FOREWORD

This report was initiated by the 6570th Aerospace Medical Research Laboratories, Aerospace Medical Division, Wright-Patterson Air Force Base, Ohio. The design concepts for the Aerospace Environment Simulator covered herein were conceived by the principal investigator, Mr. Otto Schueller of the Altitude Protection Branch, Physiology Division, Biomedical Laboratory. Mr. Schueller's basic design concepts for the simulator were initially reported in 1957 as part of a staff study conducted by the Aerospace Medical Research Laboratories to accelerate and expand the human factors research necessary to support a manned satellite program. The research upon which this report is based was performed between November 1957 and March 1962, under the direction of Fred W. Berner, Ph.D., Technical Advisor, Aerospace Medical Research Laboratories.

ABSTRACT

A critical requirement exists for a special Aerospace Environment Simulator, complementary to other USAF test and research facilities, for studying problems of personal protection in the vacuum and thermal radiation environments of space; for indoctrination and training of astronauts in personal protective equipment, and for biomedical and ecological research related to survival of man outside the atmosphere of the earth. Existing physiological altitude test chambers, large aerospace systems environmental chambers, and balloon and orbiting laboratories are either inadequate for this purpose or too hazardous and uneconomical. This report presents a proposal for a relatively small, versatile Aerospace Environment Simulator designed to meet the specific requirement of aerospace medicine.

PUBLICATION REVIEW

This technical documentary report is approved.

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AEROSPACE ENVIRONMENT SIMULATOR

Otto Schueller

SECTION I

INTRODUCTION

The high cost and hazards of space flights necessitate the highest attainable performance and reliability of aerospace vehicles, astronauts, and personal protective equipment. Flight testing in space is extremely hazardous and expensive (one launching of a satellite costs several million dollars). Therefore, ground test facilities are required to simulate aerospace environmental conditions and to provide the most economical and practical methods to test the reliability of all components, mechanical as well as human, comprising a complex aerospace system. Realistic evaluation of the astronaut's performance under the multienvironmental stresses of space missions would require the simulation of entire space flight profiles in a continuous cycle, including emergency escape situations.

During a lunar expedition, for example, the astronaut will be exposed during launch to high G loads, noise, and vibration, and to mechanical shocks during booster separation. This will be followed by a period of near weightlessness for two and a half to three days or more, with subsequent higher G loads and mechanical shocks during landing. He will then be exposed to 1/6 G and after leaving the space vehicle in a personal protective assembly, will be in a vacuum environment and subjected to the stress of either intensive thermal irradiation during the lunar day or a cold radiative heat sink during the lunar night, accompanied by ionizing radiation and the possibility of meteoritic impacts. During the return flight, a similar sequence of environmental stresses will occur, aggravated by aerodynamic heating during reentry into the earth's atmosphere. In addition to these physical and physiological stresses, the astronaut will be subjected to high psychological tensions and excitement during the entire mission, starting with the prelaunch preparations and countdown period, and probably continuing beyond the return to the earth.

To simulate the whole sequence of events in a single facility would be ideal but impractical. It appears feasible, however, to provide a well coordinated spectrum of bioastronautical test and research tools simulating selected groups of those environmental parameters that occur simultaneously during well distinguished phases of aerospace missions such as high G loads together with altitude, vibrations and heat on a special acceleration facility to simulate launching, reentry and certain escape phases. This acceleration facility could be complemented by other research tools such as a weightlessness simulator, a multi-degree-of-freedom motion simulator, a vertical accelerator and decelerator, and a drop tower for shock, landing, and impact studies. In addition to these biomechanical test facilities, an aerospace environment simulator for simulating the high vacuum and thermal radiation stresses and effects anticipated during the phases of orbiting, interplanetary travel, lunar, and planetary explorations is essential.

Some of the components of a bioastronautical facility complex should be closely integrated to minimize any time lapse between subsequent exposures to the various environmental stresses. Thus, environmental extremes such as high and simulated zero G loads would follow immediately one after the other, and possible cumulative physiological and psychological effects could be studied without the experimental artifact of even a short recovery period. Ionizing radiation would not have to be simulated in this facility complex. The heat generated by ionizing radiation encountered in space missions is negligible compared with that of thermal radiation. For studying the problems of protection against ionizing radiation, the existing charged-particle accelerators, nuclear test facilities, and space shots can be used and the results coordinated and integrated with those of the other protective requirements.

This report is concerned with the aforementioned aerospace environment simulator. The environmental parameters simulated in this facility are: (a) direct solar radiation, (b) indirect solar radiation scattered and reflected from planets and their atmospheres and from space vehicles, (c) the infrared radiation emitted from planetary surfaces and equipment, (d) the radiative heat-sink of the star-speckled, black sky, (e) the high vacuum of space, and (f) the known planetary atmospheres. Ground test facilities to simulate these specific parameters as they exist in orbits around the earth and the nearer planets, Mars and Venus, and the environmental extremes on the moon have been suggested by the Aerospace Medical Research Laboratories (AMRL) during the past four years in various papers (refs. 2, 13, 14 and 15). The Air Force need for the proposed simulator follows from Air Force involvement in a number of contractual and in-house projects on the problems of intra- and extra-vehicular personal protection during aerospace missions. The results of much of the effort expended on these projects will remain academic until the theoretical investigations can be compared, proved, and corrected by practical experiments and tests in the type of facility proposed. The feasibility of constructing aerospace environmental simulation facilities large enough for testing full-scale aerospace vehicles has been established by the Arnold Engineering Development Center (AEDC), Tullahoma, Tennessee (refs. 7, 8).

The Aerospace Medical Research Laboratories, which has both, suitable buildings for containing the proposed facility and the volunteers required in statistically valid numbers for bioastronautical serial experiments, is considered an ideal location for the facility, considering:

1. An aerospace environment simulator is a necessary complementary research tool to existing AMRL facilities such as the physiological altitude chambers, the biothermal and humidity altitude chamber, and the heat chamber. It would also complement such AMRL biomedical research tools as the dynamic escape simulator and the weightlessness simulator. On locations lacking these complementary facilities, the aerospace environment simulator would be somewhat isolated.

2. A core of medical and observation teams experienced in monitoring and operating physiological altitude chambers, and engineers and technical personnel competent and skilled in cyrogenics, oxygen equipment and high vacuum and radiation techniques are available at AMRL for biomedical monitoring and for technical operation and maintenance of the aerospace environment simulator.

The design criteria for any test facility are determined by the special problems to be studied. Personal environmental protection is one of the major and typical problem areas of bioastronautics; therefore, this problem area shall be discussed and defined first.

SECTION II

THE PERSONAL PROTECTION PROBLEMS

The problem complex of personal environmental protection has raised much controversy. One school of thought recommends the so called "shirt sleeve environment," that is, the design engineer of spacecraft and personal protective equipment should provide the normal earth environment to which man is adapted through his long evolution process.

Another school concludes, from experiences with oxygen systems and pressure suits for high altitude flight, that use should be made of man's natural environmental tolerances to the extent that the quality of his performance is unimpaired.

Still another school, extending certain methods of heart surgery, suggests changing the human organism to adapt it directly to the space environment by the use of such extra-corporeal devices as the heart-lung machine for artificial oxygenation of the blood, artificial kidneys, and plastic covering of the skin.

The essential requirements of personal environmental protection and the prospectives of these various schools of thought are condensed in the following conclusions of A.M. Mayo (ref. 10):

> The critical requirement is not only a satisfactory physical environment but a total environment, physically and psychologically conducive to the human operators most important functions, his clear thinking and free decision-making ability. These are the functions justifying why man's role in space cannot be replaced by machines.

Any system subjecting the man to an environment significantly different from the normal earth environment should be scrutinized to insure that obvious advantages are not far outweighed by resulting reductions in man's efficiency.

In view of the very long evolution process of man, it is likely that very radical changes can be made in the machine in shorter time and with more certainty of results than even minor changes to the human operator. The Russians have proved this point. Unrestricted by weight limitations, they have supposedly provided a normal atmosphere in their first manned orbital flights.

It would, however, be irresponsible to follow their footsteps in this direction and to generalize without discrimination. The shirt-sleeve environment is certainly a desirable goal for the future, particularly for long-term missions on space stations and lunar bases. But the word "shirt sleeve" should not be taken too literally. Even the Russian astronauts were not in shirt sleeves but wore an emergency pressure suit. The objective should be to modify and improve present emergency pressure suits, so that they approach the comfort of shirt sleeves during normal operation and still protect the man in case of decompression of the space cabin or malfunction of the air-conditioning system.

For missions of shorter duration, particularly for extravehicular space suits and space-worker capsules, and also for emergency situations, a judicious utilization of man's tolerances and adaptability to decreased atmospheric pressures and temperature extremes will undoubtedly lead to greater reliability, efficiency, and economy of future aerospace systems and their components.

Therefore, the basic principles of pressure protection and heat control shall briefly be reviewed in their physical and biological aspects, and a few promising concepts for their application discussed.

Pressure Protection

The primary reason man requires pressure in his environment is to maintain adequate oxygenation of the blood. A minimum pressure of approximately 140 mm Hg, breathing pure oxygen, is required. This represents the final physiological boundary for all practical purposes. This minimum internal lung pressure of 140 mm Hg also determines the external pressure requirements, because even small degrees of pressure differential across the chest are poorly tolerated. The pressure supply to the lungs must in any case be pneumatic. But there are two basic ways to supply the required external pressure:

1. By surrounding the body with a gas or liquid of the same pressure as the air pressure in the lungs, e.g.. full pressure suits and pressurized capsules and compartments

2. By applying mechanical pressure to the skin equal to the air pressure within the lungs, e.g., the capstan partial-pressure suit and the mechanical pressure suit proposed by H.A. Mauch in his "Proposal for the Development of an

Individual Protection System for Short Term Missions Outside a Space Vehicle."*

The common bladder suit and the multi- or microcell bladder suit may be considered as a combination of pneumatic with mechanical pressurization.

Design engineers prefer to keep the pressure within space suits and capsules as low as possible to reduce total weight, leakage rates, and sealing problems and to improve mobility and comfort and; thereby, increase reliability and safety. The limitation of low pressure will be determined by the effect on the required quality of the astronaut's performance.

Sufficient information is not yet available on the effects of long-term exposure to pure oxygen and gas mixtures at decreased atmospheric pressures, and on the effects of the total absence of nitrogen. Experience in high altitude flight, and studies of mountain dwellers, indicate a wide tolerance range and adaptability of man to lower atmospheric pressures and pressure changes.

Examples:

> In 1962, experiments were conducted at the U.S. Naval Missile Center, Point Mugu, California, using human test subjects in pressure suits at a simulated altitude of 34,000 feet for five days. In an oxygen atmosphere, a pressure of 180 mm Hg or 3.5 psi was tolerated for the 120-hour period without significant impairment of the wearer's efficiency (ref. 4).
>
> In 1954 in experiments in the altitude chambers of the Aerospace Medical Laboratory at Wright-Patterson Air Force Base at simulated altitude of 50,000 feet, six men fitted with MC-1 capstan partial pressure suits tolerated 100% oxygen at a pressure of 140 mm Hg or 2.7 psi for six hours and one man for seven hours. They experienced only mild fluctuating bends in the joints, and fatigue but could adequately perform the required mission.†

The increase in safety, reliability, mobility, and comfort is inestimable if, for example, a space suit or capsule could be pressurized with only one fifth (about 150 mm Hg) of an atmosphere instead of a full atmosphere; 150 mm Hg is approximately the partial pressure of the oxygen in the normal earth atmosphere.

