properties of the existing and proposed candidate materials were evaluated to determine their sterilization compatibility. The prime consideration during this initial assessment was the determination of thermal stability of these fabrication materials. The factors that affect thermal stability are

1) Tensile stress (Fig. 6).
2) Tensile yield (Fig. 7).
3) Flexural modulus (Fig. 8).
4) Heat aging effects (Fig. 9).
5) Comparative creep behavior (Fig. 10).
6) Comparative heat deflection temperatures (Fig. 11).

In order to determine the suitability of a material for thermal applications, it must first be determined whether the material will retain its initial properties during continuous or long-term intermittent exposure to temperatures equal to, or exceeding, those required. In addition, the thermal coefficient of linear expansion and thermal conductivity must be analyzed to calculate the thermal stresses which may develop. These stresses, which are usually incurred as a result of differential thermal expansion, may, and usually do, occur under transient conditions, where interacting parts are changing at different rates. Another equally important consideration was the strength of the materials at process temperatures. The possibility of oxidation, chemical reaction, and vapor release had to be considered in light of possible toxicity problems and interference with equipment function. Frequently, the above problem areas can be readily and economically identified and verified by simple tests. Such tests have advantages in addition to economy; one of the advantages is that the inadequacy of materials can be demonstrated in a way that no amount of properties data can approach, and unanticipated problems can be readily identified. An iterative series of analyses, tests, and materials replacement or substitution was utilized in achieving the ultimate sterilizable design in this program.

C. PRELIMINARY VERIFICATION TESTS

One of the Bird Mark 7 ventilators of the then-current design was evaluated in two preliminary thermal tests. These tests were intended to verify the identified

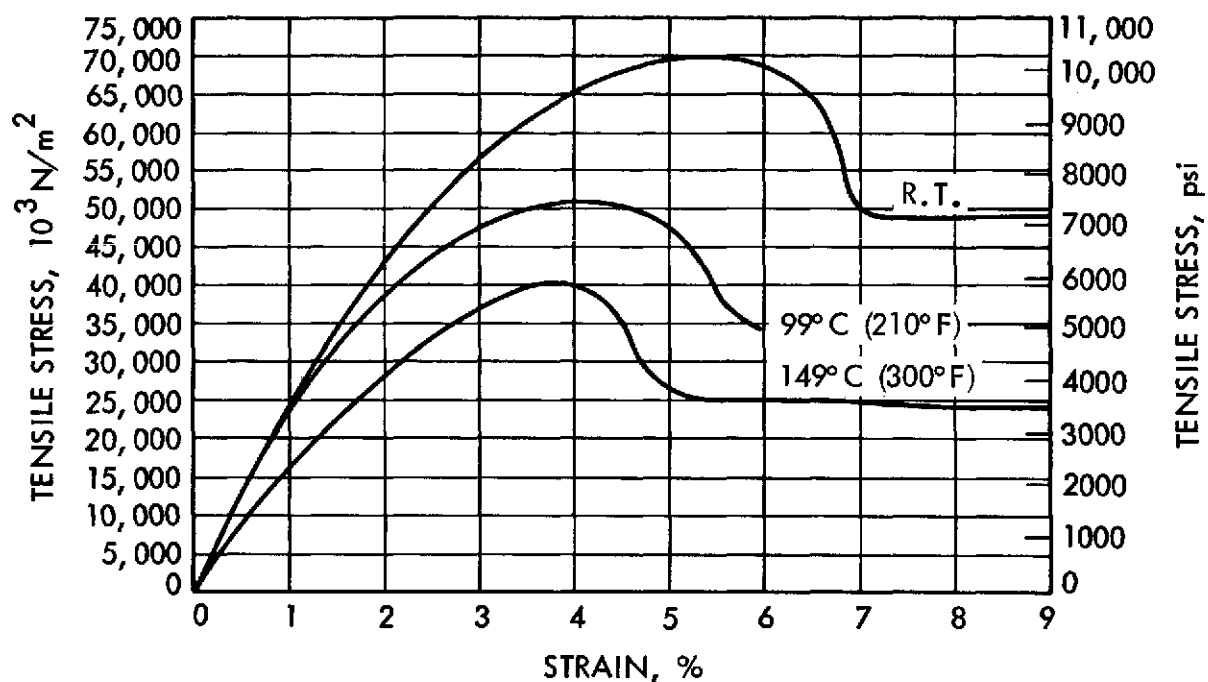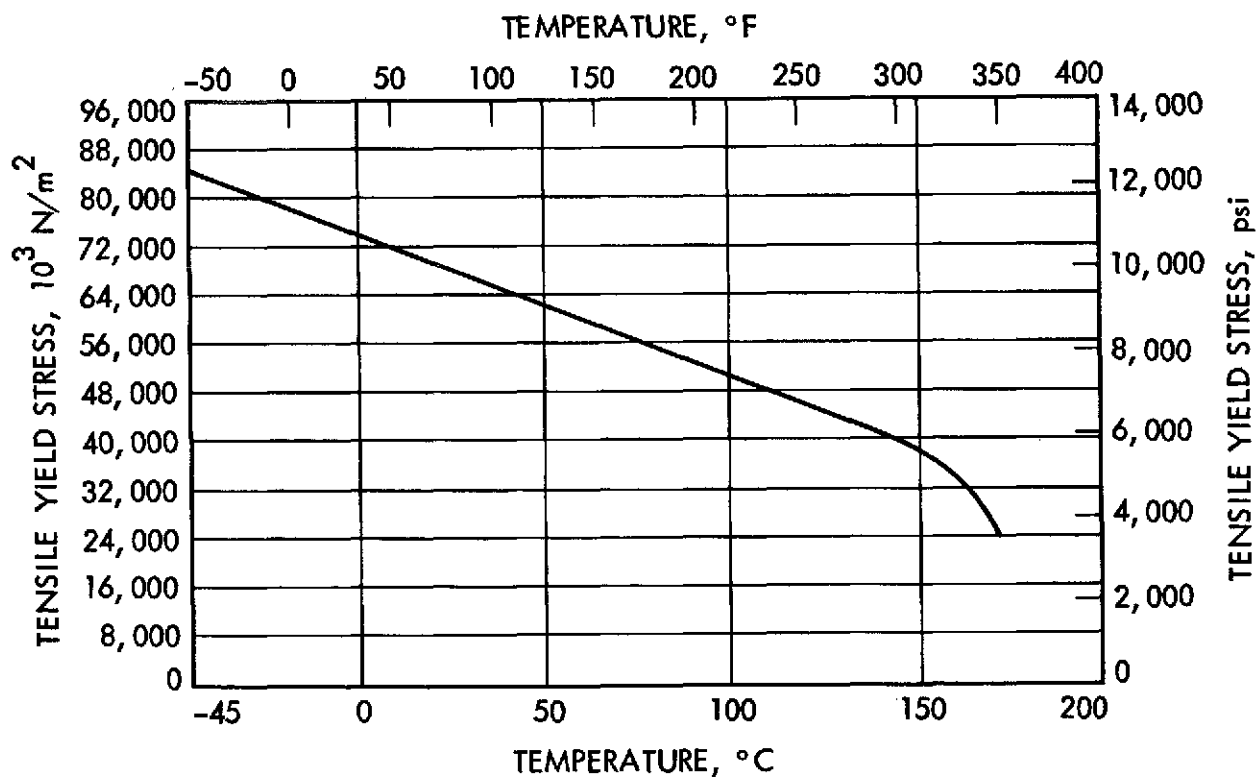Fig. 6. Polysulfone tensile stress strain curves

