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CLOSED ECOLOGICAL LIFE-SUPPORT UNIT FOR PRIMATES

Berkeley, California

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Research and Development

UCRL-10589
UC-48 Biology and Medicine
TID-4500 (18th Ed.)

UNIVERSITY OF CALIFORNIA
Lawrence Radiation Laboratory
and
Space Sciences Laboratory
Berkeley, California

Contract No. W-7405-eng-48

CLOSED ECOLOGICAL LIFE-SUPPORT UNIT FOR PRIMATES

Mitchell Sabanas

December 10, 1962

Printed in USA. Price 50 cents. Available from the
Office of Technical Services
U. S. Department of Commerce
Washington 25, D.C.

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CLOSED ECOLOGICAL LIFE-SUPPORT UNIT FOR PRIMATES

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and
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ABSTRACT

A closed ecological life-support unit was fabricated. Design and construction details of this unit are presented together with photographs and graphical illustrations. The arrangement is ground-based and is designed to serve as a research tool for physiological studies. The unit consists of a hermetically sealed cabin, regenerable air-purification means, and water and food dispensers. The combination of silica gel and molecular sieve constitutes a regenerable adsorption system for removal of carbon dioxide and moisture. The system described maintains a primate unrestricted and controls its life-support system automatically.

The feeding system is sealed into the cabin with a provision to deliver and control the quantity of food and water for the enclosed primate. For convenience of storage and disposal, the food is packed in gelatine capsules. Capsules are placed on conventional sticky masking tape and rolled into a reel. A specially designed dispensing unit delivers a food capsule to the primate at preset time intervals. Functioning principles of the feeder can be utilized under zero-gravity conditions.

Results of a 25-day test run are reported.

A cardiac-pressure simulator is described and illustrated.

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I. INTRODUCTION

A cabin was built with hermetically sealable openings, feeders, and air-purification and waste-removal means. The cabin was designed to sustain an unstrapped primate for as long as 30 days. This arrangement partially simulates environment for life support in space.

An early objective was to study physiological changes in an animal during the encasement time. During this period both normal and abnormal atmospheres and varying diet were to be maintained. However, to perform such studies continuously without removing the primate from the cabin, there is need for sensors or probes to be implanted into or attached to the primate. These sensors should generate electric signals in response to changes in blood pressure or other physiological parameters. Furthermore, since the primate is unrestricted, a wireless transmission of these signals needs to be arranged. To meet this requirement both sensors and a transmitting system are being developed concurrently. Laboratory models have been constructed but they are not ready yet for actual installation in primates.

To date, experimental runs with an enclosed primate were conducted to test equipment-functioning and the primate's reactions in this environment. The primate's physical condition was recorded before and after enclosure.

The present unit is constructed of commercially available components, avoiding use of any of the biologically sophisticated but unproven life-support systems theorized by many authors. It is hoped that experimental runs with the enclosed primate will help to determine actual needs and that the whole arrangement will be improved accordingly.

II. DESCRIPTION OF THE UNIT

The unit with its life-support system is composed of sensing and regulating components, valves, ducting, tubing, condensing unit, and interconnecting wiring assembled around the cabin.

The values given below were used as design parameters and were based on the metabolic turnover of a primate weighing approximately 5 kg.

Respiratory volume	75 liters per hour
Carbon dioxide evolved . . .	4 liters per hour
Heat evolved	20 kcal (79.4 Btu) per hour
Water evolved	9 grams per hour
Oxygen consumption . . .	4 liters per hour

These values served as a guide for determination of needed quantities of adsorbent, means of heat removal, and ventilation capacities.

A ventilation blower, 75 cfm capacity, is mounted in a closed loop, located outside the cabin and connected with two outlets for air withdrawal and return. An activated-charcoal filter and cooling coils from a small refrigeration unit are also mounted in the loop. Air is propelled through the loop by the blower to remove mechanical particles and filter out some of the noxious gases. Heat removal and temperature control are accomplished by the cooling coils and thermostat.

A second closed-loop circuit is arranged to force air flow through an adsorption bed at approximately 1.2 cfm. The air is passed first through silica gel to adsorb moisture, and then through a molecular sieve to adsorb carbon dioxide. These were combined in the same adsorption bed because the metabolic relationship between the rates of generation of water vapor and carbon dioxide are relatively fixed. Therefore, controlling the relative humidity in the chamber indirectly controls the amount of carbon dioxide.

To eliminate leakage of ambient gases into and out of the cabin, attempts were made to keep the still air in the cabin at atmospheric pressure. However, cabin pressure varies because of the metabolic unbalance between CO_2 and O_2 consumption and also because of dilution of cabin air with nitrogen when the adsorption beds are purged. This happens when a small amount of cabin air, represented by the free volume in the adsorption bed, is purged to atmosphere and is replaced by the same volume of dry nitrogen.

A photograph of the unit with the enclosed primate is shown in Fig. 1.

A. Cabin

The cabin is cylindrical, 24 in. in diameter and 42 in. long and is formed of No. 10 gauge (0.1019-in.) stainless steel sheet. The all-welded construction has gasketed doors and tapped holes around the cabin to serve as outlets for air circuits, gauges and electrical wires; outlets have 1- and 2- in. standard pipe taps. The addition on top of the cabin houses the feeder. The cabin is divided into two parts--the main and waste enclosures. The