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*Mauch, H.A., unsolicited proposal, Mauch Laboratories, Inc., Dayton, Ohio, 14 December 1958.

† Kaufman, William C., Ph.D., Major, USAF, personal communication.

One of the most urgent and important tasks of aerospace medicine is to determine, by systematic serial experiments on a scale that provides statistically valid results, the boundaries of human tolerance and adaptability to low-pressure atmospheres of various composition for various durations of exposure and activities of man.

Heat and Humidity Control

Pressure protection is inseparable from simultaneous heat and humidity control. Heat exchange of the human body and the surroundings can be effected in four basic ways: (1) conduction, (2) convection, (3) radiation, and (4) evaporation of water from the lungs and skin. The most essential facts the design engineer has to consider with regard to heat and humidity control in aerospace missions are: (a) cooling of the human body by conduction, convection, and radiation becomes ineffective as the temperature of the surrounding air or walls approaches approximately 35° C (95° F) and (b) cooling by evaporation of water from the lungs and skin remains as the only physical principle for survival of man during extended exposure to surrounding temperatures above 35° C (95° F). There is obviously no cooling effect if the surrounding air is already saturated with moisture and the sweat runs off without evaporation. A man can stand exposure to a temperature of 120° C (250° F) for a short period of time (about 20 min.) if the air is dry, but a temperature of 35° C (95° F) may in a few hours be fatal if the air is saturated with moisture. Evaporative cooling is most effective in a vacuum environment. The great importance and efficiency of evaporative cooling is evident by the following consideration:

> To remove the heat output of an average man at rest, 70 kcal/hour, requires the evaporation of only 120 grams/hour or cc/hour of water. But to remove the same heat output solely by convection would require a ventilation rate of about 4,600 cft/hour or 63 kg/hour of oxygen at a pressure of 258 mm Hg = 5 psi and a temperature rise of 10° F (5.6° C).

The application of simple evaporation of water from the skin in a vacuum environment together with mechanical pressurization offers a much higher safety factor than the full-pressure principle with a complicated ventilation and air-conditioning system. The mechanical pressure suit need not be airtight but the degree of communication of the skin with the vacuum must be controlled. The boiling point of water depends directly upon the ambient atmospheric pressure as indicated in table 1. At a pressure of 4.6 mm Hg corresponding to an altitude of 114,000 feet, for example, water boils at a temperature of 32° F, the normal freezing point at atmospheric pressure.

The simplicity and reliability offered by the use of evaporative cooling by exposure of the skin to controlled vacuum has not yet been exploited. A systematic experimental study of this method in its physiological aspects is an important and urgent task. The same method can be applied to semipneumatic types of pressure suits such as the common bladder suit and the multi- or microcell bladder suit using existing altitude chambers for preliminary experiments. The pressure achievable in these chambers, however, is in the order of a few mm Hg or at best

TABLE 1

BOILING TEMPERATURE OF WATER OR SUBLIMATION TEMPERATURE
OF ICE AT VARIOUS ALTITUDES AND PRESSURES*

Altitude Feet	Pressure mm Hg	Boiling Temperature of Water or Sublimation Temperature of Ice	
		° C	° F
0	760	100	212
63,000	47	37	98.6
100,000	8.3	8.5	47.3
200,000	0.17	-35	- 31
300,000	7.6×10^{-4}	-76	-105
400,000	1.35×10^{-5}	-98.4	-145

*Extrapolated from Handbook of Chemistry and Physics, 40th Edition, 1958-1959, (Editor) Charles D. Hodgman, M.S., Chemical Rubber Publishing Co., Cleveland, Ohio, p. 2324.

a few tenths of a mm Hg, and imposes severe limitations in this research area (see table 1). The final tests of this principle require a chamber with higher vacuum capability and thermal radiation conforming to the actual conditions in space.

This brief review of the basic principles of pressure protection and heat and humidity control of man himself suggests how human tolerance and adaptability to decreased atmospheric pressures and the body's heat control mechanism could be utilized to make personal protective assemblies and whole systems more practical, reliable and safe. We come now to the next problem area, the heat exchange of the protective assembly with the surroundings.

Heat Exchange of Protective Assemblies with Space Environments

Maintenance of a somewhat comfortable climate within a space suit or space capsule is an extremely intricate and severe problem, usually underestimated. When an air-conditioning system fails on the ground, as frequently happens, this means no more than a little discomfort. But when it fails in space or on the moon, this may be fatal for the man or even for a whole expedition.

The comfort zone for man is very small. At normal atmospheric pressure, sedentary or slightly active men are comfortable when the dry-bulb temperature of the surrounding air is within the range of 23 to 25° C (73 to 77° F) and the relative humidity is within a range of 25 to 60%. At the lower pressures in a closed-cycle ventilated capsule or in a space suit, these values will be somewhat different due to the higher speed of movement of the air and the increased cooling effect by evaporation of water from the skin.

The small comfort zone of man (of about 4° F) has to be maintained against his own varying heat output of about 70 kcal/hour at rest to about 500 kcal/hour at heavy work on one side and against the extremely varying external environmental conditions on the other side; such as, for example, the surface temperatures and thermal radiations on the moon, which may vary from about plus 130° C (plus 270° F) with a solar irradiation of 1200 kcal/m^2/hour during the lunar day to about minus 150° C (minus 240° F) with a cold, radiative heat sink of about 4° K (minus 453° F) during the lunar night.

Concerning the heat control problem, the design criteria for life support systems and personal protective assemblies are determined by the summation of the most extreme external and internal environmental parameters; such as,

Lunar day or continuous orbiting in sunshine at the time of highest heat generation by man and equipment

Lunar night or periods of orbiting in the shade of the earth or a planet during the period of lowest heat generation by man and equipment

The aerodynamic heating period during reentry

The major problem of temperature control on space cabins and space suits is rather to keep the man cool enough in a hot environment such as that during the lunar day, than to keep him warm enough in a cold environment such as that of the lunar night. The latter requires only an effective thermal insulation, for which purpose the vacuum of space can be utilized in a similar manner as the vacuum of thermos bottles. But to cool a space suit or cabin, heat has to be removed into the outside surroundings. The lack of an atmosphere in space and on the moon excludes heat transfer by convection which is the main contributor to heat exchange under normal conditions in our daily life. In the vacuum environment of space, two physical principles of heat exchange can be applied: (1) heat exchange by radiation and (2) heat removal by evaporation of an expendable coolant. A third principle, conduction, accounts for heat exchange only occasionally as, for example, when parts of a protective assembly are in contact with the lunar surface. Weight limitations and the high cost of transportation into space, however, restrict the use of expendable coolant (such as water) to situations where it is absolutely necessary; e.g., for emergency and reentry, and demand utmost utilization of heat exchange by radiation. The temperature control system may be a modified version of a conventional fluid-cycle heat pump or an advanced electrical heat pump utilizing the Peltier effect. Whatever system is used, the heat pumped to the condenser of the refrigerator or to the hot thermopile of the electrical heat pump, finally has to be emitted into space by a radiator. The basic principles of radiative heat exchange as essential for heat control of personal protective assemblies shall, therefore, be reviewed briefly and illustrated by some examples:

The overall temperature in a protective assembly, such as a space suit or space capsule, is determined by the following factors:

The heat absorbed from the sun, earth, or other planets, the moon or a space vehicle

The heat generated internally by man and equipment

The heat emitted from the external surface by radiation

The heat removed by an expendable coolant

At equilibrium, the energy balance is simply:

Heat absorbed + heat internally generated = heat emitted by radiation + heat removed by expendable coolant.

The heat absorbed and the heat emitted by radiation depend upon the shape of the protective assembly, the optical surface properties of spectral absorptivity, emissivity, and reflectivity, and the distribution of the heat throughout the assembly. The influence of shape and optical surface properties is best illustrated by a few examples:

Black Capsule in Earth Orbit

Consider a spherical capsule with a cross section of one square meter circling around the earth in sunshine in a 300-mile orbit. The heat generated internally shall be 400 kcal/hour. The capsule would first be coated with black paint and be kept at room temperature of about 80° F or 300° K. A perfect black body at this temperature emits approximately 400 kcal/m^2/hour. The direct solar irradiation in the earth's orbital space (and at the moon) is about 1200 kcal/m^2/hour. The direct solar irradiation hits only that fraction of the whole body area that is projected against the sun, but the whole surface area is available for emission. The area of a sphere projected against the sun is, in any position, the same and equal to the cross-sectional area (in our example, one square meter). The total surface area of a sphere is four times the cross-sectional area (in our example, four square meters).

The capsule would also be heated by a large fraction of reflected solar radiation that is scattered from the earth and its atmosphere. This fraction is called albedo and averages about 35% of direct solar radiation or up to about 430 kcal/m^2/hour.

A third source of heat input is the invisible infrared radiation emitted from the earth and its atmosphere, that amounts to about 110 to 280 kcal/m^2/hour.

The heat balance for our black capsule then would be approximately as shown in table 2. This example shows that the heat absorbed and internally generated could not be removed from a black capsule solely by radiation, and that some expendable coolant (about 1 liter of water per hour) would be required to keep the capsule at room temperature. Without removal of about 300 kcal/hour by an expandable coolant, the black capsule would reach an equilibrium temperature of 314° K or 106° F.

TABLE 2

BLACK CAPSULE IN ORBIT AROUND THE EARTH*

	kcal/hour
Heat absorbed:	
1. Direct solar irradiation	1200
2. Solar radiation reflected from earth (Albedo)	100
3. Infrared radiation from earth	200
Total heat absorbed	1500
Heat internally generated	400
Total heat to be removed	1900
Heat emitted by radiation	
$4m^2 \times 400$ kcal/m^2/hour =	1600
Heat to be removed by expendable coolant	300
Total heat removed	1900

*Assumed polar orbit in continuous sunshine, low albedo.

White Capsule in Earth Orbit

The effectiveness of spectrally selective coating is shown below:

About 98% of the solar energy is carried by the solar spectrum in wave lengths from 0.2 to 3 micron. This is in the region of the ultraviolet, visible light, and near infrared, with the maximum at about 0.5 micron in the yellow part of the visible spectrum. But about 96% of the energy of a radiator at room temperature of 80° F or 300° K is carried by the invisible far infrared in wave lengths from 5 to 50 microns, with the maximum at about 10 micron (see figure 1 and ref. 18).

