SPACE VEHICLES AND REMOTE-HANDLING EQUIPMENT

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I. INTRODUCTION

Under the current stimulus of international competition, the key factors of space programs are time of accomplishment and cost. Time of accomplishment, which represents the principal measure of national prestige, is strongly constrained by limited budgets and by the weight of payload capable of being launched. These restraints, however, may be largely overcome by the establishment of orbital refueling operations and by the orbital assembly of structures or vehicles whose size, weight, and/or structural limitations prevent their being launched as a single unit. Suggested missions involving orbital assembly are as follows:

- The assembly of an orbital base or station for personnel transfer, refueling, and storage of supplies

- The assembly of large vehicles for lunar, planetary, or deep space penetrations

- The assembly of a space laboratory to study (a) man's adaptability to space environment; (b) the suitability of materials, structures, and equipment for space operations; and (c) the communication and control problems associated with space

- The assembly of an orbital astronomical observatory

A more specific proposal is that of Williams et al. (11) who estimate that the most reasonable and least costly transportation system for placing a manned 10,000-pound payload on the moon in 1970 would make use of orbital operations.

It is apparent that the orbital operation will be an important element of future space explorations. It is an operation in which man will be called upon to perform unique and complex tasks. The artists' impressions showing helmeted workmen dangling in space while performing various operations in the assembly and maintenance of space structures overestimate the capability of the human component in space. In contrast, as illustrated in Figure 1, the orbital workman will require special vehicles and equipment that are carefully planned and designed for the tasks and environment associated with each specific mission.

The problem presented by the design of an orbital assembly system, in essence, is the same as that associated with the nuclear laboratory or with underwater operations. That is, man is required to interact or manipulate objects in an environment which is hostile to his well-being and from which he must be isolated. The difference, of course, is that the orbital operation requires that man be contained in the artificial atmosphere of a pressure vessel and, in addition, accomplish his tasks under the stressful conditions imposed by the space environment. Thus, the orbital workman will require space assembly vehicles and special handling equipment such as the manipulators used so effectively by the nuclear scientist.

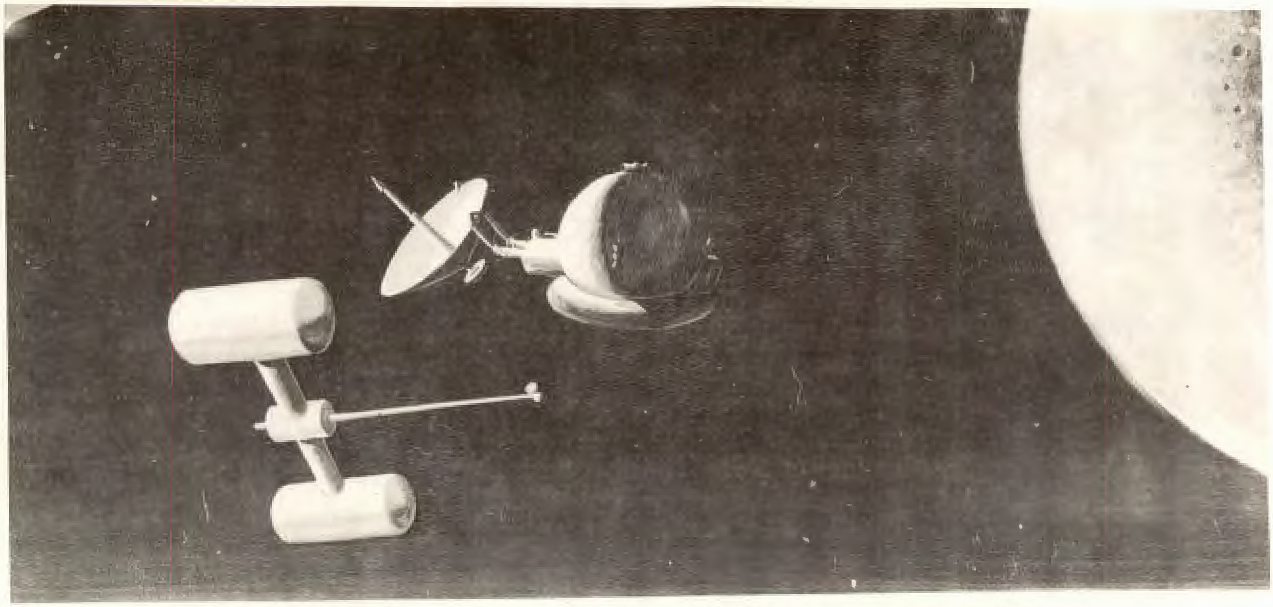

Figure 1. Orbital Assembly Operations

This paper considers the general aspects of the problem of equipping man to perform orbital assembly operations. The orbital operation may be regarded as the function of a system comprised of four principal elements: (a) the space environment, (b) the man, (c) the orbital task, and (d) the assembly vehicle and associated equipment. The characteristics of each of these elements are discussed with respect to their role in the determination of the assembly system design requirements. A number of assembly vehicle concepts and a ground simulator for the development of space assembly systems and the training of personnel are described in the concluding section.