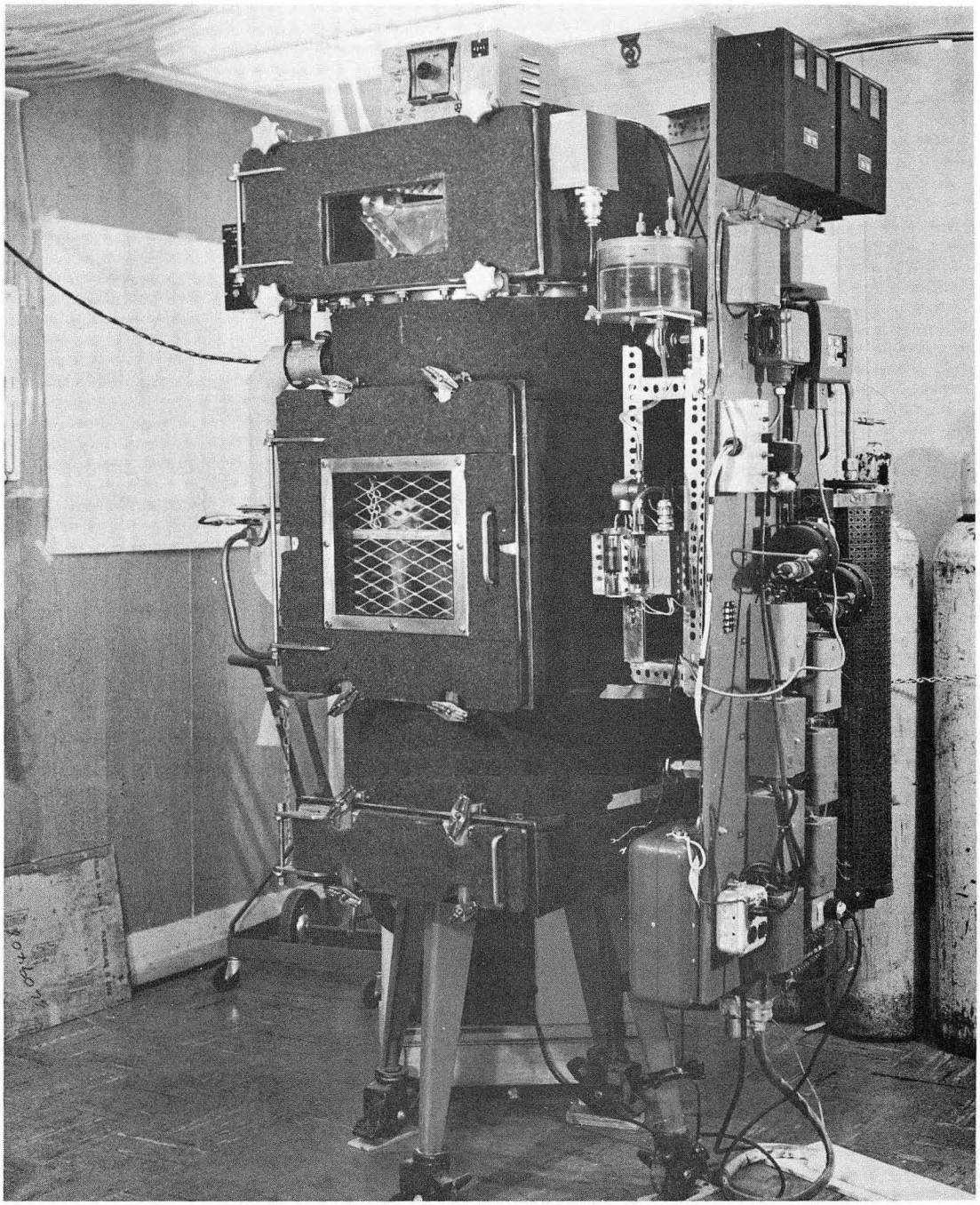

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Fig. 1. General view of the cabin with the enclosed primate.

primate is accommodated in the main part of the cabin. A small platform bracketed to the cylinder walls serves as a rest place for the primate. The lower portion of the cabin is separated from the main part by an expanded-metal sheet. The funnel-shaped bottom below the expanded metal has two openings. Two sliding blades mounted on a rotating shaft wipe off feces and deposit them through openings into bags. The shaft is driven intermittently by an electric gear motor. A timer supplies the power for the drive at preset time intervals. Provision is made to obtain samples of urine and feces during prolonged test runs without opening the cabin.

B. Oxygen Supply

Pure oxygen is supplied to the cabin from a pressurized cylinder according to demand. Air from the cabin is sampled continuously; it is taken from the discharge side of the ventilation blower, passed through the oxygen analyzer, and returned to the cabin on the suction side of the blower. When the partial pressure of oxygen inside the cabin drops below a preset value, the analyzer actuates a solenoid valve to admit oxygen from the pressurized cylinder to the cabin. When diluted air is replenished with oxygen, thus raising its partial pressure, the analyzer cuts off the power to the solenoid valve to stop the oxygen flow. This analyzer functions very well and allows maintenance of oxygen partial pressure at the desired level. From time to time the analyzer is standardized by applying a "zero reference," which is nitrogen, and a "span reference," which is atmospheric air.

C. Removal of Carbon Dioxide and Moisture*

Air is purified by being forced from the cabin through an adsorbing bed. The bed consists of an 8-in.-high column containing 615 g of silica gel, in which water vapor is removed, and of a 22-in.-high column containing 1360 g of molecular sieve, in which the carbon dioxide is removed (see Fig. 2).

Chamber air is driven through the adsorption loop by two pressure sources--the ventilation blower, and a small 28-volt dc vane axial blower located in the adsorption loop. The air is returned from the adsorber to the cabin at the suction side of the ventilation blower.

Two such beds are arranged. When one bed becomes saturated with water vapor and carbon dioxide, the air stream is directed through the second bed to start a new adsorption cycle while the first bed is regenerated by heating the bed and purging with dry nitrogen. (Four-way valves are actuated after 4 hours' adsorption.) This constitutes a regenerable system in which adsorption and desorption are carried out in a continuous cycle.

The beds are vertically mounted. They are made of aluminum and have a 2-7/8-in.-diameter cavity 30 in. long. Six fins (1/16×1 in. by 30 in.) are welded inside the cavity and on the outside surface of the bed for better (quicker) heating and cooling. Purge heaters, consisting of several strip heaters bolted to the outside fins, are connected in a parallel circuit and powered from the 230-volt ac input. Two thermostat switches are wired in series; the one associated with the adsorbing bed is at room temperature

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* Equipment constructed by Minneapolis-Honeywell, Minneapolis, Minnesota.