Should we coat our capsule with a white paint consisting of silicon alkyd pigmented with rutil, which absorbs only 20% of the direct solar radiation, and reflects the remaining 80%, but which behaves in regard to the long wave infrared almost like a perfect black body with an emissivity of 95%, the heat balance for our capsule would be completely different from that of the black capsule, and would be approximately as shown in table 3. The absorption of the coating for the energy reflected

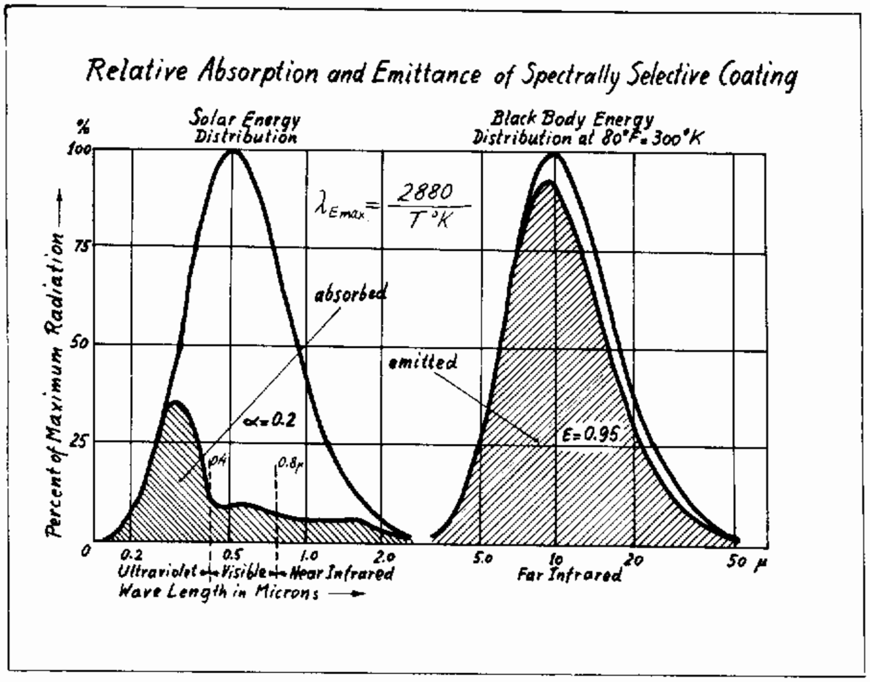


Figure 1. Relative Absorption and Emittance of Spectrally Selective Coating

TABLE 3

CAPSULE WITH SPECTRALLY SELECTIVE COATING
IN ORBIT AROUND THE EARTH*

	kcal/hour
Heat emitted by radiation at 300° K or 80° F =	
Total heat removed: 0.95 × 1600 kcal/hour	1520
Heat absorbed:	
1. Direct solar irradiation: 0.2 × 1200 kcal/hour =	240
2. Earth albedo: 0.18 × 100 kcal/hour =	20
3. Earth infrared: 0.95 × 200 kcal/hour =	190
Total heat absorbed:	450
Heat internally generated:	400
Additional heat to be generated internally:	670
Total	1520

* Assumed polar orbit in continuous sunshine, low albedo.

from the earth and its atmosphere is a little lower than for direct solar radiation (18% instead of 20%), because the atmosphere absorbs most of the short-wave ultraviolet which would also be absorbed by the coating if it were reflected from the earth.

Table 3 shows that no expendable coolant is now required but that an additional 670 kcal/hour must be generated internally to keep the capsule at 80° F. Without this additional heat generation, the capsule would reach an equilibrium temperature of only 257° K or 3° F.

Gray Capsule in Earth Orbit

Any desired temperature between 106° F of the black capsule and 3° F of the white capsule could be obtained by a gray capsule, by a capsule with black and white fields, or by a capsule half black and half white with adjustable orientation towards the sun.

White Moon Suit During Lunar Day

Unfortunately the same white, spectrally selective coating which proved so effective in earth orbits, would completely fail on the moon if no other means for temperature control were provided. The reason lies in the temperature extremes of the lunar surface, from about plus 275° F during the lunar day to minus 243° F during the lunar night. During the lunar day, the infrared radiation from the moon surface and from crater and mountain walls irradiates the body surface from all sides, while the parallel incident sun rays only strike the part of the surface projected against them. Figure 2 illustrates this situation on a man working in a moon suit. The radiation emitted from a body increases with the fourth power of the absolute temperature. While a black body at 300° K emits about 400 kcal/m^2/hour, it will emit at 400° K (the surface temperature of the moon).

$$(400/300)^4 \times 400 \text{ kcal/m}^2\text{/hour} = 1270 \text{ kcal/m}^2\text{/hour}$$

This is about three times more. The volcanic material on the surface of the moon behaves almost like a black body. The energy maximum of the emitted radiation lies according to Wien's law at a wave length of:

$$\lambda E_{max} = 2880/T = 2880/400 = 7.2 \text{ microns}, \ (T \text{ in } °K)$$

in the long wave infrared. A suit coated with the same spectrally selective coating as our white capsule discussed above, this is a coating with 20% absorptivity for the solar radiation and 95% absorptivity or emissivity for long wave infrared, would almost completely absorb the infrared radiation of the lunar surface and would reach an overall temperature of about 390° K or 242° F, if no heat were removed by an expendable coolant. To keep the overall suit temperature at 80° F would require the evaporation of 1.6 liters of water per hour (table 4).

The situation shown in figure 2 is an extremely severe one, and lunar expeditions will try to avoid landing in a valley or crater. Such situations, however, will be encountered and protective equipment must be provided to cope with them in the future, although the first landings may be attempted during the lunar night.

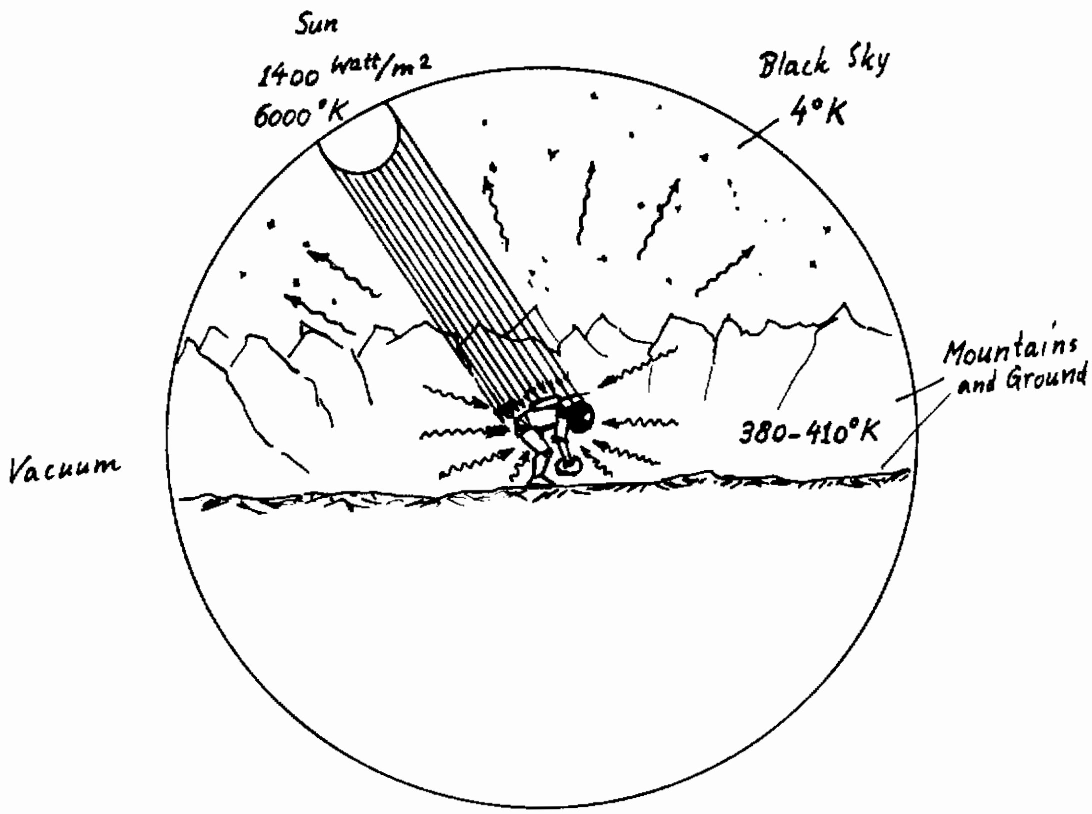


Figure 2. Lunar Day, Man Working

White Moon Capsule During Lunar Night

Figure 3 shows another extreme situation, a man at rest in a moon capsule during the lunar night. If the same coating with an emissivity of 95% for long wave infrared were used as above, the heat of the capsule would be emitted into space and the capsule would cool down to a temperature of 178° K or minus 139° F, if no additional internal heat source were provided. To keep the capsule at 80° F would require the generation of 1,665 kcal/hour by an additional internal heat source (table 5).

TABLE 4

MOON SUIT WITH SPECTRALLY SELECTIVE COATING DURING LUNAR DAY

	kcal/hour
Heat absorbed:	
1. Direct solar irradiation:	
0.2×1200 kcal/m^2/hour $\times 0.5$ m^2 =	120
2. Moon albedo (= 7%):	
$0.18 \times (0.07 \times 1200$ kcal/m^2/hour) $\times 0.6$ m^2 =	10
Moon infrared (400° K or 260° F):	
0.95×1270 kcal/m^2/hour $\times 0.8$ m^2 =	965
Total heat absorbed	1095
Heat internally generated:	
Man 300 kcal/hour, equipment 100 kcal/hour	400
Total heat to be removed	1495
Heat emitted by radiation at 300° K or 80° F:	
0.95×400 kcal/m^2/hour $\times 1.4$ m^2 =	530
Heat to be removed by expendable coolant	965
Total heat removed	1495

White Moon Capsule with Adjustable Venetian Blinds for Lunar Day and Night

From the last two examples, the problems of temperature control on lunar protective assemblies can be defined:

During the lunar day, the infrared radiation from the lunar surface and the solar radiation has to be reflected and at the same time the internally generated heat has to be emitted to avoid overheating. During the lunar night, the exact amount of internally generated heat must be emitted; neither more nor less. If more heat were emitted than generated internally the capsule would cool down. If less heat were emitted, it would become too warm even during the lunar night. If, for example, the man were put into a large Dewar vessel, he may suffer heat stroke resulting from his own metabolic heat generation if the heat were not removed by an expendable coolant.

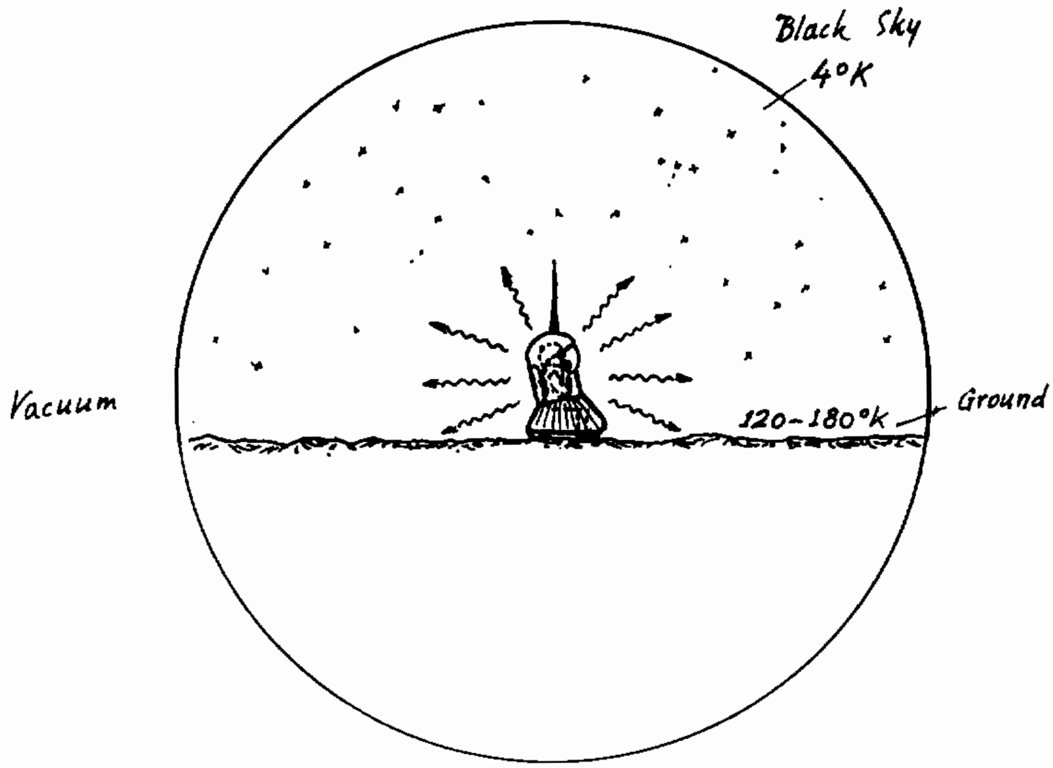


Figure 3. Lunar Night, Man at Rest

TABLE 5

MOON CAPSULE WITH SPECTRALLY SELECTIVE COATING DURING LUNAR NIGHT

	kcal/hour
Heat emitted by radiation at 300° K or 80° F:	
0.95×25 kcal/m^2/hour $\times 5$ m^2 = Total heat removed	1900
Heat absorbed:	
Infrared from lunar surface (150° K or −190° F): 0.95×25 kcal/m^2/hour $\times 4$ m^2 =	95
Heat generated internally:	
Man at rest 70 kcal/hour, equipment 70 kcal/hour =	140
Additional heat to be generated internally:	1665
Total	1900

The same surface cannot reflect the infrared radiation from the lunar surface and at the same time emit into space the internally generated heat in the same spectral region. This dilemma can be partially solved by the use of metallic or metal coated, adjustable Venetian blinds, on an assembly with a white, spectrally selective surface, as indicated on figure 4.