Fig. 7. Tensile yield of polysulfone vs. temperature
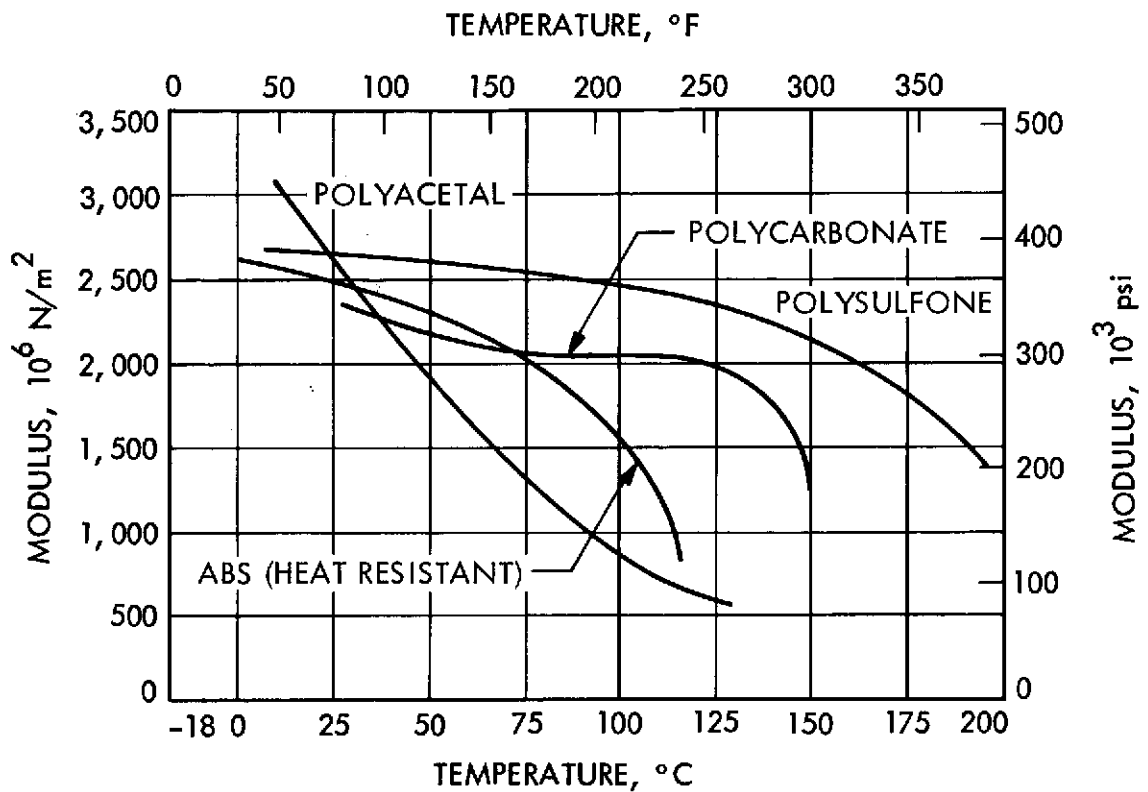
TEMPERATURE, °F

Fig. 8. Flexural modulus vs. temperature
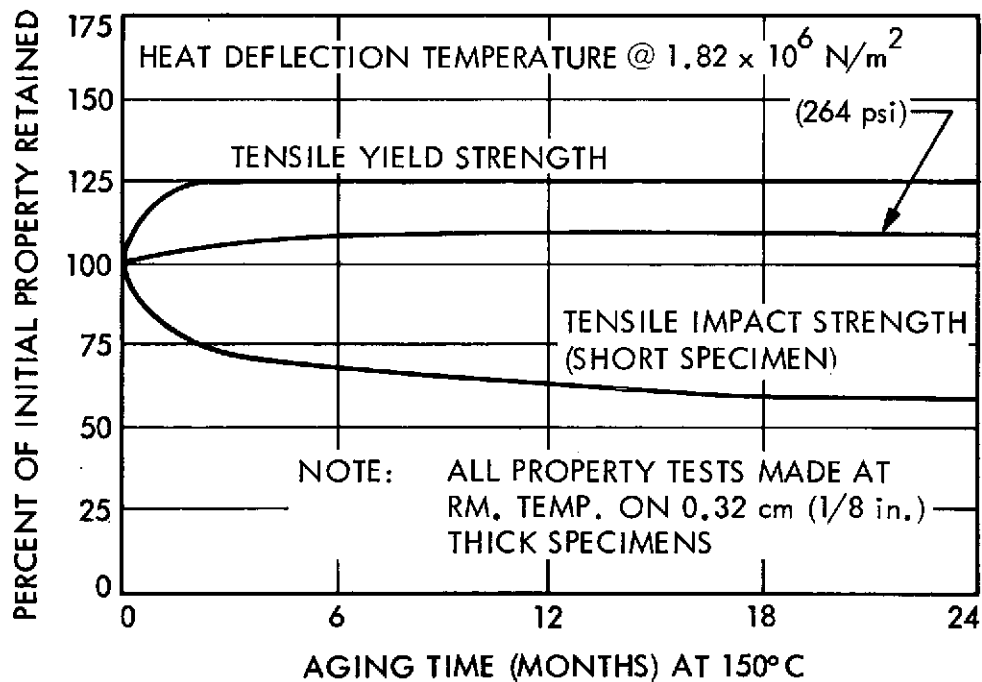

Fig. 9. Effect of heat aging on polysulfone properties

STRESS = 20.7 x 10⁶ N/m² (3000 psi) TENSION
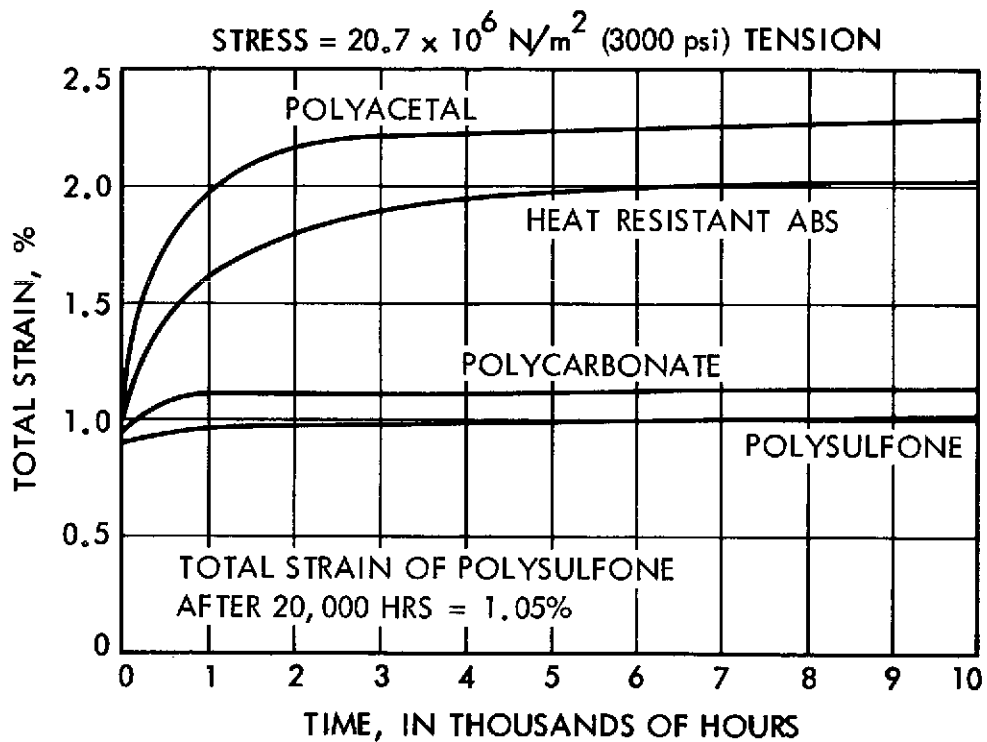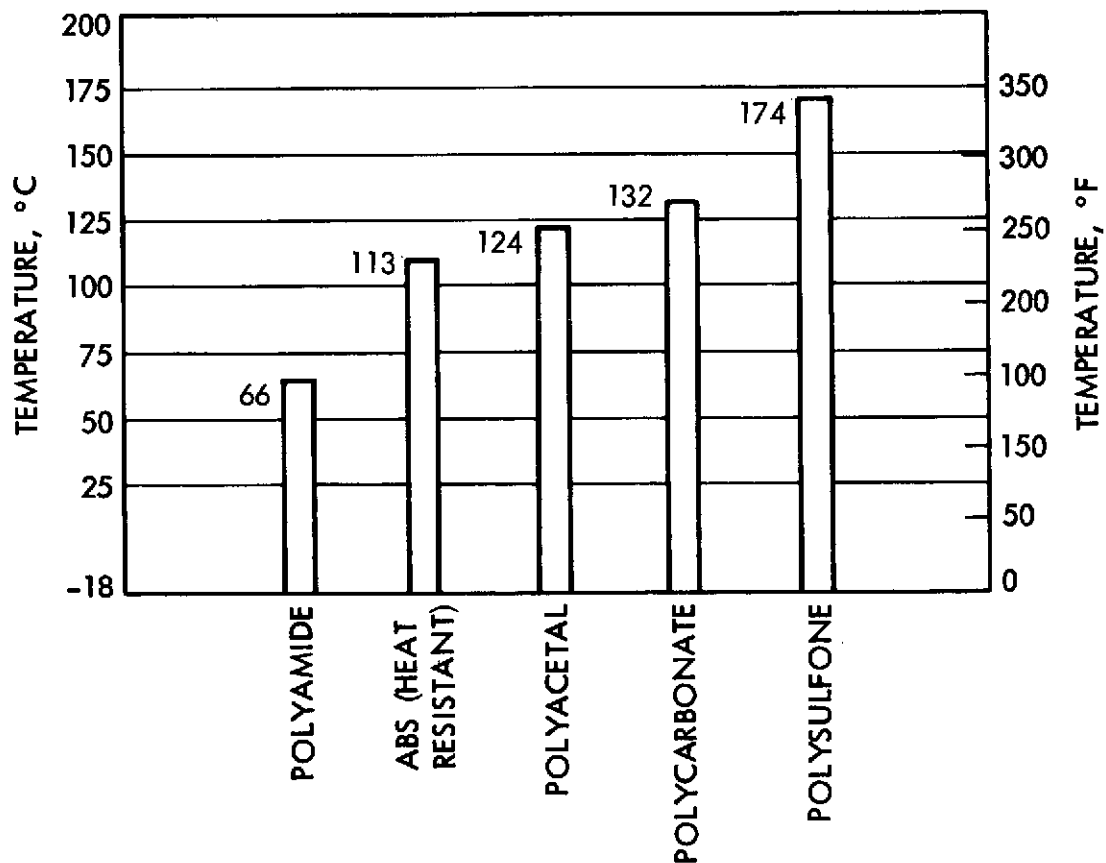
Fig. 10. Comparative creep behavior at 22° C in air