(and therefore continuously closed), while that associated with the desorbing bed operated to control the purge heaters on the desorbing bed so as to maintain them at approximately 300° F. The relay switching circuitry is wired in such a way as to apply voltage only to the heaters on the desorbing bed being purged.

Sequential operation of the adsorption and desorption cycles is accomplished by a timer equipped with a gear rack which drives three cams, each controlling a microswitch. The timer sequence is illustrated in Fig. 3.

On-and-off control of air flow through the adsorption beds is by a relative-humidity sensor. The same sensor controls the CO_2 indirectly because the column lengths of the two adsorbents are proportioned to accommodate the quantities of CO_2 and H_2O generated.

D. Cooling

A refrigeration unit of 1/4-hp capacity provides air cooling inside the cabin. A cooling coil (or "evaporator," as it is often called) is mounted in a closed air loop. Freon-12 refrigerant is compressed and then condensed to a liquid. This liquid is throttled down to the evaporator pressure by the thermostatic expansion valve. The result is a sharp drop in temperature of the refrigerant liquid. The cooled liquid in the coil absorbs heat from the warm cabin air that is forced through it by the blower. The coil is made of fin-tubing for more efficient heat exchange.

The cooling arrangment has suitable controls to ensure automatic operation. The cabin and ventialation ducting had to be insulated with half-inch-thick felt; this was necessary due to the high ambient temperature, which sometimes reached more than 90° F. The high room temperature accelerated the heat transfer through bare metal walls, so the refrigeration unit was not able to cool the inside air to 80° F. The felt insulation alleviated this problem.

E. Water Dispenser

Water metering and delivery to the primate is accomplished by the arrangment shown in Fig. 4. Water from the supply container is delivered via a solenoid valve to the chamber containing two magnetic level switches. These switches make or break contact when the float containing the magnet travels up and down the rod with the water level.

Starting with the empty chamber, the system functions as follows: The timer located in the control box controls the power to the normally closed solenoid valve, thus allowing water to flow into the chamber. When water reaches the preset level, the power supply to the solenoid valve is cut off by the left float and water flow is stopped. The end of the water suction nipple inside the cabin is maintained at the same height as the level where the left float breaks contact. When the chamber is full of water the training light is on—indicating water availability to the primate. The primate has learned to suck water through the nipple whenever it feels thirsty and water is available.

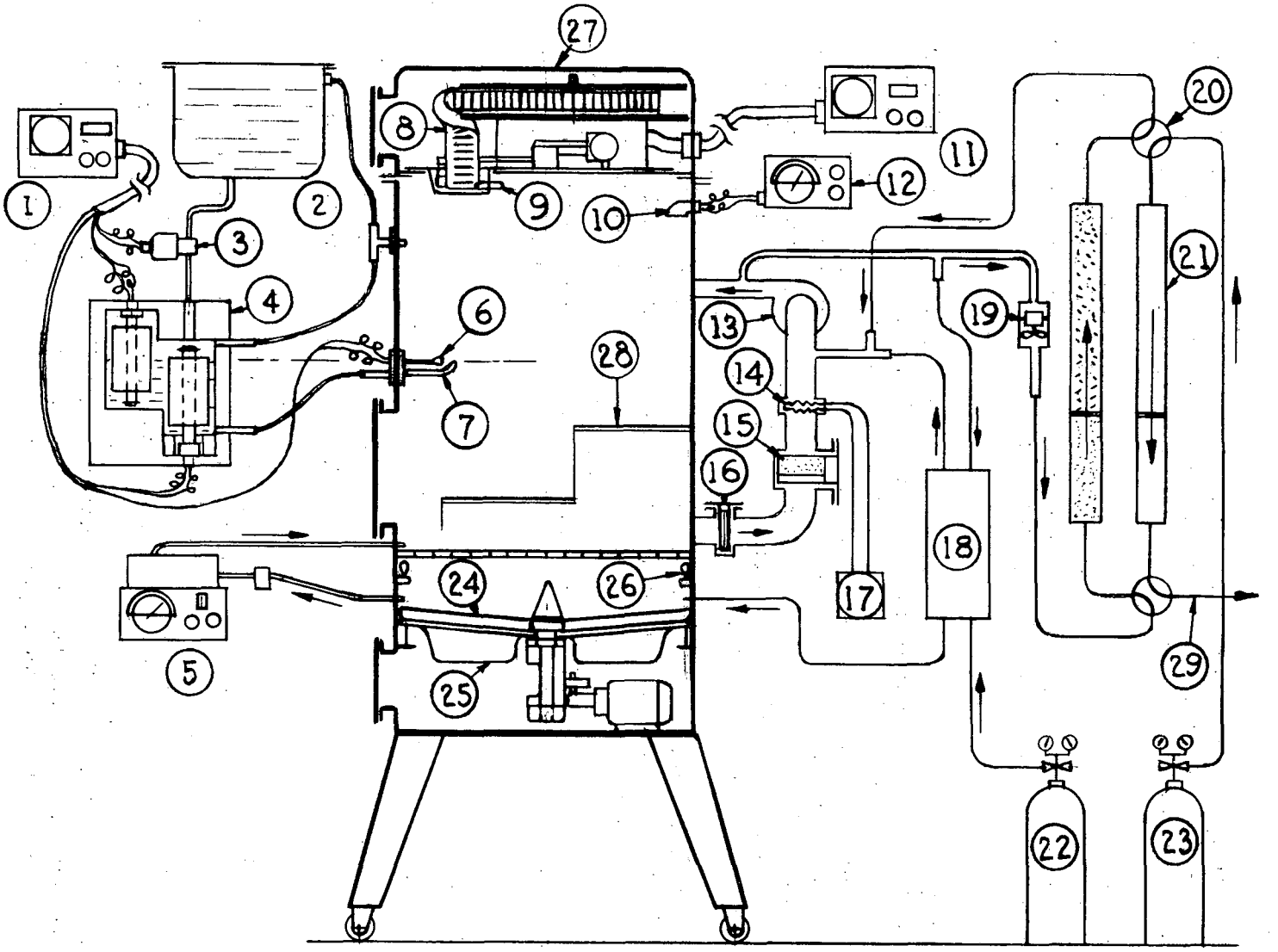

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Fig. 2. Schematic diagram of the closed ecological unit with air circuits and control units.