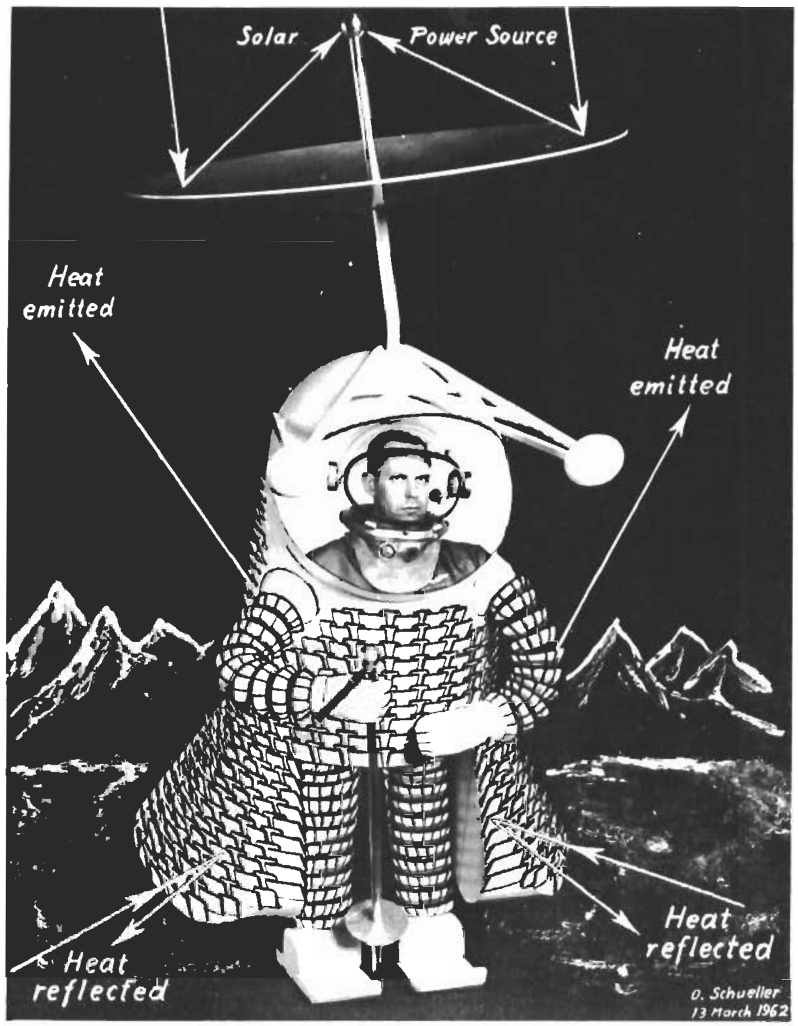


Figure 4. Moon Capsule with Venetian Blinds and Spectrally Selective Coating

Rockes, Southend, 1964 (op. cit.)

During the lunar day, the blinds can be opened and the openings directed towards the sky. A large fraction of the infrared radiation from the lunar surface would be reflected back and the white surface coating of the assembly would be shielded against direct lunar surface radiation. On the other hand, the white spectrally selective coating can emit heat through the channels between the blinds to the black sky and also reflect a large fraction of the solar radiation partially incident through the slits.

During the lunar night, the blinds can be closed to prevent too large a loss of heat by radiation from the white surface.

Such an arrangement would eliminate or at least minimize the requirement for an expendable coolant as well as an additional heat source.

These examples are intended to illustrate, in a simplified way, basic principles of radiative heat control and to demonstrate the sensitivity and complexity of the problem. Actually the problems are far more complex. For example, we have not taken into consideration the unequal heat distribution throughout the protective assembly and the influence of various orientations with respect to the sun. An upright man on the moon will receive more solar energy when the sun is at the horizon than when it is overhead, because more area is exposed to the direct rays and their intensity is not weakened in the absence of an atmosphere. Furthermore, the influence on the heat control of shielding material against ionizing radiation may have to be considered.

A theoretical analysis of a complex technical problem usually requires a certain simplification and abstraction of the real conditions; otherwise, the mathematical procedures become too involved. On the other hand, the validity of the results and conclusions derived from an oversimplified abstract model is sometimes questionable, and the necessary evaluation is difficult if not impossible, as illustrated by the following example:

The temperature control problems of space suits in orbit were analyzed under the following simplified assumptions: The anthropomorphic space suit was replaced by a single cylinder, subjected to solar heat influx only at one end, the external heating absorbed by the total end area concentrated uniformly around the circumference of the end area and the metabolic heating uniformly distributed only along the inner cylinder wall. Even with these oversimplified assumptions, the analysis led to a differential equation that could not be solved analytically. A machine computation program was developed. The result was the suggestion of a space suit consisting of an aluminum shell of 1.22 inches thickness and 352 pounds weight, or a 5/8-inch-thick water jacket with a circulation system (ref. 6, 7).

According to this theoretical analysis, a space suit would be impractical. The great discrepancies between the oversimplified mechanical model and a real space suit with a living man in it, however, make the validity of the conclusions and recommendations of this analysis questionable. In reality the dynamic physiological and psychological reactions of the man will greatly influence and change the whole situation. The man will turn around when he feels too warm or cold on one or the other side, and the body's heat control mechanism will automatically regulate metabolic heat generation and will direct blood circulation and sweat excretion to the areas where they are needed.

This example illustrates the limitations of theoretical analysis and the doubtful validity of oversimplified assumptions and abstract models, particularly when the complex and unpredictable human reactions are involved, and makes the necessity of practical experiments evident. But before presenting a design proposal for a test facility adequate to study the problem areas illustrated in the foregoing sections, let us first investigate how far already existing and planned test facilities and laboratories could be used for this purpose.

SECTION III

USE OF EXISTING AND PLANNED ENVIRONMENTAL TEST FACILITIES AND LABORATORIES

To eliminate unnecessary requirements and duplication of effort, it is necessary to define the provinces of bioastronautical research in the field of environmental protection that can be covered by existing physiological altitude test chambers, planned aerospace systems environmental chambers, proposed balloon platforms, and orbiting laboratories.

Physiological Altitude Test Chambers

Most existing physiological altitude test chambers can simulate only the low atmospheric pressure ranging up to altitudes of 100,000 feet to 200,000 feet. This pressure, on the order of a few mm Hg, is the only condition not existing at ground level, and is the determining criterion for the design of such altitude protective equipment as pressure suits and oxygen systems. The aviator is exposed to low barometric pressure only in an emergency, since the aircraft provides an adequate pressure and climate for him during normal operation. In an emergency bailout, the aviator, protected by an emergency pressure suit, returns to the ground within a few minutes. Such environmental parameters as the low temperature at high altitudes, have little significance for altitude protection because of the short duration of exposure to them. Simulation of the pressure only in the physiological altitude chamber was therefore sufficient and realistic for research and development in the traditional field of aviation medicine.

In bioastronautics, however, the situation is quite different. First, the astronaut will need personal protective assemblies that enable him to perform useful work outside the vehicle or space station during orbiting and interplanetary travel as well as during lunar and planetary surface explorations. Second, in most cases, he cannot return to his normal environment of the earth within a few minutes in an emergency as the aviator does, except during a launching escape. Personal protective equipment for the astronauts, therefore, must be self-contained assemblies to provide emergency protection and working capability for the astronaut during extensive exposure to the various multistress environments encountered in space, lunar and planetary missions. These multistress environments differ greatly from those encountered in present high-altitude flight and emergency ground exposure, not only in their magnitude but also basically in their effects.

The vacuum in space, many orders of magnitude higher than that in high-altitude flight, completely excludes heat exchange of man and equipment with the surrounding space by conduction and convection, the primary method for heat exchange on ground and in present high-altitude flight. The state of weightlessness during certain phases of space expeditions also excludes the natural convection of the air in a pressurized compartment, since convection depends upon the difference in weight of air at different temperatures.

The energies and temperatures of thermal radiations in space, on the moon, and on the nearer planets vary between much greater extremes than those on earth. The energy of the solar irradiation above the earth's atmosphere is about 1400 Watt/m^2. This is about 40% higher than the energy falling on the ground on a summer day with the sun directly overhead, the difference being reflected, scattered and absorbed by the atmosphere. The solar irradiation energy in the solar orbit of the planet Venus, about 2600 Watt/m^2, is more than 2-1/2 times the highest solar irradiation on the ground of the earth. On the other hand, the star-speckled black sky above the earth's atmosphere represents a radiative heat-sink equivalent to a black body with a mean temperature of approximately 4° K (minus 453° F). The surface temperatures on the moon range from about minus 243° F during the lunar night to about plus 275° F in the hottest areas during the lunar day. The day-night cycle on the moon lasts about 27 earth days. (The world's official lowest surface air temperature observed in Siberia is minus 90° F, the highest official temperature ever recorded in the world is 136° F, and was observed in Lybia (ref. 5).

Besides the extremes in thermal radiation, bioastronautical research must consider such ionizing radiations of high energy as, primary and secondary cosmic radiation, the radiation of solar flares, the charged particle radiation of the Van Allen Belts, in addition to impacts by meteoric particles and interplanetary dust. Besides these natural environments, consideration must be given to such induced environments of space flight as high accelerations, weightlessness, shocks and impacts, noise and vibration, aerodynamic heating, and nuclear radiation from future power sources.

From this brief review, it is obvious that the existent physiological altitude test chambers impose severe limitations on applied research and development in in the field of bioastronautics.

The barometric pressure achieved in present chambers is not low enough to eliminate the thermal conductivity of the air in the chamber. As predicted by the kinetic gas theory and confirmed by experiment, the thermal conductivity of a gas, in which the mean free path is small compared with the distance between the heat source and the heat-sink, is independent of the gas pressure until the pressure becomes quite small. However, as the pressure approaches the micron range (about 10 to 100 micron Hg), there is a sudden marked decrease in the rate of heat transfer and at pressures below 1 micron Hg (295,000 feet altitude) the rate is nearly proportional to the gas pressure (ref. 16). At this low pressure, the thermal conductivity of the air practically vanishes and heat can be transferred only by radiation. This effect is well known from its application to Dewar vessels and thermos bottles.

At pressures of a few mm Hg or at best a few tenths of a mm Hg achieved in present biomedical altitude chambers, the thermal conductivity of the air in the chamber is still practically the same as at normal atmospheric pressure. These chambers, therefore, are inadequate for studying radiative heat exchange problems encountered in space missions. Modification of these chambers by improving the vacuum and by addition of solar simulators, infrared radiators, and a radiative heat-sink achieved by cooling the chamber walls with liquid gases, is impractical since the useful space in these relatively small chambers would be too small for all practical purposes.