II. THE SPACE ENVIRONMENT

The space environment is characterized by a lack of atmosphere and gravity, by radiation and micrometeorite hazards, and by solar flare activity. To the designer of orbital vehicles and equipment, this environment presents unique engineering problems. Moreover, if a man is to be included in the orbital system, the designer will also be confronted with a complex of physiological and psychological problems which must be considered in the system design.

The atmospheric void, the salient feature of space, probably is the most challenging problem with respect to the manned space system. It obviously requires that man be provided with the artificial atmosphere of a life-supporting pressure vessel. Two other factors stemming from the lack of atmosphere must also be considered by the designer. First, the isotropic background of scattered light, such as exists within the denser regions of the atmosphere, will be absent. Second, the intensity of the direct rays will be greater, by a factor of approximately 7, than at the surface of the earth. As a result, there will be an extreme contrast between surfaces of bodies facing the sun and those which face away.

It is important to note that the space environment as an element of the orbital system is not completely fixed, but is dependent on the orbit selected. The availability of sunlight, for example, will be dependent on orbit location and time of operation. An east-west orbit will result in several hours of darkness out of each day, whereas a north-south orbit will result in darkness for part of the day during less than two-quarters of each year. System designs must account for the fact that darkness will prevail during certain periods regardless of orbit.

The radiation characteristics of the orbital environment will also vary with the orbit selected relative to the van Allen belts and with the degree of solar flare activity. As a means of protection against solar flare radiation it is suggested that one segment of the vehicle to be assembled in space contain a compartment or some means of providing against solar flares. Arranging to make this segment available (i.e , placed in the assembly orbit) at an early stage of the operation will provide a refuge for the workman should a solar flare occur prior to the completion of assembly operations.

The probability of micrometeorite impact may also vary with orbit. There is a definite need for more refined data on the size, frequency, and velocity of micrometeorite particles, their effect on structural materials, and their orbits.

The orbital assembly operation also must take place at an altitude sufficiently high enough to avoid the regions of high air drag. For example, Schnitzer (10) has selected an orbit altitude (circular) of 400 miles for a proposed space laboratory, in order to stay below the van Allen radiation belts and above the regions of high air drag.

The orbital environment will be void of gravity. The effect of this condition on man is still largely unknown. Data from the WADD C-131B studies have indicated that short-term weightlessness will pose no particular problems with respect to the accomplishment of psychomotor tasks, such as the operation of manipulators, provided that the operator is firmly secured to his seat. There were no significant physiological effects of weightlessness in these studies. On the other hand, the effects of prolonged weightlessness are not yet known. Data from Project Mercury and Lockheed's null-g simulator (3) may soon provide a basis for predicting the effectiveness of human performance over prolonged periods of weightlessness.

III. THE ORBITAL WORKMAN

Utilization of man as an element of the orbital assembly system requires the consideration of three factors:

- o Man's anthropometric characteristics
- o Man's life support requirements
- o Man's capabilities as a system element

Anthropometric Characteristics

Spacemen will be at a premium for some time to come. The orbital workman will be selected on the basis of rigid criteria in which height and weight are far down the list of selection factors. In fact, if past Air Force "Aces" offer a valid indication of future spacemen, it is expected that the spaceman will be taller and heavier than the average man. Restricting the larger man from space duty would eliminate a high percentage of the most capable potential spacemen. Work station details and vehicle and equipment controls must be designed to accommodate the full range of anthropometric sizes. The added space restrictions imposed by the pressure suit, should one be worn as a back-up in case of pressure loss, must also be considered. For example, the USAF MC-2 suit increases sitting height by 1.5 inches (2.8 inches inflated) and elbow breadth by 2.8 inches (7.4 inches inflated).

The location of the spaceman's center of gravity is also an important anthropometric consideration in the small orbital vehicle, where the weight of the man is a high proportion of the weight of the total system. The effects of man's movements should avoid gross body displacements. However, the operator does require some freedom of movement. He should be provided with enough space to flex his extremities and neck and to assume occasionally an erect posture. Provision for some freedom of movement is also important psychologically because man needs to know that he can move.