Component Identification

The components in the schematic diagram are:

1. Water controls
2. Water supply
3. Solenoid valve
4. Float-magnetic switches
5. CO_2 Analyzer
6. Training light
7. Water suction nipple
8. Food dispenser
9. Food delivery
10. Humidity and temperature sensors
11. Food-dispenser controls
12. Relative humidity and temperature readout
13. Main blower
14. Cooling coils
15. Activated-charcoal filter
16. Dust filter
17. Refrigeration unit
18. Oxygen analyzer
19. Booster blower
20. Four-way valves
21. Adsorption beds
22. Oxygen supply
23. Nitrogen supply
24. Waste disposal
25. Waste storage
26. Lights
27. Sealed cabin
28. Platform
29. Exhaust to atmosphere

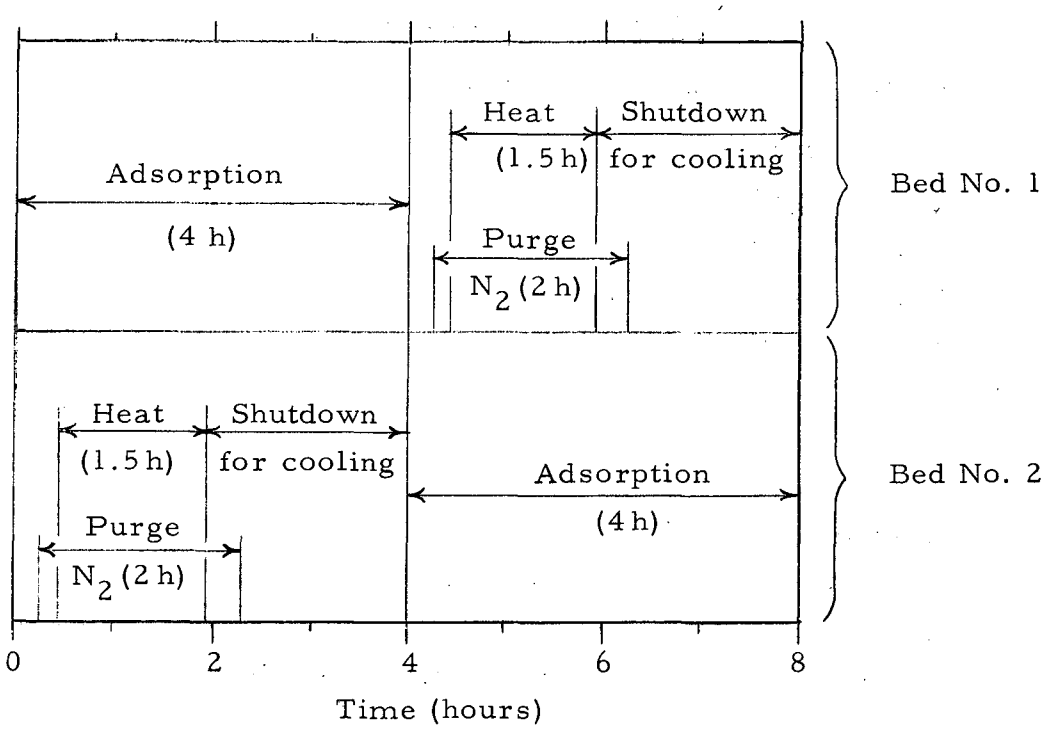

Fig. 3. Time sequence for adsorption and desorption cycles of both beds.

When the water is consumed, the level reaches the bottom of the chamber, the light goes off, and the counter in the control box advances one digit. The chamber is ready for another filling as soon as the timer mounted in the control box allows power to flow to the solenoid valve again. The chamber volume is 33 cc. Each change of one digit on the counter represents a 33-cc change in volume. The control of water supply to the primate is accomplished by manually setting the time intervals on the timer. This setting is the time interval between fillings. The present timer allows any interval between 15 minutes and 5 hours. The entire water supply system is reliable and functions well.

Originally an arrangement to accomplish the above outlined functions was constructed by using thermistors, but they did not function as expected. Some of the thermistors corroded in water. The system was not reliable and frequent failures were encountered.

F. Food Dispenser

The main objectives of this dispenser were to provide food and means of delivery to the primate during experiments. In general, the dispenser had to be able to:

1. Provide food or food mixed with medicine and vitamins

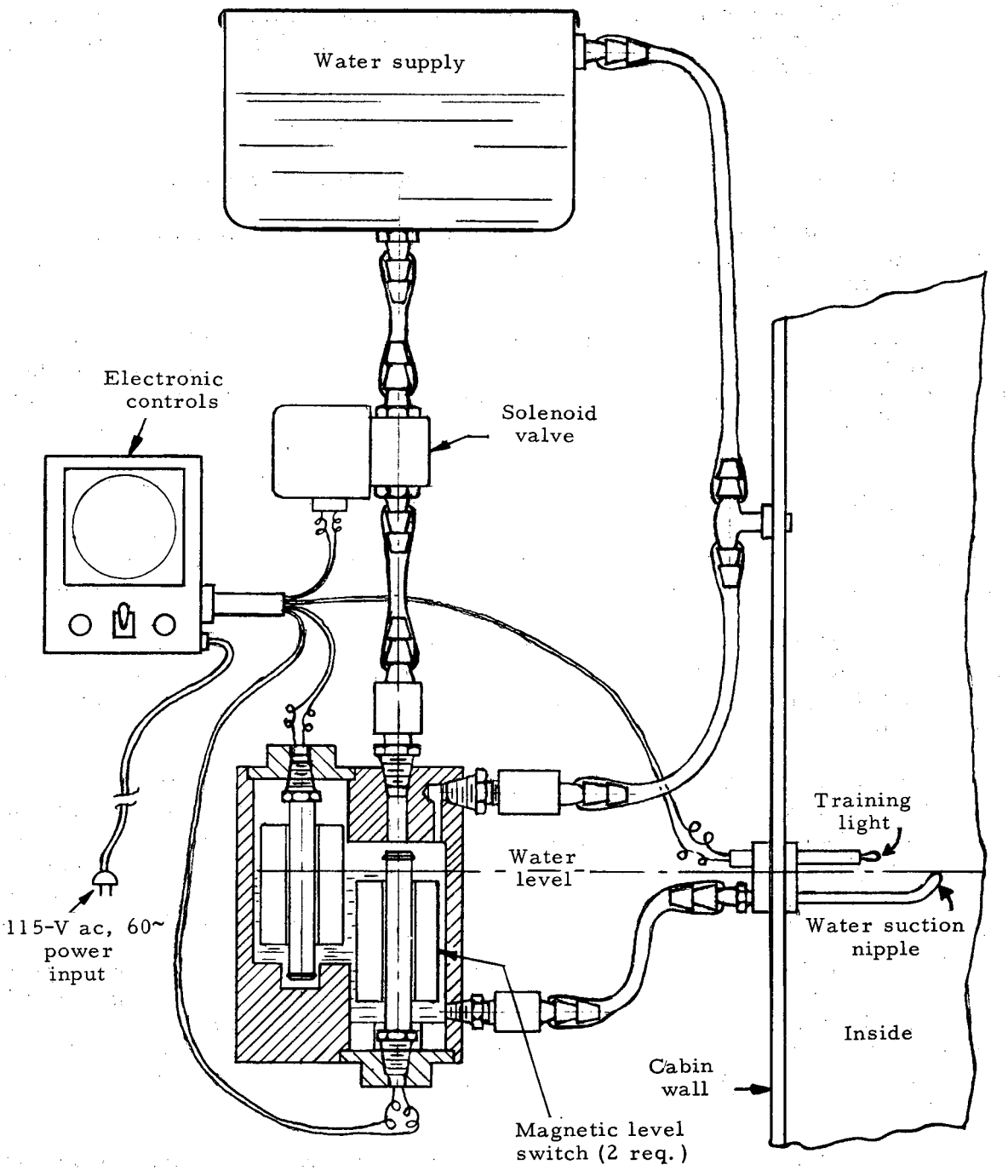

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Fig. 4. Water delivery and metering arrangement.

2. Store the food inside the cabin in such a manner that a variable diet, day-to-day or week-to-week, could be maintained in feeding the primate.

3. Be completely sealed from the outside atmosphere

4. Vary the amount of food delivered to the primate.

A unit having all the above outlined features has been constructed (see Fig. 5). It consists of a reel–where food is stored–frame, drives, timer, counter, and microswitches.

This entire arrangement is sealed on top of the cabin and hidden from the primate to prevent breakage. Wire leads to the control box are placed in a sealed plug. A small hole in the recess on the bottom plate is provided for food delivery.

Food is packed into gelatin capsules 3/8-in.-in diameter and 1-in.-long. Each capsule contains approximately 1 gram of dry food. These capsules consist of two telescoping halves, into which any food or food mixture can be packed. Then the halves can be reassembled and sealed with a drop of water. These capsules are of course consumed with the food.

Capsules filled with the desired food are placed on a sticky masking tape and rolled into a reel. Such an arrangement allows the storage of food to last for long periods of time, and makes possible delivery at preset intervals of time.

Several unique features are built into the unit. For example, the time interval for food delivery can be set from 15 seconds to several hours. If the delivered capsule is not taken by the primate, another cycle will not start, and the counter is not actuated. The entire operation is carried out automatically. Attendance is necessary only when time intervals are changed for food delivery. A complete count of delivered food capsules is maintained.

By turning a switch, this unit will bypass the timer and will operate on a 28-volt dc signal. This arrangement will deliver one capsule only if the signal is shorter than 10 seconds, and then will keep delivering food if the dc power is on continuously, providing that the food is taken by the primate. Delivery of a food capsule starts only if the preceding capsule is taken out.

This conversion (to 28-volt dc) was made for experimental behavior studies during which the primate gets food and water after performing certain tasks.

A loading device was constructed to prepare reels for the feeder–see Fig. 6. Capsules are first placed in the container on top. With the help of drives and microswitches, this device then deposits the capsules on masking tape and winds the tape into the reel. A unique feature of this loader is that the quantity of capsules is easy to control. For example, if we wish to load say 50 capsules packed with one kind of food and 50 capsules containing another kind of food, we can preset a counter to give an audible signal when the first 50 capsules are deposited on the tape. Then the other 50 capsules would be started through the loading procedure.