The only areas concerned with bioastronautics in which the existent physiological altitude test chambers could still find some useful application are:

a. For testing of intravehicular emergency protective assemblies by simulating decompression of the crew compartment of a space vehicle and failures in the oxygen supply system

b. For a crude evaluation of the mechanical and mobility properties of intra- and extravehicular protective assemblies to the extent they are not influenced by environmental parameters other than low pressure

c. After modification and improvement, these chambers could also be used for some physiological studies of the effects of human exposure to low-pressure atmospheres of various composition over extended periods of time, simulating intravechicular atmospheres of aerospace vehicles

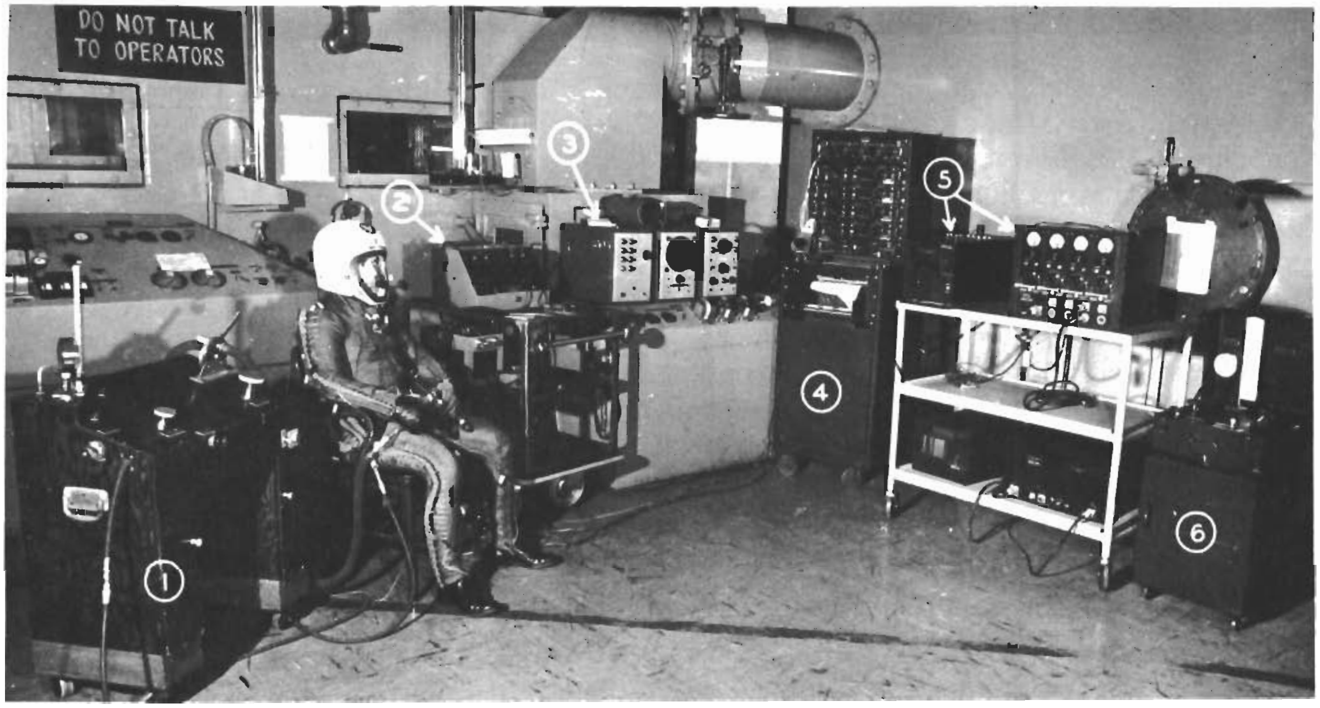
The complex problem of personal protection during extravehicular missions and emergencies occurring in the phases of orbiting, interplanetary travel, lunar and planetary explorations, requires a facility in which the multistress environments encountered in these phases can be simulated.

Aerospace Systems Environmental Chamber

The cost of the planned AEDC Aerospace Systems Environmental Chamber Mark II is estimated at 150 million dollars or more. The cost suggests that the chamber be made a national facility, available for research and development in all areas of space technology, including bioastronautics. This concept is even more attractive when it is anticipated that maintenance personnel, technicians, scientific personnel, and crew of aerospace vehicles will necessarily be inside the chamber to perform duty during simulated environmental testing of full-scale aerospace vehicles and vehicle components. Human access to the chamber under simulated aerospace environmental conditions depends on the presumption that fully reliable, operational personal-protective equipment is available, including self-contained space suits, space-worker cabins, and life-support systems. The use of the same chamber for experimental and developmental testing of personal-protective assemblies with human subjects and for evaluating their physiological responses to this equipment would be too hazardous for the following reasons:

a. Many years of experience of the Aerospace Medical Research Laboratories in testing pressure suits and oxygen equipment in altitude test chambers have shown that frequent malfunctions of protective assemblies must be expected during the developmental stages of equipment design (ref. 19). Loss of useful consciousness occurs within about 10 to 15 seconds when protective equipment fails and man is suddenly decompressed to a vacuum. Vacuum in the biological sense means any pressure below 47 mm Hg at which pressure the body fluids begin to boil and the gases in the lungs are completely replaced by water vapor. If a man is exposed to vacuum for more than 50 to 60 seconds, aeroembolism with irreversible neurological damage is highly probable and could result in permanent disability or death. To prevent accidental exposure of the brain and nerve cells to extreme lack of oxygen, altitude chambers for tests on humans are designed to be repressurized within a few seconds from the moment an emergency situation is recognized. They are equipped with highly sensitive biomedical instrumentation (figure 5) for surveillance of the man and for early recognition of emergency situations by an experienced observer team.

b. The experience of the Aerospace Medical Research Laboratories with physiological altitude test chambers served as the basis for establishing the biomedical safety requirements and provisions for the Mark II chamber. Emergency rescue operations for biomedical altitude chambers cannot be directly applied to the Mark II chamber because the large size of the chamber, the danger of severe injury to man and damage to costly equipment by repressurization airblast, and the inertia and continuation of cryo-pumping and cooling effects all combine to make it impractical to repressurize the chamber quickly in an emergency. The unique conditions and requirements of the Mark II facility made it imperative to consider new biomedical surveillance and safety provisions for both routine and emergency situations in order to protect and rescue personnel inside the facility without impairing their working capability. These new biomedical safety provisions, however, depend more than ever upon the presumption that operational personal



1.Training Aid, Regulator, High Altitude, Pressure Breathing. 2.External Defibrillator-Pacemaker. 3.VecTo-Cardiograph. 4.Multi-Channel, E.K.G. 5.Amplifier, Oscillograph. 6.Training Aid, Regulator, High Altitude, Pressure Breathing.

Figure 5. Medical Equipment to Monitor High Altitude Flight

protective and rescue equipment of great reliability is available. It is evident that the use of the Mark II chamber for developmental testing of this protective and rescue equipment would be too hazardous for human subjects. It would also be uneconomical and impractical to set a chamber of about 200-foot diameter in operation for a test on a six-foot-tall man.

For these reasons and for testing protective and rescue equipment as well as for physiological experiments on man, use will be required of a special bioastronautical chamber small enough to permit instantaneous reversal of the test conditions and repressurization of the chamber within a few seconds.

The large Mark II chamber, however, could be used effectively for the final indoctrination and training of astronauts in full-scale aerospace vehicles under simulated space environmental conditions after the operational reliability of personal protective and rescue equipment has been thoroughly tested in the bioastronautical chamber.

The volume of the bioastronautical chamber under consideration (see figure 6) would be less than one percent of that of the Mark II chamber and the cost would be correspondingly lower.

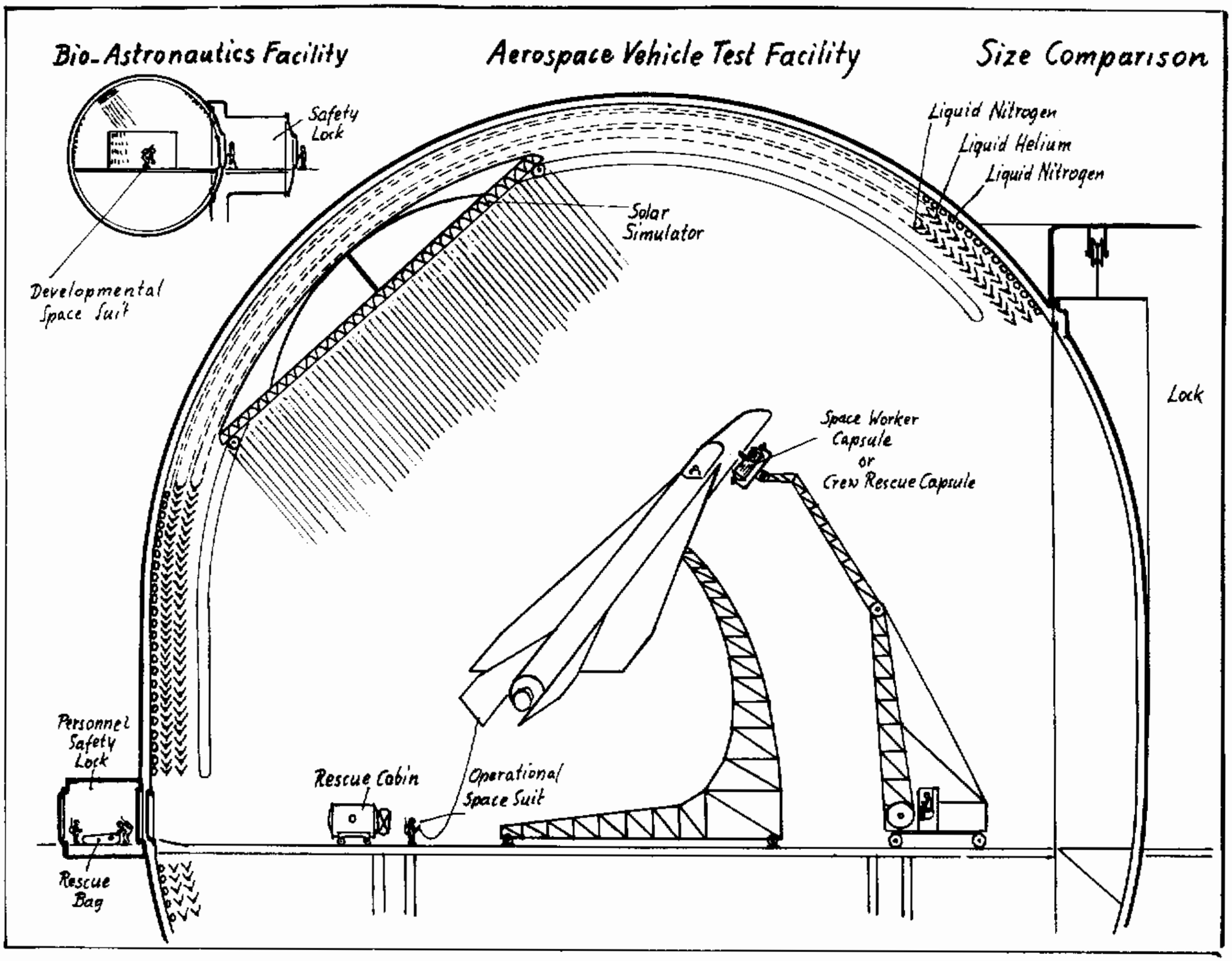


Figure 6. Size Comparison of Bioastronautics and Aerospace Vehicle Test Facilities

Balloon Laboratories

The National Geographic Society-Army Air Corps Explorer balloon flights, the Strato-Lab program of the Office of Naval Research, the Manhigh program of the Aerospace Medical Field Laboratory, Holloman Air Force Base, New Mexico, and the Excelsoir program of the Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, have established the feasibility of manned balloon flights with systems of the weight of the Mercury capsule and higher, up to about 114,000 feet. With the famed 3,700,000-cubic-foot Explorer II stratosphere balloon and a load weight of the gondola including equipment and crew of 4,497 pounds, Captain Orbil A. Anderson and Captain Albert V. Stevens of the Army Air Corps reached an altitude of 72,395 feet on 11 November 1935 (ref. 11). During his 32-hour flight on 19-20 August 1957 with the three-million-cubic-foot Manhigh II balloon and a load weight of 1710 pounds David G. Simons, Major, USAF, MC, reached 101,516 feet (ref. 17). Captain Joseph W. Kittinger, Jr., of the Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, parachuted from 102,800 feet on 16 August 60 (ref. 12). With the ten-million-cubic-foot Strato-Lab High 5 balloon, Comdr. Malcolm D. Ross and Lt. Comdr. Victor A. Prather, Jr. reached 113,740 feet on 4 May 1961 (ref. 12).