Fig. 11. Comparative heat deflection temperatures at 1.82 x 10⁶ N/m²(264 psi)

materials problems, examine some of the potential problem areas, and to identify unexpected problems. The first test consisted of 8 hours at 125°C with the unit completely disassembled to evaluate the materials independent of interaction. The second test was for 24 hours at 125°C with the unit completely assembled. This second test resulted in additional thermal stability information and preliminary interaction data.

As was expected, a number of parts sustained damage:

1)   The polyvinyl chloride (PVC) breathing circuit hose softened during the initial test and was torn by its own weight at attachment points during the second (Fig. 12).

2)   The acrylonitrile-butadiene-styrene (ABS) air mix control knob was distorted and had to be removed prior to the second test.

3)   Minor dimensional changes occurred in the polypropylene, polycarbonate, and nylon parts as a result of the first test.

4)   The exhalation valve tee (polypropylene) was distorted along the injection mold seam; thermal expansion differences caused an interference fit, preventing separation.

5)   The end compartments (polycarbonate) showed extensive crazing, cracking and dimensional distortion as a result of the second test (Fig. 13).

6)   Other polypropylene and nylon parts were distorted in varying degrees.

7)   The end compartment "0" rings changed dimension.

In addition to the above, the following conditions were observed as a result of the tests:

1)   The PVC tubing interconnecting control parts showed substantial discoloration.

2)   The pressure gauge needle indicated a permanent offset from the zero point during each test.

3)   The mask and test lung exhibited catastrophic failure with the materials softening beyond use. This result was completely unexpected
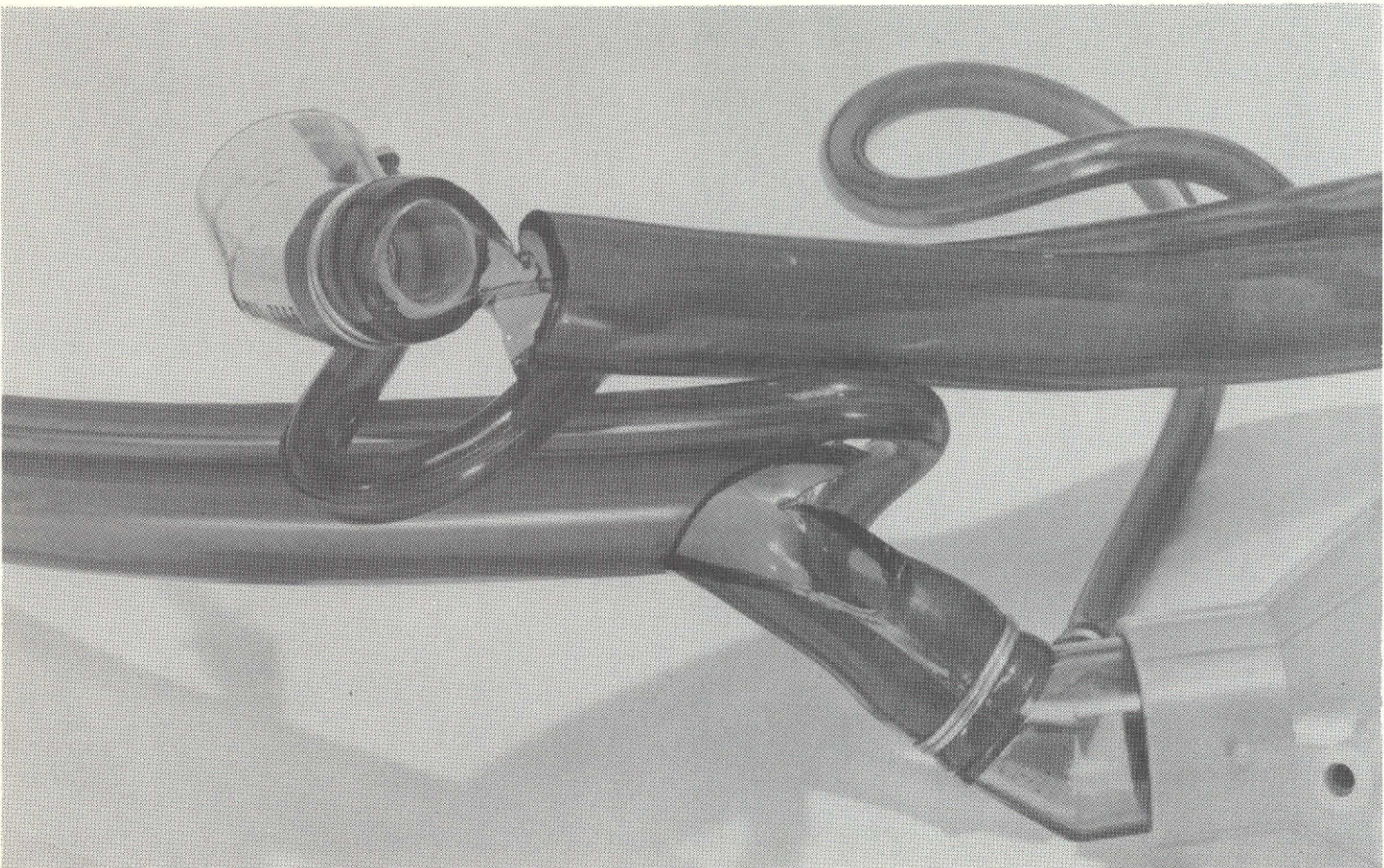
10 CENTIMETERS (~4 INCHES)

Fig. 12. Breathing circuit hose of existing IPPB apparatus,
showing damage from heat sterilization at 125°C

Fig. 13. End compartments, showing damage from routine chemical
decontamination followed by heat sterilization at 125°C

since they were shown as neoprene rubber in the materials list. They were obviously a combination of alternative materials. Replacement with heat-sterilizable materials was considered feasible; therefore, the materials which had caused the unexpected failure were not investigated further.