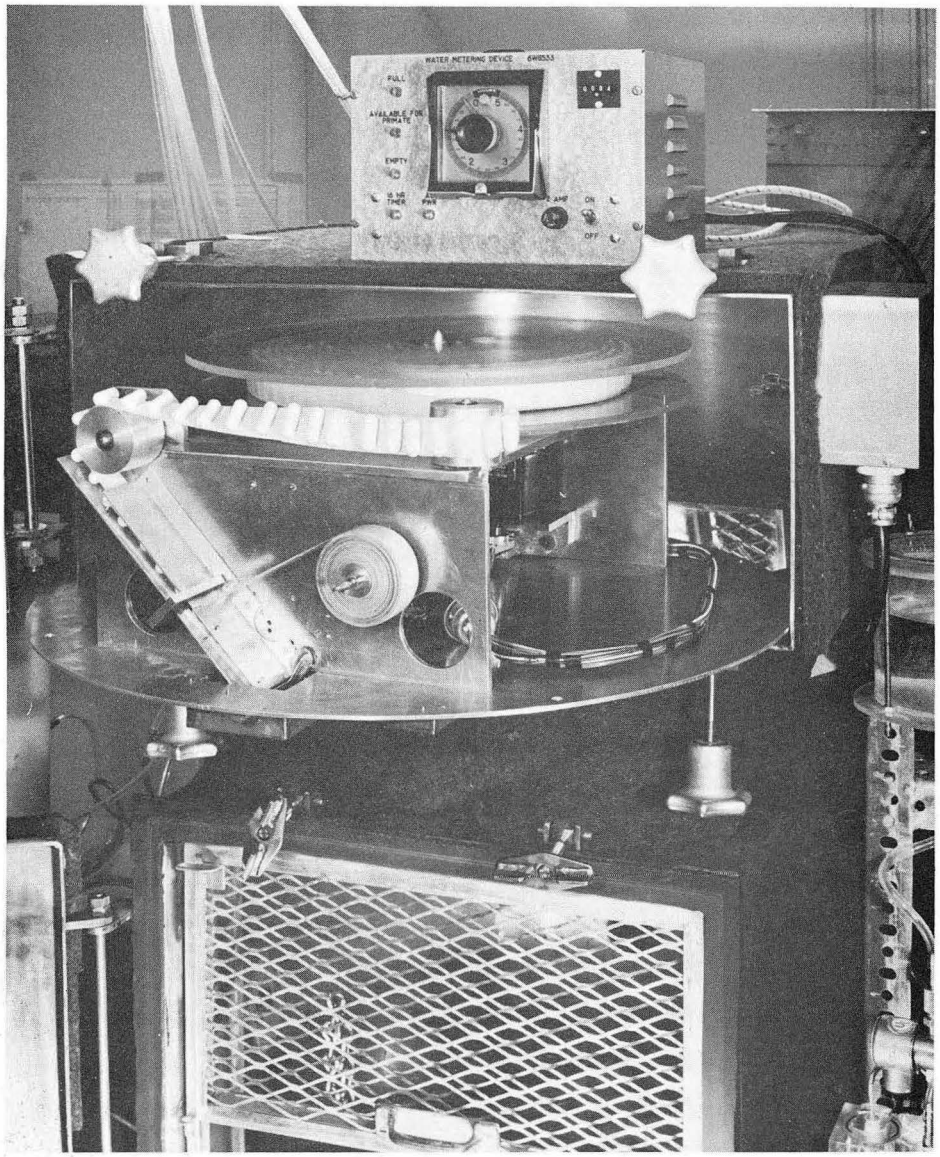

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Fig. 5. Feeder partially removed from its actual location.

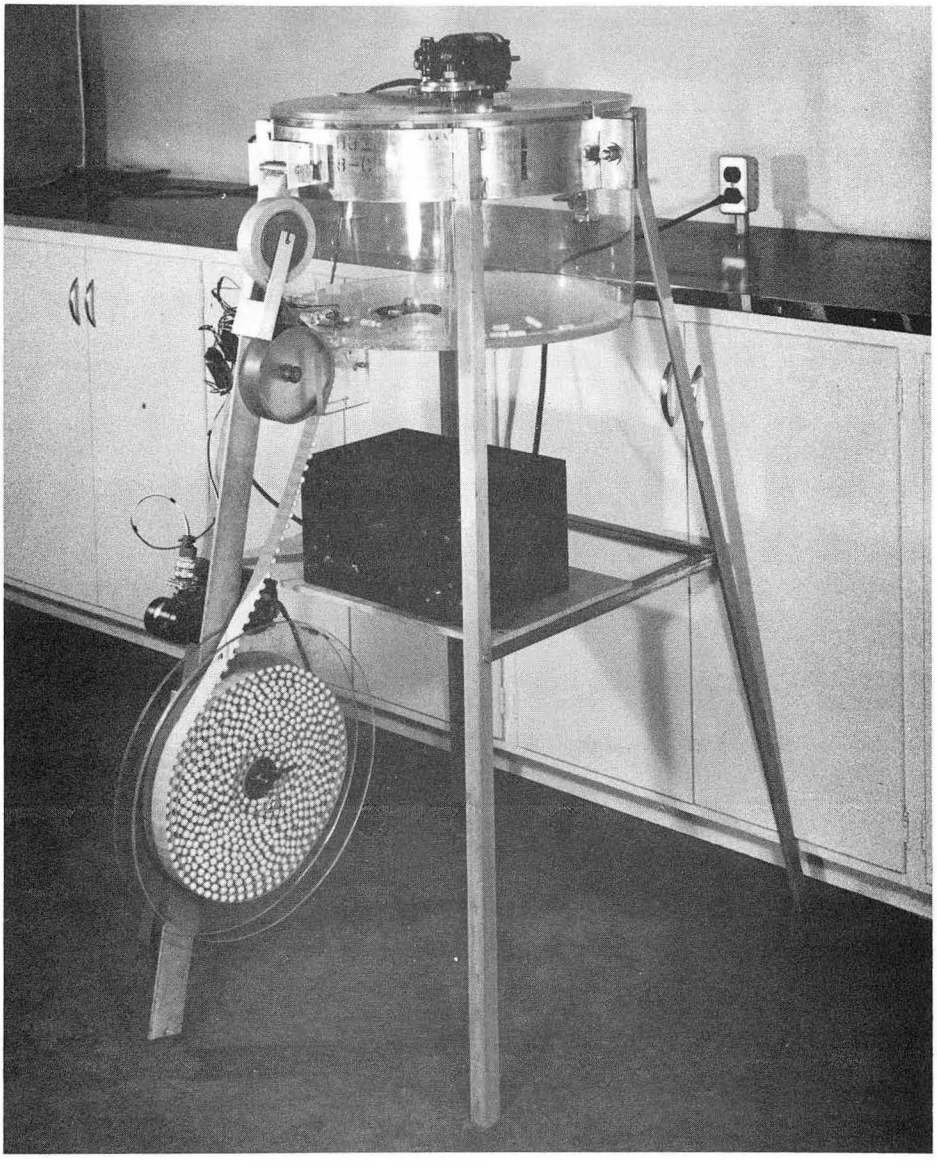

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Fig. 6. Device for automatic loading of the food capsules into the reel.

G. Instrumentation

1. Carbon dioxide analyzer: Continuous check of CO_2 level in the cabin is made with a Beckman Infrared Analyzer and strip-chart recorder.

2. Humidity and temperature sensor: Periodic checking is made of the read-out instrument, which is calibrated to read relative humidity and temperature.