High altitude balloon flights may be considered as a step between ground tests and actual space flight, and are the best present means for simulating certain hazardous conditions and psychological stresses of space flight at relatively low cost:

The meteorological considerations and launch preparations, the hazards of balloon failure during launching, the danger due to brittleness of the polyethylene plastic envelope at the low temperatures and pressures at higher altitudes, the hazard of wind shear by the jet streams in the upper atmosphere, then the supernal impressions of the blue-black void of space and the grandoise view of sun rise, sun set, and the curvature of the earth; furthermore, the tension during descent about the uncertainty of location of landing and severity of impact, and, finally, the rescue procedures, all these conditions resemble closely the sequence of the various phases of an actual space flight, except, of course, the state of weightlessness.

The psychological aspects of high-altitude balloon flights are of particular importance because the psychological tensions of actual space flight are not experienced and cannot be thoroughly studied in ground test facilities. Balloon flights could also be used for equipment tests and for indoctrination in personal protective assemblies, after their operational reliability has been thoroughly tested in ground facilities. Tests of space suits and space worker capsules on a balloon platform would closely resemble the conditions on a space station. However, the thermal control problems on protective assemblies for extravehicular use in orbital flights and in lunar explorations cannot be thoroughly studied in balloon flights. At 100,000 feet, the atmospheric pressure is about 8 mm Hg. At this pressure, the thermal conductivity of the air is practically the same as on ground, and the low air temperature of about minus 40° F may still be perceptible although heat transfer by convection is considerably reduced. The large balloon prevents radiative heat transfer through a considerable solid angle towards the black sky.

For a thorough study of the personal protection problem, it will be necessary to simulate the high vacuum of space and the thermal environments, inclusively the various day-night cycles in earth orbits and on the moon as well as of the solar spectrum and the radiative heat-sink of the black sky. Existing techniques are available to simulate these conditions with sufficient accuracy in ground facilities.

Orbiting Laboratories

The biomedical aspects of an orbiting laboratory would lie mainly in the fields of study of the effects on animals and man of long-term exposure to weightlessness and cosmic radiation, and the training and preparation of astronauts for lunar and planetary expeditions. The use of an orbiting laboratory for developmental testing of such hardware as space-worker suits would be uneconomical and too hazardous. The orbiting laboratory should be reserved for final hardware tests only and for those physiological tests that cannot be performed in ground facilities.

A design proposal of an aerospace environment simulator for bioastronautical research is presented in the following section.

SECTION IV

THE PROPOSED AEROSPACE ENVIRONMENT SIMULATOR

The first design proposal of an aerospace environment simulator was presented at the Second Astronautics Symposium, Denver, Colorado, on 28 April 1958 (ref. 13). Subsequent designs, including the AEDC Mark I and Mark II chambers have followed the same basic design concept. The proposal described below again follows the same principles but provides both greater versatility and closer approximation to reality than do prior designs, and is particularly adapted to the specific requirements of bioastronautics.

Figures 7, 8, and 9 illustrate the basic concept of the proposed bioastronautical test facility for simulation of the high vacuum and thermal radiation environments encountered in orbits around the earth, the nearer planets Mars and Venus, and the environmental extremes on the Moon. The facility consists of a high vacuum chamber with a radiative heat-sink, a solar simulator, infrared radiators, and a biomedical safety lock.

Vacuum Capacity

The high-vacuum chamber would be double-walled similar to a Dewar vessel to improve thermal insulation and reduce leakage and sealing problems. The chamber would be evacuated by a set of roughing pumps, holding pumps and diffusion pumps. Instead of a series of conventional diffusion pumps, a special high-capacity diffusion pump could be arranged inside the chamber. This would reduce energy consumption and sealing and leakage problems, and would save material and space by utilizing the otherwise dead space below the chamber floor.

The inside of the inner chamber wall would be blackened, and cooled by such liquid gases as nitrogen and helium to simulate the radiative heat-sink of the black sky. The heat-sink works automatically as a large cryo-pump. Most of the vapors and gases will condense at the low temperatures of the cryo-panels. A part of the cryo-panels or fins of the cooling coils could be shielded against thermal radiation