The "case history" of the pressure gauge in the unit is significant to the problem of heat sterilization of complex equipment. The gauge is a purchased item and thus was listed on the parts/materials list without any details as to design or materials of construction. It was identified as an unknown and thus a potential problem area. The decision was made to evaluate it by testing rather than by obtaining detailed data from the manufacturer and analyzing the design.

During the initial tests it was observed that the zero-offset in the pressure gauge was small and decreased with each cycle. Examination of the internal construction of the gauge indicated the effect to be a minor relief of fabrication stresses and not significant to the function of the gauge. This indication was verified by subsequent extensive thermal cycle testing. The gauge then became an item in the unit which would require a thermal-anneal cycle and reset of the zero point and was no longer considered a potential problem area. Late in the program, when units were being prepared for hospital field testing, assemblies received from Bird included gauges which were nominally the same but which failed during sterilization cycles. Disassembly of the gauge revealed that the brass backing plate holding the gauge mechanism had been replaced with some unidentified polymeric material. For most applications this change would not affect the function of the gauge, but for heat-sterilizable equipment the gauge was no longer suitable. For equipment which is subject to heat-sterilization temperatures, it is necessary to verify the suitability of the materials and design and to assure that no changes are made which are critical to sterilization compatibility.

D. MATERIALS REPLACEMENT

Following the initial tests, candidate replacement materials were selected for those which had failed or indicated probable long-term problems. The

selection was based not only on fabrication processes which were applicable to large-scale production but also on the functional requirements previously discussed with the hospitals and the manufacturer, as well as the inherent thermal stability of the candidate materials. The unsatisfactory materials and their candidate replacements are shown in Table 6.

Table 6. Presently used materials and replacement candidates*

Present Material	Replacement Material
Polyvinyl chloride (PVC)	Silastic rubber
Polypropylene (tenite or noryl)	Polysulfone, Tefzel, Tenite-6PRO
Polycarbonate	Polysulfone
Acrylonitrile-butadiene-styrene (ABS)	Metal
Nylon (Zytel)	Polysulfone
Acetal (Delrin)	Polysulfone

*See Appendix B for identification of materials manufacturers.

Manufacturer's facilities in Palm Springs and Berkeley were visited to discuss the replacement materials and fabrication problems that might be associated with the use of these materials. The corporation agreed to provide the suggested heat-sterilizable replacement parts as rapidly as possible. Owing to the nature and cost of die installation in their injection-molding equipment, considerable time elapsed before all replacement parts could be obtained. In addition to parts fabricated from JPL-recommended materials, parts made of other heat-sterilizable materials were also supplied for our evaluation.

In some cases mold-shrinkage differences between the original materials and the replacement polysulfone resulted in dimensional mismatch of parts. Design changes (see Section V) made it possible to compensate for these differences in final dimensions without the requirement (and cost) for new or modified molding dies.

E. STERILIZATION SIMULATION TESTS

An existing Bird Mark 7 ventilator was retrofitted with all of the available sterilizable replacement parts and a series of thermal cycles was initiated duplicating the anticipated sterilization time and temperature parameters. The experimental conditions consisted of 24 hour periods at 125°C, after which the unit was physically examined and functionally tested at frequent intervals throughout the investigation.

The test configuration included molded polysulfone replacement parts for the polycarbonate ambient and pressure compartment covers, as well as polypropylene exhalation valve and tubing ties. Some of polypropylene micronebulizer parts were replaced with polysulfone parts and others with Valox. All tubing was changed to silicone rubber.

After the third cycle — i. e. , 72 hours at 125°C — the unit was functionally tested for 12 hours using a nitrogen gas source. No malfunctions were noted. At the same time, a smoke test was performed to examine the possibility of backflow of air through the head assembly and to study the flow of incoming ambient air. The test indicated that there was no apparent backflow through the breathing circuit. The smoke test also indicated that ambient air entered the ambient compartment approximately equally through the existing micromesh filter and through other openings in the compartment. The micromesh filter, recognized to be ineffective in filtering out bacteria, was furthermore filtering only approximately half of the incoming air. JPL modifications eliminated this filter (and the need for sealing the existing ambient compartment leaks — see Section VI).

F. INITIAL THERMAL EFFECTS

Inspection and test after the 10th cycle (240 hours at 125°C) indicated operational malfunction. The unit was completely disassembled and examined in detail for material degradation and dimensional changes. The following conditions were observed during this test series:

1)   Surface crazing was observed at the tapered fitting joint between the micronebulizer and the exhalation valve after 5 cycles

(120 hours at 125°C). Cracking was noted after 168 hours at temperature; this degradation was the result of excessive stress during the thermal cycle. Subsequently, parts were satisfactorily sterilized with this joint separated. The joint was reconnected after sterilization, while still bagged.

2) Pink discoloration of the silicone tubing was noted after 216 hours at temperature (9 cycles); this was considered to be caused by deposition of outgassing products from the lubricant and/or neoprene parts. Both were subsequently changed.

3) After the 10th cycle the air mix control rod ceased to function properly, and the ceramic valve was constrained in the inspiratory position by the diaphragm assembly. The neoprene 0-rings on the control rod had hardened and deformed and the lubricant had evaporated. The neoprene diaphragm had distorted and hardened, constraining the ceramic valve. To correct the problems, the control rod 0-rings and diaphragm were replaced with silicone rubber and silicone oil was substituted for the original lubricant.

4) Neoprene centerbody 0-rings degraded, hardened, changed dimensions and shape, and took a permanent set. Samples were tested and it was found that, after the 10th cycle, tensile strength had decreased 10%; elongation decreased by 50%; and hardness had increased by 10%. All neoprene 0-rings were replaced with silicone rubber.

5) The polysulfone pressure compartment cover evidenced some distortion, crazing, and cracking as a result of excessive thermal stresses during the tests. Modification of the compartment attachment and seal designs was required.

G.   ADDITIONAL CHANGES AND REPLACEMENTS

Following the test series described above, thermal cycling was suspended to permit incorporation of the necessary design changes and fabrication of additional sterilizable parts. Three units were retrofitted with replacement parts for continuation of thermal testing. In these units all 0-rings and the diaphragm were replaced with silicone rubber and all lubrication was done with silicone oil. Most of the molded parts were replaced with polysulfone. A few of the parts

in the exhalation valve and micronebulizer were available only in Tefzel and Valox because of molding problems associated with polysulfone; the small size and shape of these parts; and the use of original dies which could not compensate for the difference in thermal expansion of the polysulfone material.

The three units also differed in the configuration of the 0-ring seal for the end compartments; two had new 0-ring designs and the third used essentially the existing design.

The first two cycles on these three units were run at 125°C for 24 hours to evaluate the effects of possible temperature override in the oven during sterilization. After these two cycles, the units with the new 0-ring configuration (see Section V, Design Modification) developed stress cracks and crazing in the areas where the "0" exerted excessive pressure. The original 0-ring groove configuration did not show the same effect in this test. The configuration of the 0-ring groove in the compartment and the 0-ring were modified to reduce the thermal stresses in these areas for the new design.

Subsequent to this change, the three units were subjected to 20 cycles of 24 hours at 125°C (a total of 528 hours at temperature) without additional failures except for some minor crazing of the polysulfone parts. This crazing only occurred in the threaded areas where the magnetic controllers are attached to the compartment and in the threaded area of the exhalation valve. Correction of this problem was achieved by relieving the threaded areas (increased tolerances).