Life-Support Requirements

It is fundamental that the orbital workman be sealed in a life-supporting pressure vessel, which may range from an anthropomorphic space suit to a large space "tug" capable of maneuvering large structural elements. In this paper, these are referred to as orbital vehicles regardless of size or shape. The physiological requirements of such life-supporting vehicles are now widely recognized and need only brief mention in the present paper. These may be broadly classified as follows:

- o atmosphere requirements
- o thermal requirements
- o radiation protective requirements
- o metabolic and nutritional requirements

Atmosphere Requirements

The orbital vehicle must be supplied with an atmosphere providing for adequate oxygen tension, air purification, pressurization, and efficient temperature regulation. These requirements are summarized by Table 1.

The life-support requirements of the small orbital assembly vehicle are essentially those of the larger space cabin; however, certain considerations are much more critical because of the size of the container. For example, the accumulation of noxious fumes or carbon dioxide presents a much more acute problem and is less easily detected and corrected in the small capsule. This suggests the need for automatic environmental monitoring and alarm devices. The capability of monitoring the orbital vehicle from the mother vehicle or the ground should also be provided.

Even more critical is the possibility of pressure loss caused by micrometeorite penetration or mechanical failure. It should be noted that the time of consciousness following total decompression is only 5 to 7 seconds. Total decompression is unlikely to be survivable. Although the probability of meteor penetration of the small unit is unlikely, the rate of loss of pressure is proportional to cabin volume. Thus, decompression of the small vehicle would be extremely rapid. In view of the risks involved, the orbital workman will probably wear a full pressure suit such as the USAF MC-2, to be pressurized only in the event of loss of vehicle pressure.

Table 1

Atmosphere Requirements for the Orbital Assembly Vehicle

Total Pressure	5 psi
Oxygen Partial Pressure (100%)	5 psi
Carbon Dioxide Partial Pressure (0.5%)	0.16 psi (max.)
Temperature	70 - 90° F
Circulation	20 cfm/occupant
Relative humidity	40 - 60 percent

Thermal Requirements

At a given distance from the sun, the absorption of solar radiation by a body in space depends upon the area which it presents to the sun. Assuming equal absorption factors and equivalent dark-side losses, the heating effect upon a small object will be proportionately greater than on one of larger volume. Since it is anticipated that the orbital workman will be required at times to work under the direct glare of the sun, the demands upon the heat-regulating mechanisms of the vehicle will be heavy. Temperature regulation presents a complex problem that must be considered along with humidity and ventilation, individual tolerances, clothing, and level of activity. Variation from optimum temperature not only may affect the physical and mental efficiency of the spaceman, but also may have secondary effects such as a lowered tolerance to hypoxia and motion sickness from heat or an increase in incidence of aeroembolism from cold. The major thermal requirement evidently will be the dissipation of heat. It has been roughly estimated that heat production will be one-third from man and two-thirds from support equipment. Thus, locating support equipment outside of the pressure vessel will serve to diminish the cooling system requirements.

Radiation Protection

As previously noted, the extent of radiation protection required will vary with the orbit selected. In view of the excessive weight penalties imposed by shielding, it is quite important that this factor be given detailed consideration during the mission planning stages.

Metabolic and Nutritional Needs

Man's nutritional needs and metabolic factors must also be considered. The extent of these problems will, of course, be dependent on the duration of the orbital operation. Table 2 summarizes these requirements over a 24-hour period.

Table 2

Approximate Metabolic and Nutrition Factors (Pounds/Day/Man)*

Needs		Wastes	
Oxygen	2.0**	Total heat output	11,907 BTU/day
Food (3200 calories)		CO_2	2.4
Nutrient Matter	1.4	Water	
Non-Nutrient Matter	0.2		
Water (in food)	3.2	Vapor in perspiration and urine	1.9
Net Food Intake	4.8	Liquid in urine and fecal matter	3.6
Water		Net Water Output	5.5
In Food	3.2		
Drinks	2.7	Solids, Urea, and Minerals	0.14
Manufactured in metabolism	0.8		
Net Water Needs	6.7		

* Data based on average man 30 years of age doing light work for 8 hours and sleeping for 8 hours in a 24-hour daily cycle

** 2.5 - 3.0 pounds usually specified in order to provide a reserve

It should be noted that the data in Table 2 represent average requirements. Metabolic factors are markedly affected by a large number of variables which must be considered in determining the needs of man for a specific mission. These include factors such as: level of activity, sleep-wakefulness, ambient temperature, body weight, height, age, and psychological stress.