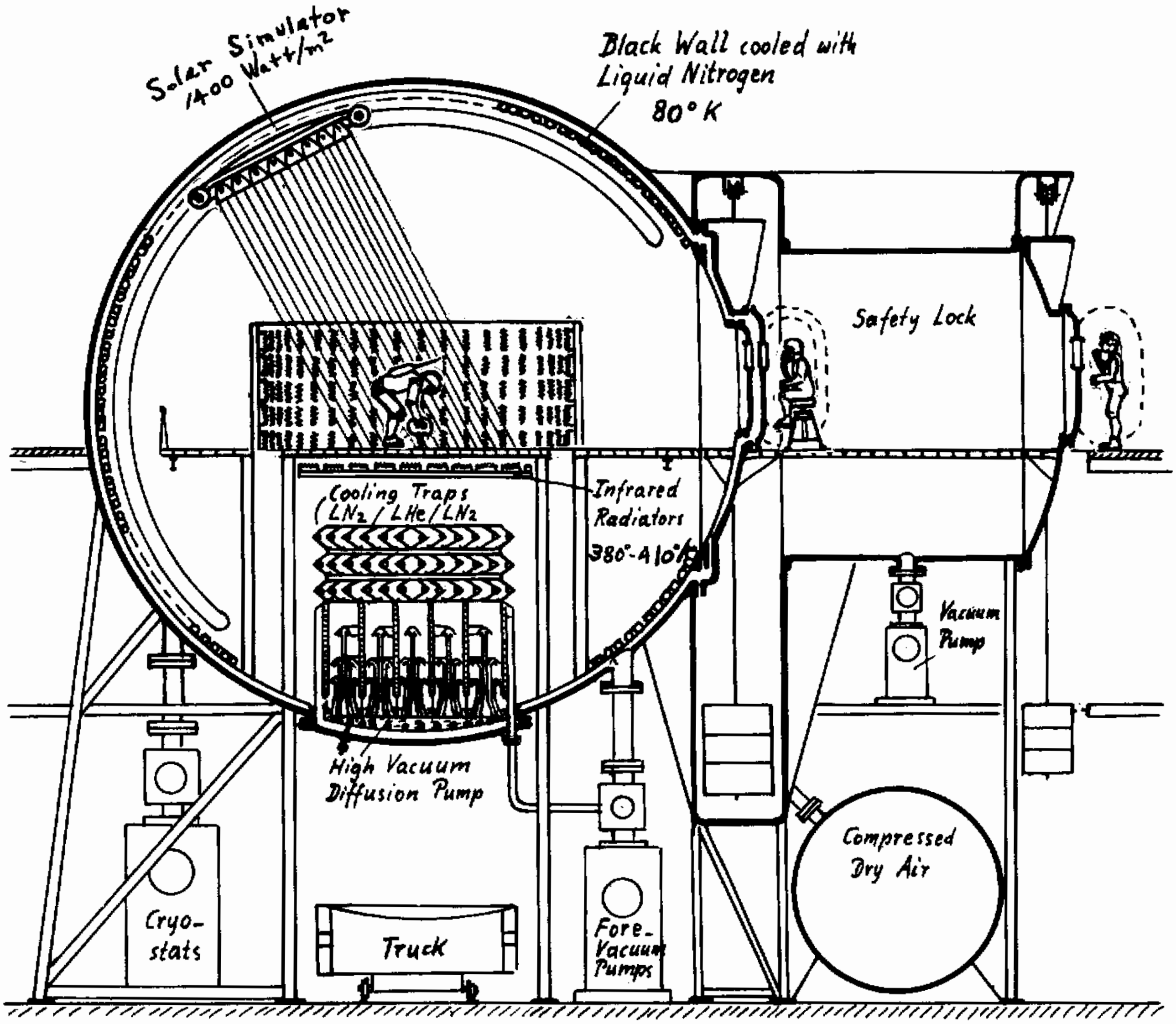


Figure 7. Lunar Day Simulated, Man Working

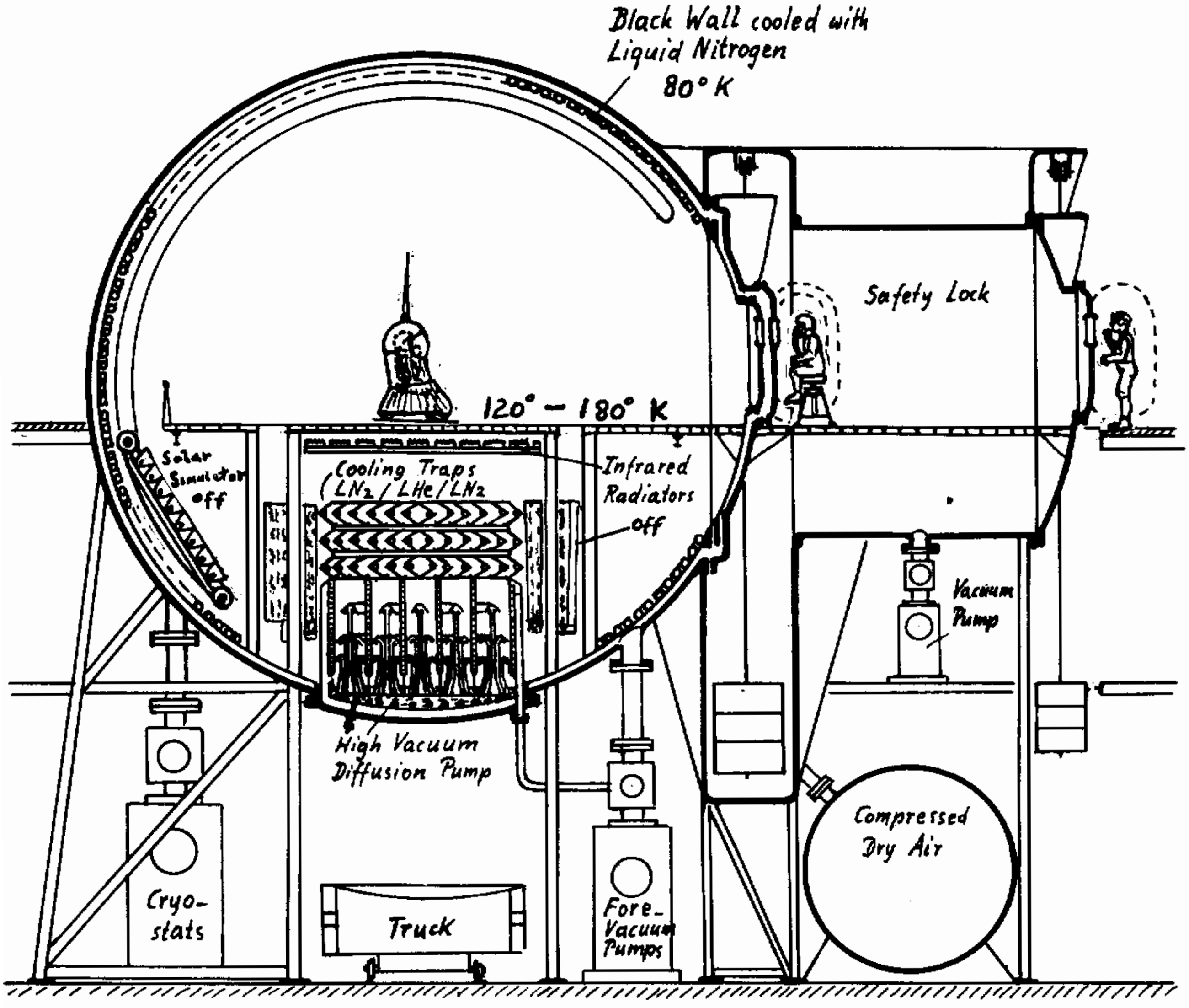


Figure 8. Lunar Night Simulated, Man at Rest

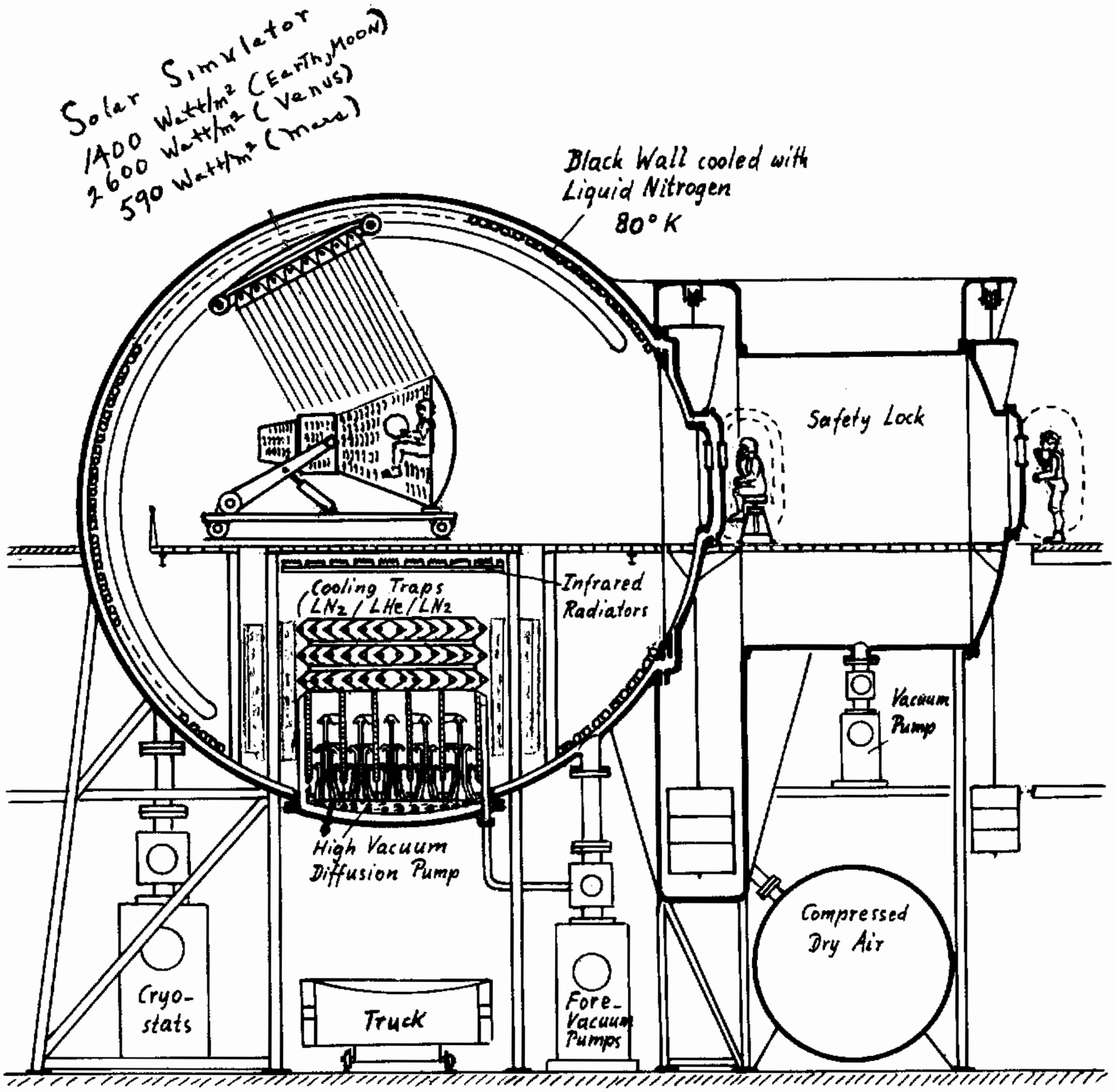


Figure 9. Orbiting Around the Earth Simulated (Venus, Mars)

and coated with a sorbent such as activated charcoal or molecular sieves cooled by liquid or gaseous helium and could be used as cryo-pumps for noncondensable gases. The cryogenically cooled chamber wall would closely resemble the infinite vacuum capacity of space. Molecules leaking or gassing from the test subject would be condensed or adsorbed by the cryo-panels. They will disappear as they do in space and not be bounced back from the chamber walls as in a common vacuum chamber.

For studying thermal control problems, a vacuum of 10^{-4} to 10^{-5} mm Hg would be enough since the thermal conductivity of the air begins to vanish at about 10^{-3} mm Hg (ref. 16). The cryo-pumping effect of the radiative heat-sink however, will automatically increase the vacuum capacity of the chamber to about 10^{-6} to 10^{-7} mm Hg or higher. This high vacuum capacity also permits study of problems of interface friction and cold-welding, effects caused by the disappearance of an air-molecular layer on surfaces exposed to the high vacuum of space. The coefficient of friction increases appreciably with a vacuum of the order of 10^{-5} mm Hg or higher. The phenomena of interface friction and cold-welding may be a critical factor in the design of such mechanical and electromechanical components of personal-protective equipment as sliding restraint systems on space suits, and joints and manipulators on space worker and moon capsules.

If cryo-sorbents are used they have to be baked out from time to time. This could be done by flooding the cooling coils with hot air or another fluid, or by the use of heat lamps prior to chamber operation.

The Radiative Heat-Sink

The black fins of the cryo-panels or coils build a great number of hollow spaces that almost completely trap any incidental thermal radiation and closely approach the 100% absorptivity of an ideal black body. The radiative heat-sink will absorb practically all incidental thermal radiation as the black sky in space does without reflecting a large fraction of radiation to the test subject as the polished walls of a common high vacuum chamber would do. The thermal radiation emitted at the low temperatures of the cryo-panels is negligible. Compared with the radiation emitted at room temperature of 300° K, the radiation emitted at 77° K, (the boiling point of nitrogen at atmospheric pressure) is only $77^4 : 300^4 = 0.0045$. This is less than one-half of one percent.

The Solar Simulator

The energy spectrum of the sun, consisting of about 51% infrared from 7,000 to 100,000 A wavelength (1 A = one Angstrom unit = 10^{-7} mm), 41% visible light from 3,800 to 7,000 A, and 7.5% ultraviolet from 2,000 to 3,800, can be simulated by several methods, e.g., carbon arcs with various impregnations, high-pressure mecury lamps, xenon lamps, and their combinations with tungsten lamps, filters, lenses and reflectors.

The short-wave ultraviolet from 100 to 2,000 A represents less than 0.2% of the total energy; it could be simulated by high-voltage, low-pressure gas discharge.

The X-ray region from 100 to 1 A could be reproduced by a low-voltage X-ray source.

The choice of the source depends upon the purpose and required accuracy of simulation. For the facility in question, simulation of the wave-length region between 0.2 and 4 micron (2,000 - 40,000 A) that includes about 99% of the total solar radiation, would be sufficient.

Three sources: (1) the xenon lamp, (2) the xenon-mercury lamp, and (3) the carbon arc, that closely approach the solar spectrum in this wave-length region, are presently used for most solar simulators. The filtered xenon lamp, more convenient in use than the carbon arc, matches this main part of the solar spectrum with about 90% accuracy. More sources will probably be developed in the near future. The solar simulator of previous designs is usually arranged in a fixed position outside the chamber, and the energy distribution over the target area is achieved by a complex projection system which collimates the beam.

In the proposed bioastronautical facility, the solar simulator is mounted on tracks inside the chamber and can be both positioned at any desired angle and retracted below the chamber floor. This greater flexibility is required for two reasons:

First, the astronaut's performance as affected by his protective assembly and physiological and psychological responses to environmental stresses and changes have to be evaluated while he is performing various activities and the solar radiation is striking his body from various angles. In a chamber with a solar simulator fixed at the top of the chamber, he would have to lie face down on the floor to get the solar radiation on his back; of course, in this position he could not perform any work.

Second, a human test chamber has to be kept as small as possible for safety reasons. If the solar simulator were not retracted when not in use, it would cover a large fraction of the heat sink and would reflect the thermal radiation from the test subject instead of absorbing it as the black sky of space does.

The solar simulator is subdivided into smaller units to cover the range of irradiation intensity from about 590 watts per square meter on Mars, 1,400 watts per square meter in earth orbits and on the moon, to 2,600 watts per square meter in the solar orbit of Venus, without changing the spectral energy distribution. Switching on a proper number of sun lamps allows also for adjusting the irradiation field to the configuration of the test subject.

The Infrared Radiators and Albedo Simulators

The infrared radiators are combined with adjustable reflectors and a series of sun lamps to simulate the infrared radiation and albedo of the earth and its atmosphere, the moon, and the planets Mars and Venus. The radiators consist of a circular floor panel and a cylindrical wall with an opening opposite to the door in the safety lock. The cylindrical wall can be retracted below the chamber floor and elevated to any desired height.

Simulation - Versatility

The flexible arrangement of the solar simulator and the infrared radiators and albedo simulators permits an accurate and realistic simulation of the entire range of thermal and vacuum environments and their cycles between the most opposite extremes in a single chamber without mutual interference. The simulation of situations encountered in lunar and orbital missions is illustrated by the following examples:

1. Figure 7 shows the simulation of the lunar day with a man working in a space suit, corresponding to the situation shown on figure 2. The solar simulator is switched on, and the infrared radiator and albedo simulator is elevated above the floor simulating the infrared radiation and albedo from crater walls or mountains.

2. Figure 8 illustrates another extreme situation, the lunar night with a man resting in a moon capsule, corresponding to the situation shown on figure 3. The solar simulator and the infrared radiator with the albedo simulator are switched off and retracted below the chamber floor. Only the black heat-sink is still in operation to simulate the black star speckled sky.