H.   BAGGING MATERIALS

To assure unit sterility for patient use, a reliable system was needed that would preclude exposure of the assembly to microbial contamination during handling and storage between sterilization and patient use. It was decided that the required protection could be achieved by sealing the entire assembly in a disposable bag after cleaning and prior to heat sterilization and by maintaining the seal throught sterilization and storage. It was recognized that, in routine hospital use, some sort of a reusable "zip lock" bag might be advisable rather

than the heat-sealed bags used in this study. However, development and evaluation of such an approach was not deemed essential to achievement of demonstrated heat sterilizability and was accordingly considered beyond the scope of this investigation.

With incorporation of proposed design changes, particularly in the area of filtration of both pressurized gases and ambient air, it is only necessary to preserve sterility of those parts and surfaces which are not protected by the filtration system, such as the external portions of the breathing head, by closures over the ports where bacterial entry might possibly occur.

Materials for bagging were evaluated on the basis of a requirement for heat-sealable, single-use bags which would not produce toxic byproducts, would withstand the sterilization cycle, and would assure maintenance of sterility. No attempt was made to optimize selection with respect to cost, ease of fabrication, and possible reuse. Capran, a nylon film available in adequate size in roll form, and heat sealable with available heat sealing equipment, was found to meet the requirements of this program and was used for bagging of all test units prior to sterilization.

I.   BACTERIA-RETENTIVE FILTERS

Commercially available filters were reviewed for air flow resistance, particle migration, outgassing, thermal stability, size, cost, ventilator compatibility, and suitability for absolute filtration of incoming ambient air and pressurized gases. No commercial filters could be found which would meet all of these requirements; therefore, it was decided to design and fabricate a filter system which would be compatible with the modified unit (see Section VI).

J.   FIELD TESTS OF PROTOTYPE UNITS

Sterilizable ventilators, fabricated with replacement materials and incorporating design changes developed during previous phases of the program, were prepared for hospital field test. The equipment consisted of six control units fabricated to the new design by Bird Corporation and equipped with air and pressure gas filters fabricated by JPL. In addition, 36 sterilizable head assemblies were assembled by Bird Corporation. The large number of head assemblies

permitted more effective utilization of the field units in obtaining statistical data on the efficacy of the various sterilization cycles. The extra head assemblies permitted exposure to patient contamination after sterilization, without the undue delay that would result from the turnaround time of the control assemblies.

The primary objective of the field test was to develop data on the sterilization reliability of various cycles. These results are discussed in Section III of this report. In addition, the field test sterilization cycles provided an opportunity for verification of the materials and design of the heat-sterilizable assembly. Some minor problems were encountered as a result of this test. The failure of the pressure gauge has been described earlier. Two units were described by inhalation therapy personnel as exhibiting "erratic performance" during operation. Subsequent disassembly failed to reveal any mechanical malfunction, except an offset in the pressure gauge. It was shown that the erratic behavior was the result of improperly indicated pressure which led to improper adjustment of the units. Correction of the gauge deficiency is accomplished by use of an interior metal "backing plate, " as described above (Section IV-C).

K.   THERMAL ANALYSIS AND TEST

As discussed in Section III, the probability of achieving sterility by the use of a given heat-sterilization process is dependent on temperature and time. For a device such as the IPPB ventilator, the thermal cycle must be defined to assure that the element of the assembly with the slowest thermal response is held at the required temperature for the length of time necessary to attain sterility. Preliminary assessment indicated that, although the thermal lag could be analyzed, an experimental approach would not only be more practical but more reliable. The assembly was therefore examined in view of identifying the extremes of thermal lag time and the appropriate location of thermocouples for subsequent thermal testing.

One of the partially retrofitted IPPB units was instrumented with thermocouples in selected locations. Data were recorded on a multipoint recorder and subsequently analyzed for maximum and minimum thermal lag time. As

expected, the control assembly centerbody, with its large thermal capacity and limited conduction path, showed the maximum thermal lag. Other instrumented parts of the control assembly had thermal response times almost identical to those of the centerbody. A comparison of the thermal test data with oven temperature readings demonstrated that leaving the units in an oven for a specified time at the temperature indicated by the oven thermometer does not give a true indication of the "time at temperature" of the units. Thermocouples or some other temperature-sensing device should be attached to the centerbody of the most centrally located unit in the oven to determine when the units reach the sterilizing temperature selected. If the load consists of plastic parts only, the thermocouple should be attached to the part nearest the center of the load. If a direct temperature indicating device is not available, the sterilization time must be extended to increase the probability that the units were subjected to the required "time at temperature." The time required to reach temperature is a function of load, load distribution, oven characteristics, and restrictions to effective heat transfer from the oven to the coldest unit and must be established for the load and the oven.

During sterilization of the hospital field test units, one of the units was instrumented to determine the thermal lag and thus establish the total time during each cycle that the coldest parts of the units were at 125°C. An oven, 0.68 cu m (24 cu ft), utilizing a blower to circulate heated air, was used in these tests. Six control heads and 16 complete breathing circuits, including all tubing and fittings, were bagged separately and sealed. A thermocouple was attached to a bagged control centerbody which had been shown to have the greatest thermal lag. This bagged unit was placed in the center of the oven and surrounded by the remaining bagged units. Repeated tests indicated that it required a maximum of 1 hour for the instrumented centerbody to reach 125°C.

SECTION V

DESIGN MODIFICATIONS

To achieve a heat-sterilizable breathing apparatus, a number of design revisions were found to be necessary. These alterations resulted from required material changes and stresses encountered during thermal cycling of a completely assembled unit.

The major design revisions were made in the pressure compartment end cover of the control unit. These changes, which involved new sealing and attachment techniques, are described below.

A.   SEALING TECHNIQUES

Functioning of the device requires that the pressure compartment maintain a continuous seal under varying pressures during operation. Changes in the seal between the aluminum centerbody and the end cover were required to prevent undue stresses, with resultant material failure, during heat sterilization and subsequent operation of the unit. The existing design for the pressure compartment cover is shown in Fig. 14. The revised design shown in Fig. 15 permitted heat sterilization and also permitted direct replacement of the present heat-sensitive plastic covers with polysulfone covers having the same configuration, thus eliminating the expense and delay which would have been associated with fabricating new dies. The design modifications involved changing the position and shape of the O-ring groove and installing an O-ring with a smaller cross section.