3. Oxygen analyzer: This analyzer is equipped with a controller and and electronic control circuit suitable for opening a solenoid valve when the oxygen partial pressure in the cabin drops below the preset value and close it when the partial pressure is restored.

4. pH Meter: The predominant obnoxious gas in the cabin is ammonia. We have arranged comparative measurement of its quantity by pH meter. A predetermined volume of cabin air is pumped through distilled water in which ammonia is collected in solution. Then the periodic measurement of hydrogen-ion concentration is made. This kind of measurement only gives us an indication of the quantity change, and is used for comparison with previous measurements.

III. EXPERIMENTAL PROCEDURES

In general, engineering computations are not as precise as those in many branches of analysis in pure science. This is especially true in design and construction of a life-support system where multiplicity of engineering considerations have to be combined with bio-medical problems. Testing is essential to make such designs function adequately.

Several experimental runs were conducted with an enclosed primate to observe and improve the functioning of the mechanical equipment. Additional runs lasting several days were conducted to determine if the odorous gases in the cabin would be detrimental to the primate. Runs of longer duration were conducted to see the effects of the cabin environment.

A 25-day test run was conducted with a ring-tailed monkey. Her physical condition was excellent after the isolation. When the cabin was opened at the end of the run, there was a strong unpleasant odor. Despite this odor the concentrations obviously were low because the monkey lived with it unperturbed. Physical examination before and after isolation indicated no changes. Complete blood counts were within normal ranges.

The gases in the cabin originate from several sources. Flatus (intestinal gas) is one source. Flatus contains hydrogen sulphide, hydrogen, methane, and ammonia. Feces and urine are the main sources of cabin gas and–before their isolation–produce most of the obnoxious gases, due to evaporation and bacterial action.

Some of the gases listed above, together with moisture and carbon dioxide, are removed from the cabin air by the adsorption beds (silica gel and molecular sieve). These gases are discharged to the outside during purging. The rest of them are removed by the activated-charcoal filter,

which is not regenerable, but can be replaced. This filter consists of 385 grams of charcoal placed between wire mesh and porous paper in a 5/8-in.-thick 9-by 9-in.-square layer.

During a 7-day period this filter absorbed 3.7 grams per day of foreign matter. The saturation point or point of tolerable filter efficiency has not been determined but is rather important and would be desirable to establish. The problem is that there are no instruments which would measure odor and toxicity of the gases, and associate the tolerable amounts to physical stresses of the animal. This, however, may be possible to establish through behavorial studies, which we are planning to do.

The amount of accumulated odorous gases during the 25-day period was not detrimental to the primate. For us, however, the gases were almost intolerable. This is a matter of conditioning. There are many reported cases in prisons and elsewhere in which people adjust themselves to these "primitive" conditions. A reported case involving sailors on a cattle boat shows that at first odors from the cattle on board were almost unbearably offensive to the sailors. Yet within 2 to 3 days their senses were dulled to the extent that they no longer distinguished the obnoxious odors as such and reacted as though the odors were not offensive, and adjusted accordingly.

Subsequent runs will be of longer duration and attempts will be made to identify and determine quantities of the odorous gases in the cabin. Methods for behavorial studies are also being developed.

The principal food was Metrecal but capsules of dried fruit were mixed in at random (these contained raisins, prunes, apples, and peaches). The capsule ratio was 3 of Metrecal to 1 of dried fruit. The weight of the monkey before the test run was 10 lb 4 oz, and after the test run 11 lb 2 oz (a gain of 1 lb 2 oz). The gain in weight was probably because food and water was given without restriction, and monkeys have a tendency to overeat.

Food consumption was 100 grams per day, water consumption was 590 cc per day, and oxygen consumption was 2.12 liters per hour.

Although there was no indication of any weakening or physical fatigue of the primate, the experiment was terminated merely because the need for some modifications was indicated. One major modification now in progress is to make provision for urine- and feces-sampling without opening the cabin.

The following experimental work can be performed with this unit without extensive remodification:

1. Studies of long-term environmental effects

2. Baseline studies at various temperatures; such experiments are conducted to determine how long and how effectively the animals can withstand the rigors of excessive temperature

3. Survival zones under conditions of restricted diet

4. Behavorial studies in experimental psychology.

IV. CARDIAC-PRESSURE SIMULATOR

Continuous measurements of the physiological status of an animal are necessary during the enclosure period in the cabin. To perform such a task sensors, under development at the present time, are placed around an artery for the purpose of measuring pressure, pulse, or blood flow. These sensors produce an electrical signal that is sent out of the body by a miniaturized transmitter having a built-in power supply. Concurrently, work is being done to develop methods for implantation of these sensors into the animal. However, there was a need to make a quick check—without implantation—on how certain sensor configurations will function. For this purpose a device simulating cardiac pressure was built.

Plastic tubing representing the size of the artery is pressurized to the magnitude equal to "systolic ejection" pressure, and in one-half the time allowed for "diastolic filling" of the heart. Figure 7 illustrates the functioning of the device used. Incompressible fluid is being pressurized by a reciprocating piston. The piston is moved by a variable-speed drive through an oscillating arm and connecting rod. The pivoting arm converts the drive shaft's rotating motion into linear reciprocating motion and also gives a forward-to-backward stroke time ratio of 1:2. Displaced saline solution compresses the air. The air pressure can be adjusted with the second piston, mounted on a threaded rod. An adjustment is provided for increasing or decreasing the stroke of the reciprocating piston, permitting a wide range in pressures. All adjustments can be made while the simulator is running. Pressure cycles are adjustable from 0 to 150 per minute. Pressures can be adjusted from 20 to 150 mm Hg. Figure 8 shows the completed assembly.

V. RECOMMENDATIONS

1. Conduct a series of long-term runs (each of 30 days duration or longer). These exploratory runs should be directed toward improving the functioning of the life-support system, finding new techniques for various measurements, and set up of new experimental situations.

2. Study, design, and construct components that would function under a zero-gravity condition. Such components will be needed when physiological studies are expanded to include a weightless condition. Such a condition of long duration can be created only in actual orbital flight. Needless to say, this demands more from the components, and the designs necessarily become complicated. Engineering work should thus be directed to meet this condition.