3. Figure 9 illustrates the simulation of the situation shown on figure 10, a manned capsule orbiting around the earth, the moon, Mars, or Venus. The energy of the solar simulator would be adjustable to correspond to the solar constant present in the orbit of the particular planet. Orbiting in the shade of a planet can be simulated by simply switching off and retracting the solar simulator. The energy of the infrared radiator would also be adjustable to correspond to the actual situation.

Biomedical Safety Provisions

Developmental testing of personal protective equipment and physiological tests on man require special safety provisions (ref. 9). The biomedical safety provisions and standard procedures developed and proved by AMRL on physiological altitude test chambers include:

1. A biomedical safety lock for quick rescue of the test subject in an emergency:

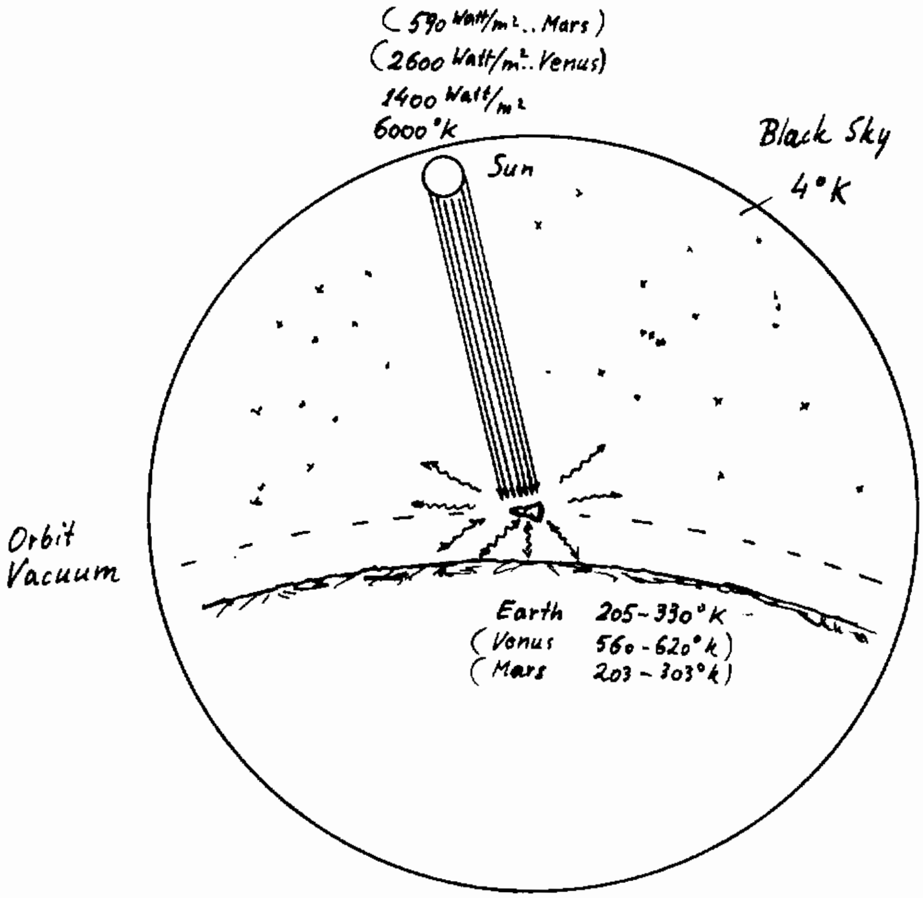


Figure 10. Orbiting Around the Earth (Venus or Mars)

The biomedical safety lock is kept at a simulated altitude of about 25,000 feet (280 mm Hg) while the main chamber is in operation. This can be considered as a safe altitude at which decompression sickness (bends) rarely occur. The inside observer in the safety lock wears an oxygen mask. In an emergency, he opens a decompression valve to the main chamber in which the test subject is located, while simultaneously another valve is actuated to repressurize the main chamber with air from the outside atmosphere or from a storage vessel containing compressed dry and even preheated air. The pressure in the safety lock first falls rapidly while simultaneously the pressure in the main chamber rises. At the moment the pressures in both chambers are equalized, the inside observer can open the door to the main chamber and enter for first aid to the test subject. Existing physiological altitude chambers are designed so that the pressures in both chambers equalize at a simulated altitude of about 40,000 feet (140 mm Hg) within a few seconds. From this point on, both chambers are repressurized together to ground level to allow removal of the test subject for further medical aid and treatment. By carrying the safety lock with the inside observer at higher simulated altitude, valuable time is saved to rescue the test subject from the most critical level above 40,000 feet. Further repressurization to ground level can be continued at a slower rate, normally not exceeding about 25 mm Hg per second which can be considered as a safe limit to prevent ear damage if the eustachian tubes remain open.

2. Highly sensistive biomedical surveillance equipment and instrumentation for early recognition of developing emergency situations:

The following type of biomedical surveillance equipment should always be available to the responsible medical personnel:

Intercommunication and direct vision of the test subject, blood pressure and pulse rate recording systems, continuous oscilloscopic and direct-writing electrocardiograph equipment, respiratory rate and volume-measuring equipment, multiple skin or rectal thermometers, pressure gages indicating chamber and suit or capsule pressure, and sensors indicating partial pressure of oxygen, carbon dioxide, and nitrogen within the protective equipment.

3. Medical equipment for physical examination and emergency medical treatment:

The following type of facilities and equipment for physical examination and medical treatment should be available at all times:

Standard medical equipment, X-ray apparatus, and an electrocardiograph. Denitrogenation consoles for preventive treatment against decompression sickness may also be added to this group.

Emergency treatment equipment should include: (a) a mechanical resuscitator, (b) an electrical pacemaker-defibrillator for the heart, and (c) sterile surgical instruments for such procedures as opening the chest to allow manual massage of the heart. (See figure 1.)

4. An alert observer team under the supervision of an experienced flight surgeon for safe chamber operation:

The flight surgeon responsible for the biomedical monitoring of the test subject, as well as each member of the observer and chamber operation team, should have at least a few years service with existing physiological altitude chambers and should have acquired the experience and alertness necessary for early recognition and rapid handling of emergency situations. Each member of this team must have passed a pressure suit indoctrination course at a physiological training unit to be acquainted with the hazards of low-pressure exposure and rapid decompression.

5. A group of mechanics and electronics specialists, supervised by an experienced engineer, to maintain the operational reliability of the facility, equipment and instrumentation:

Maintaining the operational reliability of the complex facility including biomedical equipment and instrumentation requires a group of specialists skilled in cryogenics, high vacuum technique, infrared and ultraviolet radiation technique, and fine mechanics and electronics. The group should be supervised by an engineer with a broad educational background and extensive experience.

Size

Reasons of safety and economy call for a chamber small enough to permit rapid repressurization in an emergency.

Accuracy of simulation and psychological considerations, however, suggests a chamber as large as possible.

The size of a bioastronautical chamber will, of course, be determined by the biomedical safety requirements. Estimates, based on experience with existing physiological altitude test chambers, indicate that a chamber of 20 to 25 feet clear diameter could be repressurized rapidly enough to meet the biomedical safety requirements. A chamber of this size would provide sufficient accuracy of environmental simulation and can also be considered a reasonable compromise with regard to psychological considerations.

Power Requirements

Table 6 shows an estimate of the power requirements. The power requirement for pumping down the chamber is about 200 kilowatt. The peak power during continuous operation is in the order of about 160 kw when the solar simulator, albedo simulator, and infrared radiators are in operation simulating the lunar day or orbiting around Venus in sunshine. This would be the total power required if liquid nitrogen were used as expendable coolant for the radiative heat-sink.

If a recycling air or nitrogen liquefaction plant were used, additional 200 to 250 kw are necessary. It is assumed that the vaporized gas is fed back into the system at the boiling temperature of about 80° K and that the power normally required to cool the air down from room temperature is saved. A very simplified air-liquefaction plant could be used because there are no demands on purity of the liquefied gas, and the boiled off nitrogen would be reliquefied.

TABLE 6

POWER REQUIREMENTS

I. During Pump - Down:	Kilowatt
1. 4 Roughing pumps, 1,200 m^3/hr each 4 × 30 kw =	120
2. 2 Holding pumps, 225 m^3/hr each 2 × 5.5 kw =	11
3. 2 Roots pumps, 2,000 m^3/hr each 2 × 8 kw =	16
4. 2 Diffusion pumps, 36,000 liters/second each 2 × 28 kw =	56
5. Auxiliary equipment	5
Total power during pump-down	208
II. Continuous Operation:	
1. 2 Holding pumps, 225 m^3/hr each 2 × 5.5 kw =	11
2. 2 Roots pumps, 2,000 m^3/hr each 2 × 8 kw =	16
3. 2 Diffusion pumps, 36,000 liter/second each 2 × 14 kw =	28
4. Helium - cryopumps	22
5. Solar Simulator, Albedo Simulator, and Infrared Radiators	80
6. Auxiliary Equipment (Valve and door actuators, instruments, light)	7
Total power, if expandable coolant is used for heat-sink	164
7. Air or Nitrogen Liquefaction Plant	225
Total Maximum Continuous Power	389

The peak-power requirement of the facility, including the air-liquefaction plant, would be in the order of 600 kw even if the latter would be in operation simultaneously while the chamber is pumped down.

Cost

Cost estimates of an aerospace environment simulator for bioastronautical research as shown on the figures 7, 8, and 9 range between one- and five-million dollars. The lower value is based on a comparison with AEDC Mark II chamber on an approximate cost-per-cubic-meter basis; the higher value is based on a comparison with a lunar environment simulation facility proposed by the Army Corps of Engineers (ref. 1). These estimates give at least the order of magnitude and indicate that the cost would probably still be less than the cost of one missile or satellite launching.

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

If our future manned aerospace systems are to be made less vulnerable, more reliable, and more economical, a diligent pursuit of basic and applied research must be undertaken in the field of biomechanics and in the study of the complex problems of personal environment protection.

Human tolerances and adaptability to low-pressure atmospheres and the direct utilization of the body's heat control and cooling mechanisms have not yet been fully exploited. Modified existing altitude chambers and clima-chambers with pressure, temperature, and humidity control can be used to study some of the basic functions of the human body in these areas.

The problem of personal pressure protection and heat control in space, however, cannot be solved by a physiologist's experiments on an underwear-clad man in a clima-chamber in which the anticipated internal environment of a space suit is simulated, nor can the problem be solved by an engineer's tests on a non-feeling, non-thinking manikin clothed in a space suit and exposed to actual or simulated space environments. The small volume available in a skintight space suit or in a small space-worker capsule results in a much closer mutual interaction of the protective system with the physiological and psychological responses of the man than could be simulated in the large volume available to an underwear-clad man in a large clima-chamber. Therefore, the personal protective system has to be studied together with the man as a higher complex unity under actual or simulated space conditions.

Existing physiological altitude test chambers are inadequate for this purpose. In balloon laboratories, the atmospheric pressure is too high to eliminate the thermal conductivity of the air, and the large balloon prevents accurate study of radiative heat exchange with the black sky. On the other hand, the AEDC environmental chambers used for testing full-scale aerospace vehicles and vehicle components do not provide the degree of versatility and safety required for experimental and developmental testing of assemblies with human subjects, and are too large for economical operation in testing personal-protective equipment and man.

A realistic study and evaluation of the problem complex of personal environmental protection calls for a relatively small and versatile ground facility in which space environments can be simulated.

Even a small failure in a personal-protective assembly, for example, in the air supply or humidity control, could easily be fatal for the man or result in the total loss of a space or planetary expedition. Also, the cause of the failure might never be determined, whereas the same failure in a simulated ground test would mean no more than an interruption of the test and correction of the easily observed deficiency.

Economically, the savings of cost and development time through use of adequate ground test facilities would be substantial.

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