B.   ATTACHMENT TECHNIQUES

In the original design, the molded pressure compartment cover was counterbored to a thin (2.160 mm) section at the attachment points. Assembly stress loads, as well as thermal stress loads, caused cover failure at this point. In addition, installation of the mounting screw imposed excessive compression loads on this thin section. The revised design is accomplished without
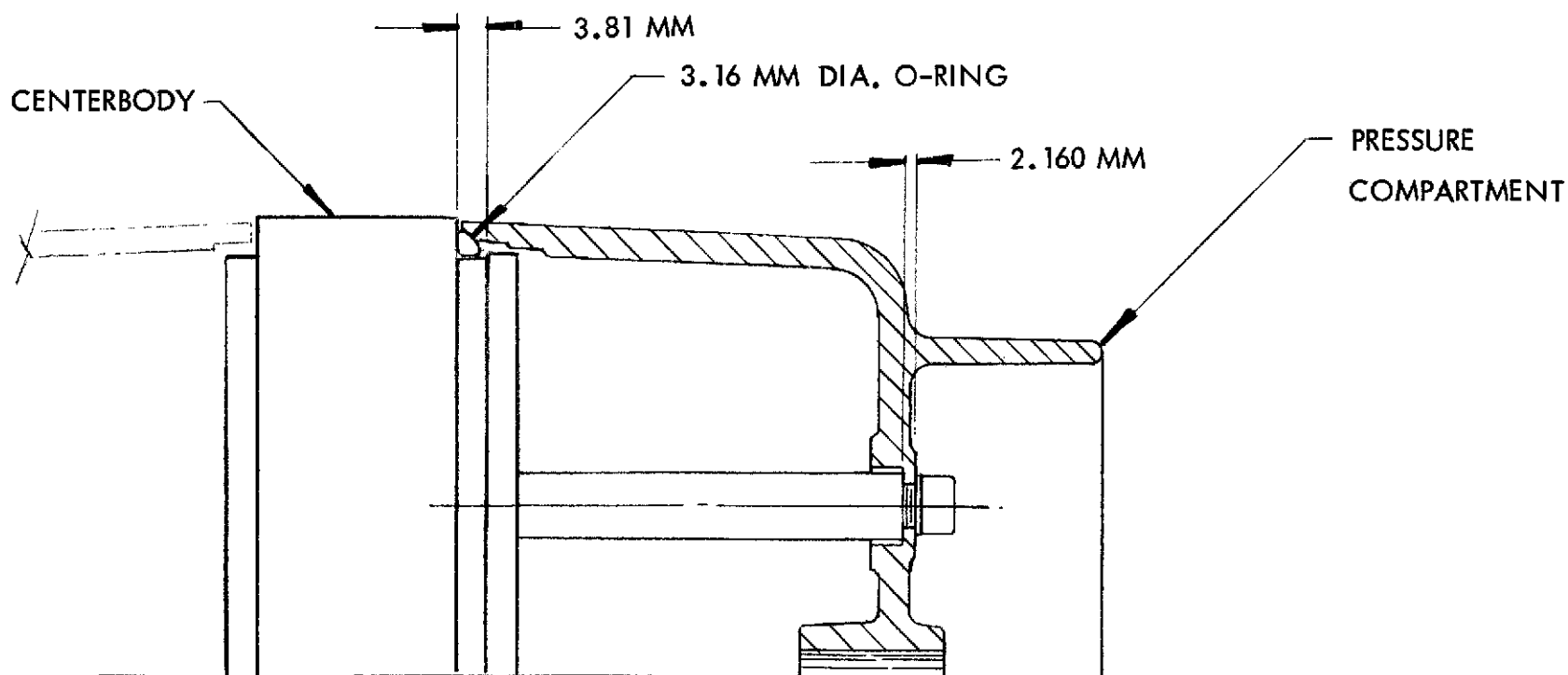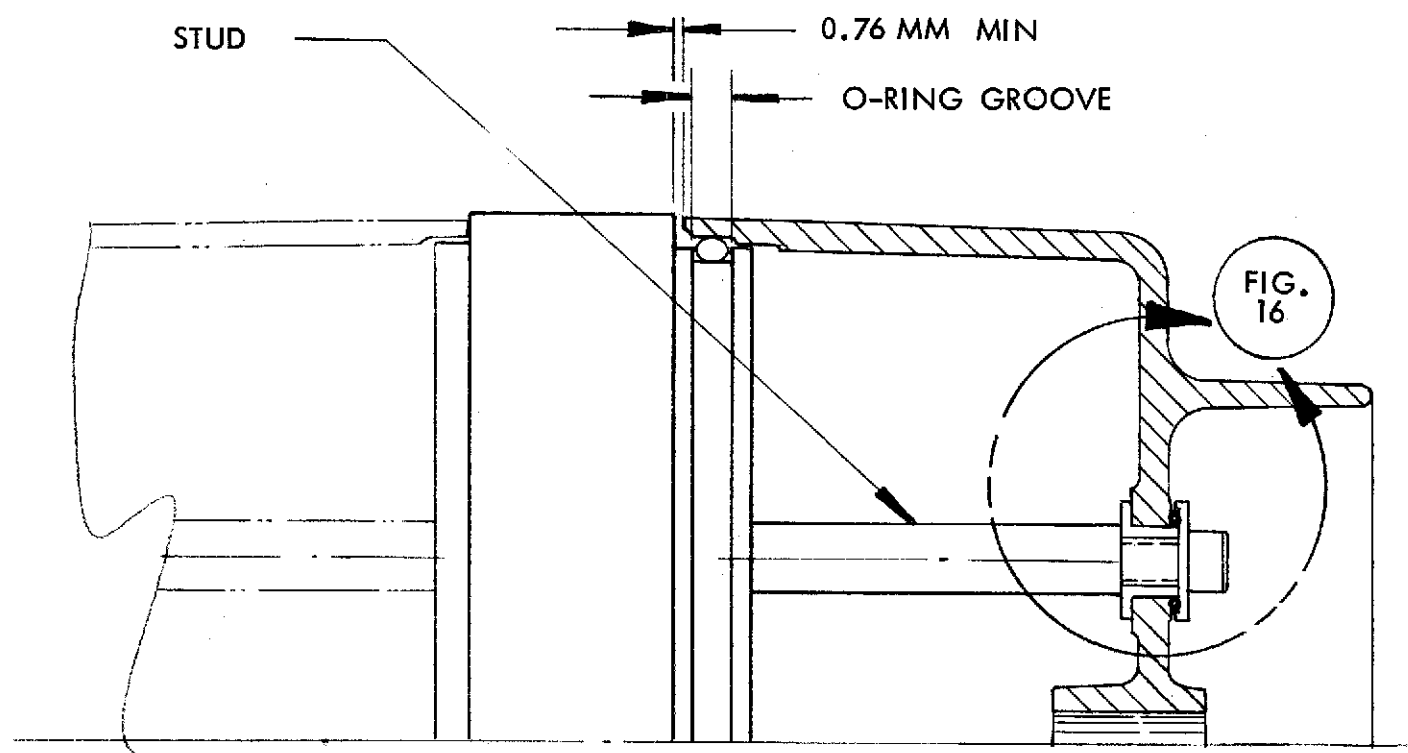
Problems:

The compartment applied compression loads against the O-ring for sealing.

Crazing occurred at the corners of the compartment where the O-ring loading was highest when the unit was heat cycled.

The recess for the mounting studs rendered the compartment too thin to hold the O-ring in compression, thereby producing excessive stress around the mounting points.

Fig. 14. Existing centerbody and pressure compartment

STUD

0.76 MM MIN

O-RING GROOVE

FIG. 16

Resolution of the Problems:

The O-ring, groove size, and groove location were changed to permit the O-ring to seal by pressing against the side walls of the compartment rather than the bottom edge.

A gap was maintained between the bottom edge of the compartment and the centerbody to eliminate compression loads on the compartment.

The fastening technique was also revised as shown in the above figure.

Fig. 15. Centerbody and pressure compartment modification

new or modified tooling. Instead, it is achieved by changing fabrication from a counterbore to a through bore, and adding a shoulder washer and O-ring to eliminate high installation stress and thermal stress failures in the attachment area. Compression loads are now eliminated by means of the shoulder washer, and compartment sealing is accomplished by means of the O-ring which also seals around the mounting screws.

It was also necessary to modify the stud length in order to accommodate the new attachment mode and to guarantee clearance between the cover and centerbody.

In the original design, the cover/centerbody seal is achieved by compartment pressure on the centerbody O-ring, applied by tightening the mounting screw. This scheme puts unacceptable loads on the cover in the area of the O-ring, and in the thin section of the cover in contact with the stud. These loads were responsible for cracking observed in the first thermal cycling of the original polycarbonate covers and for less dramatic cracking observed in the replacement polysulfone covers when using the original configuration. The original design produced excessive loads in these two areas, even without heat sterilization. Pressure compartment covers had a very high frequency of replacement in the original design.