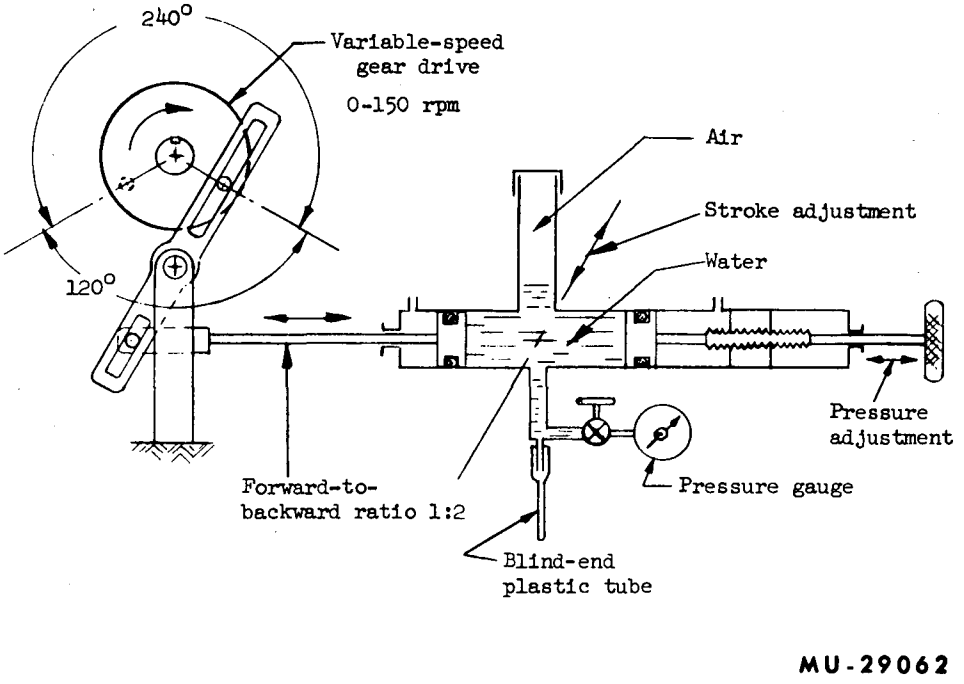

Fig. 7. Schematic arrangement of cardiac-pressure simulator.

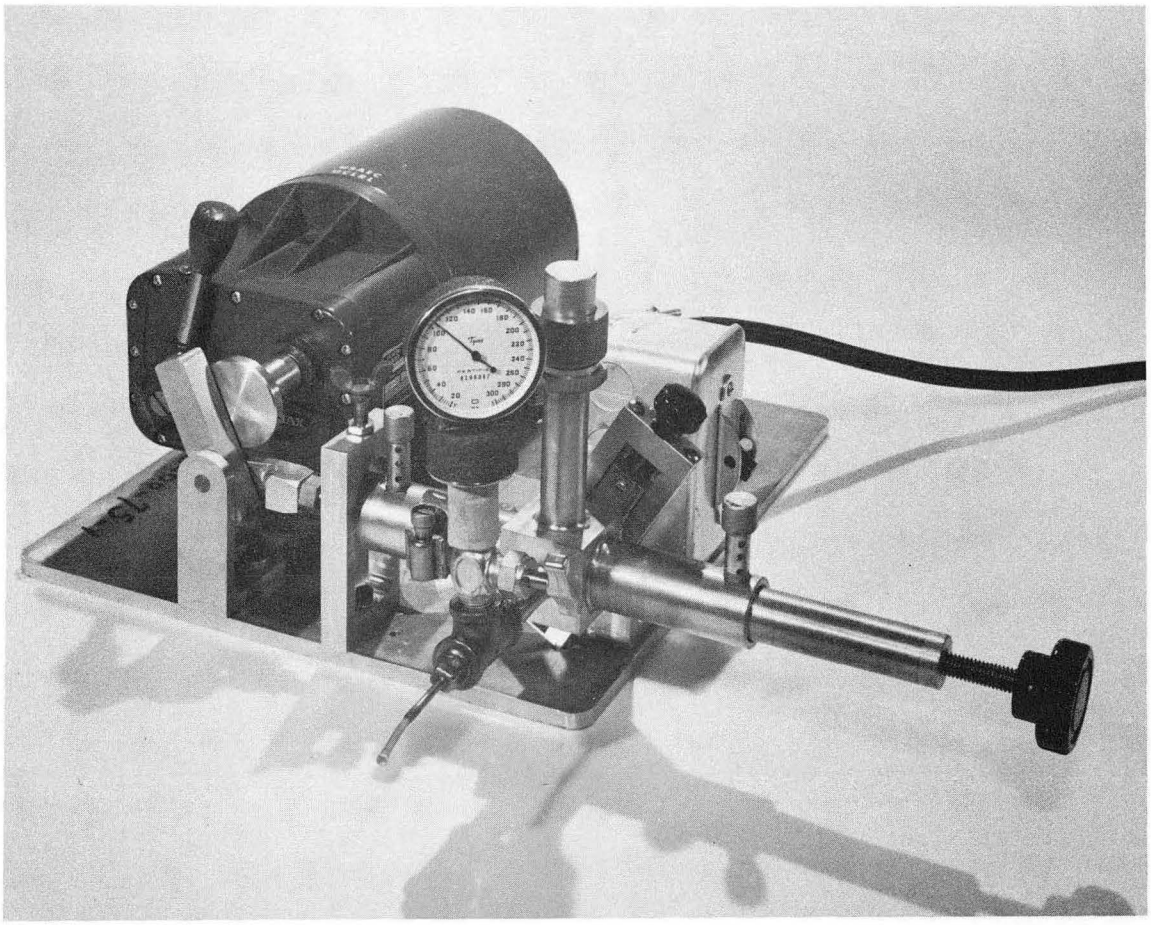

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Fig. 8. Photograph of cardiac-pressure simulator.

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