The final revised configuration, with the significant changes at the O-ring seal and method of attachment, is shown in Fig. 15. Details of the attachment point configuration can be seen in Fig. 16. Note that the cover is now free to slide over the centerbody O-ring, and there is no possibility of load on the compartment as a result of physical contact with the centerbody. The loads exerted on the cover from the centerbody, transmitted through the O-ring, are now controllable by the relative dimensions of the cover, the O-ring, and the O-ring groove. The differential expansion between the polysulfone cover and the aluminum centerbody now tend to relax, rather than increase the loads on the cover and on the O-ring at elevated temperatures during sterilization. Incorrect dimensional relationship was responsible for cracking of the cover in the first prototype revised configuration. In the final configuration the cracking was completely eliminated by the reduction in O-ring diameter and correction

1/4-28 *SCREW

O-RING

SHOULDER WASHER

STUD
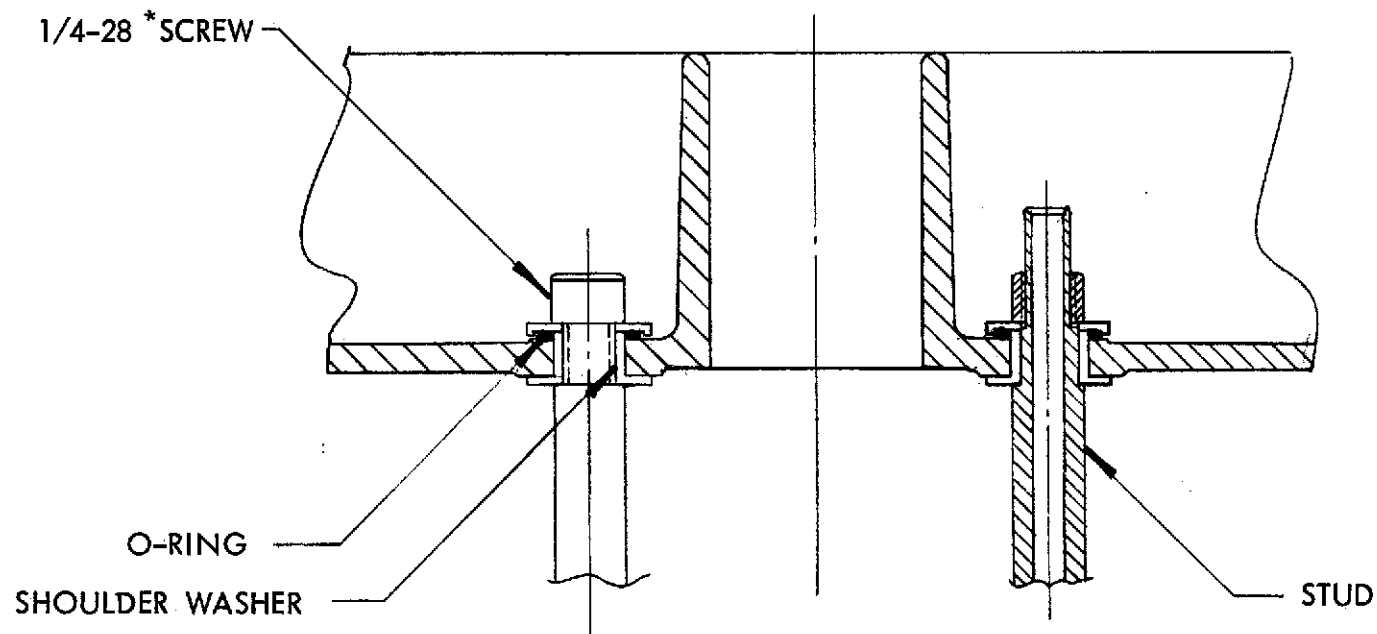
Resolution of the Problems:

The shoulder washers are designed to protect the cover from crushing loads caused when torque is applied to the screw.

The O-ring is used to seal around the holes and to position the cover.

* ENGLISH MEASURE

Fig. 16. Compartment mounting detail

of the O-ring groove dimension. The O-ring in the new configuration, resting in a conventional O-ring groove, also facilitates assembly and disassembly.

The new seal configuration required no new or modified tooling for the cover or centerbody to accommodate the improved design. Some additional changes in the cover configuration would have been desirable, but were not essential to demonstrate a capability for reliable heat sterilization. Comparison of the O-ring installation in the centerbody in Figs. 12 and 13 show the difference in original and final configuration. The centerbody consists of a complex casting and represents a major cost element of the total assembly. The new configuration was designed to permit fabrication of the centerbody from existing tooling with changes only in the final machining (to preclude the delay and cost associated with retooling). The units for hospital field tests were machined to this configuration by the Bird Corporation from centerbody castings made with the same tooling used for the existing design. Although it is not possible, without some filling, to remachine centerbodies of existing units in the field to this configuration, there are slightly modified designs which can be used for the O-ring and groove which will permit retrofit of existing units.

The Bird Corporation manufactures a number of accessory items used in various combinations with the basic Mark 7 ventilator. These accessories are used in various configurations. The system configuration used for most of the heat-cycle testing, and all of the hospital testing, is that identified by Bird as the "Q Circle System." Conceptual designs for reliable heat sterilization and maintenance of sterility were developed for the "parallel inspiratory system" and the "oxygen blender system." There are configurational and hardware availability problems associated with these latter two configurations, but they have been shown to be at least conceptually feasible. Demonstration of these other configurations was considered beyond the scope of the program and therefore they were not investigated.

SECTION VI

FILTRATION OF AMBIENT AIR AND PRESSURIZED GASES

A.   METHODS

The cover of the ambient-pressure side of the unit is not sealed in either the original or new design, and an O-ring is not used in either case. A change similar to that used for the positive-pressure side would have been required to maintain sterility of the machine and prevent contamination of the air stream from the surrounding atmosphere, if it were not for a new filter attachment configuration. In the new design, air from the ambient filter feeds directly into a sealed venturi, as does the pressurized "drive" gas (Fig. 4). Thus, in the new design the ambient compartment housing is essentially only a dust cover.

To attain the essential filtration efficiency as described in Section III and to meet the gas flow requirements of the Mark 7 ventilator, it was necessary to design and produce a new filter system.

The ambient air filters for hospital tests were fabricated by JPL, using a polysulfone 500 cc nebulizer supplied by Bird Corporation as the filter material container or housing. This particular container was used for expediency, since it was approximately the correct size, volume-wise, and the existing fittings were adaptable to the unit (see Fig. 17).

The pressurized gas filters were fabricated using a housing machined by Bird and based on a design and prototype originally built at JPL (Fig. 18).

The filters have the following characteristics:

1)   They can withstand hundreds of hours of sterilization at 125°C.
2)   They are capable of absolute microbial filtration.
3)   They retain their high flow characteristics for long periods of time.
4)   They do not produce toxic products during sterilization or use.
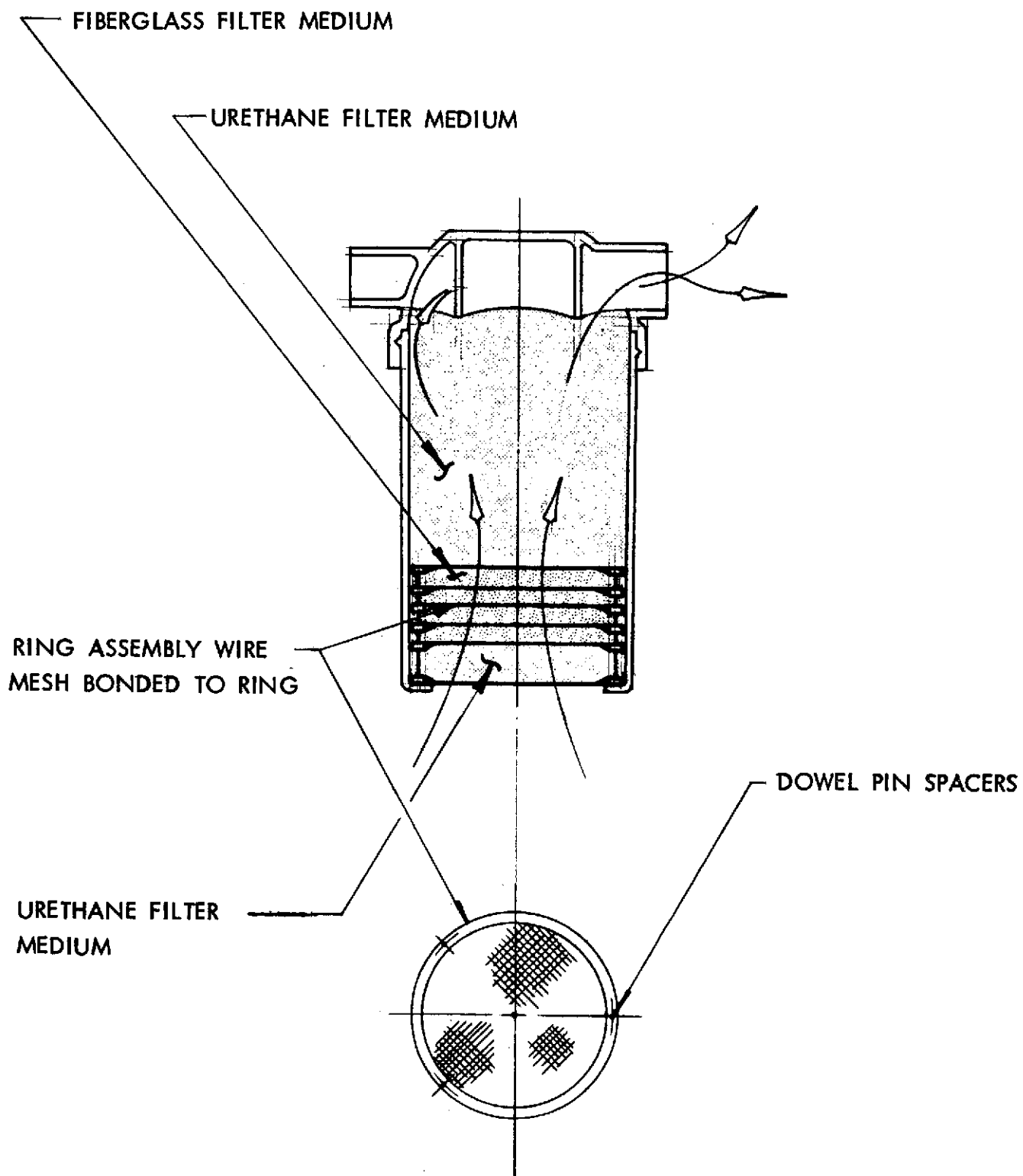5)   They are not subject to injury from normal handling or processing.

FIBERGLASS FILTER MEDIUM

URETHANE FILTER MEDIUM

RING ASSEMBLY WIRE
MESH BONDED TO RING

URETHANE FILTER
MEDIUM

DOWEL PIN SPACERS

Fig. 17.   Ambient filter
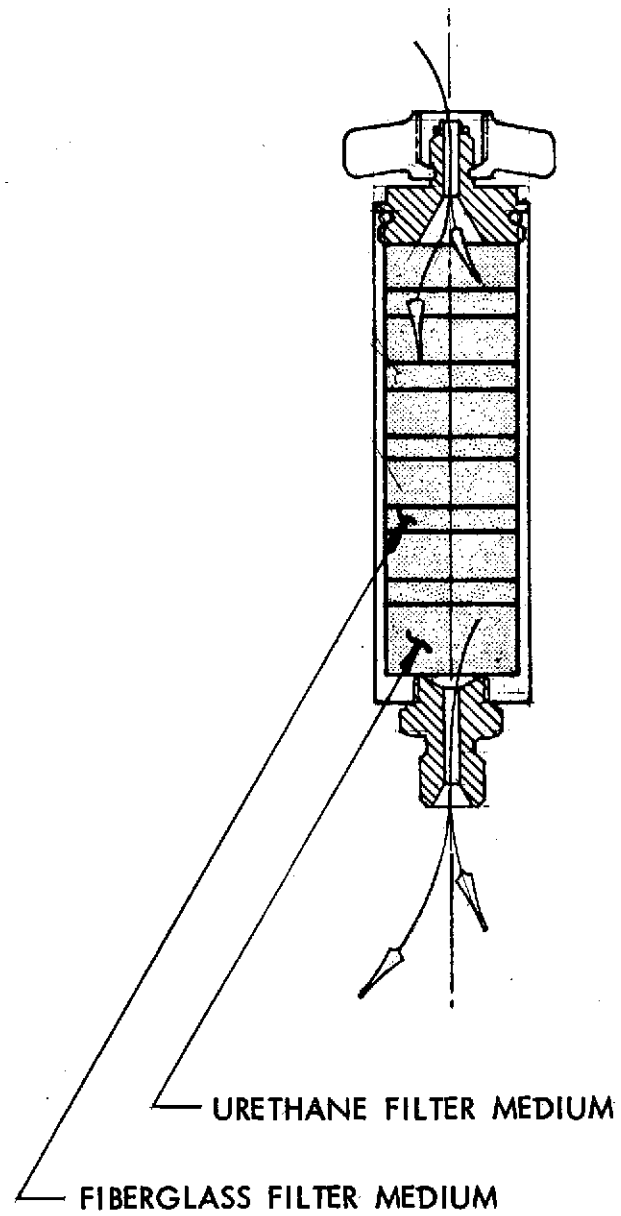
URETHANE FILTER MEDIUM

FIBERGLASS FILTER MEDIUM

Fig. 18. Pressure (gas) filter

6)   They are protected from "packing" by built-in spacers.

7)   The pre- and post-filters of urethane foam prevent premature plug-
     ging from dust particles and migration of the bacteria-retentive
     filter medium.

B.   MATERIALS

The compound filter materials used in both configurations were as follows:

1)   Bacteria-retentive filter medium: FM-004 Pyrex fiberglas wool
     filter material.

2)   Dust and Media Migration Filter: Scott Filter Foam.

SECTION VII

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APPENDIX A

LETTER FROM BIRD CORPORATION

bird
corporation

27 December 1972

Mr. Alex S. Irons
Jet Propulsion Laboratories
California Institute of Tech.
4800 Oakgrove Drive
Bldg. 233, Room 206
Pasadena, Calif.   91103

Dear Mr. Irons:

We at bird Corporation are very gratified at the progress
being made by your group in suggesting materials, designs
and procedures which will permit us to convert one or more
of our respirator designs to materials and construction
able to withstand repeated dry heat sterilization. We are
thoroughly convinced that the dry heat method of steriliza-
tion is far superior to other methods of sterilization cur-
rently available and in use for this type of equipment.

Consequently, we intend to incorporate dry heat steriliza-
tion capability as a major design criterion in all bird
products wherever it is technologically and economically
feasible. Because of the enthusiasm generated for the
heat sterilization concept through our work with your group
on the MARK 7® design we have also undertaken a parallel
project, that of converting the MARK 1® design to heat
sterilizable materials. This is a simpler task than the
MARK 7® conversion since it is a much smaller and simpler
device and, as you know, we are just about ready to pro-
duce several hundred of these units and introduce them to
the field on a fairly large scale for evaluation.

We are confident the results will confirm our confidence in
dry heat sterilization as the most efficient and effective
method for inhalation therapy and most other hospital equip-
ment.

Sincerely,

bird Corporation

W. C. Bentinck

lml

APPENDIX B

MATERIALS MANUFACTURERS

1. Polysulfone

   Union Carbide Corporation
   Plastics Division
   270 Park Avenue
   New York, New York   10017

2. Silicone Silastic Rubber - Dow-Corning

   The Fluorocarbon Co., Cole Rubber and Plastics
   1032 Morse Avenue
   Sunnyvale, California 94088

3. Tefzel

   DuPont Corporation
   Wilmington, Delaware

4. Tenite - 6PRO (Polyterephthalate)

   Eastman Chemical Products, Inc.
   Subsidiary of Eastman Kodak
   Kingsport, Tennessee

5. Polypropylene

   Amoco Chemicals Corp.
   Chicago, Illinois

6. Capran - Nylon - 6 Film

   Allied Chemical Co.
   Plastics Division
   Morristown, New Jersey

7. FM-004 Pyrex fiberglas wool filter material

   Owens-Corning Fiberglas Corporation
   Toledo, Ohio

8. Scott filter foam

   Industrial Sales Department
   Foam Division
   Scott Co.
   1500 East Second Street
   Chester, Pa.   19013