Man As a System Element

Man's role as an integrated system element consists of receiving inputs, processing the information, and, subsequently, producing the desired outputs. This process is represented diagrammatically by Figure 2. In developing the orbital assembly system, the designer must carefully consider man's ability to perform the various operations of the task. Such analyses are fundamental to the determination of the displays and equipment required to augment man's abilities so that he may effectively accomplish the orbital task.

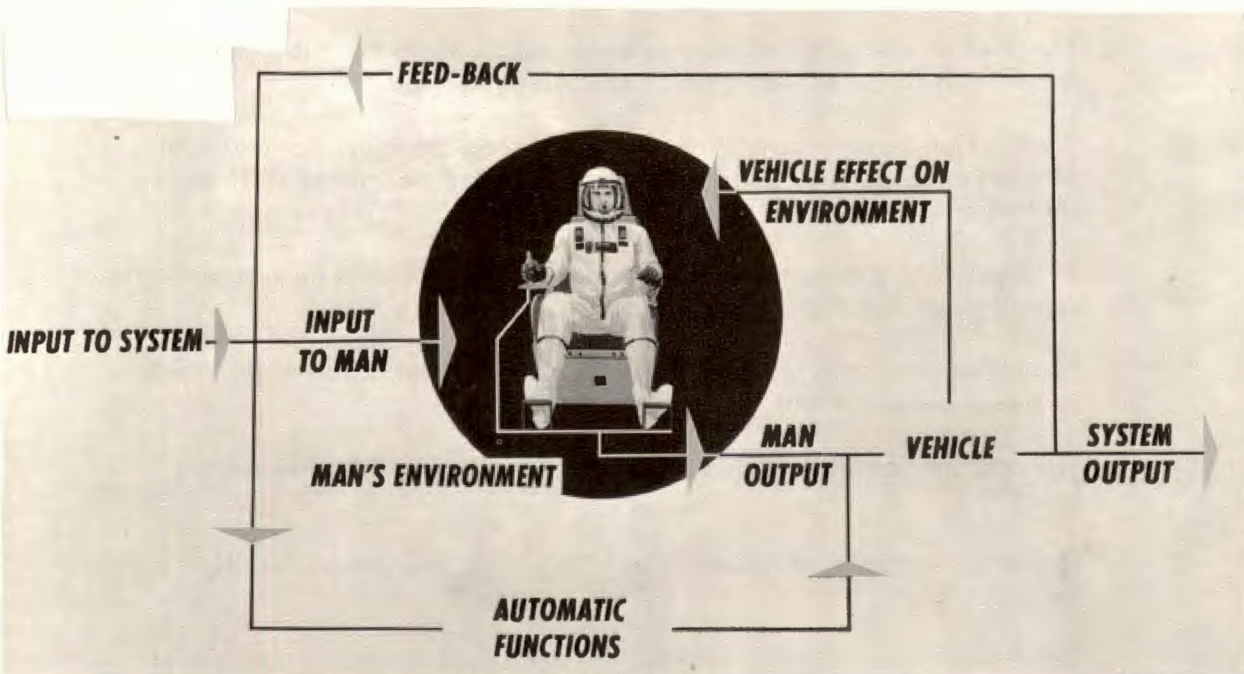

Figure 2. Man As an Integrated System Element

System Inputs

Inputs to the man represent data pertinent to the status of internal and external processes and objects. System inputs, of course, are mediated by man's sensory systems. Thus, the effectiveness of man's sensory systems in the space environment is a significant variable in the design of orbital systems.

Visual Inputs - The orbital workman will be required to utilize visual inputs to accomplish tasks such as determining the orientation, position, and relative velocity of other objects or of his own vehicle. He may also need to detect and identify objects in space. In fact, as a result of the zero gravity condition and the conflicting nature of vestibular sensations, man's visual sensations will be his most important sense. However, his ability to utilize visual inputs by direct viewing may be seriously prejudiced by a number of factors characteristic of the space operation.

- Man's ability to judge size, shape, and distance will be poor due to the lack of ancillary cues such as haze, perspective, and parallax.
- Judgments of relative motion will be difficult to make.
- The lack of visual detail may produce empty field myopia, making it difficult to detect isolated distant objects.
- Conflicting sensory cues may produce disorientation. For example, forward acceleration will produce an apparent downward shift of the stimulus object.
- Perception of the moon or earth under some conditions may produce the sensation of hanging upside down.
- Excessive glare may obscure objects, details, and colors significant to the accomplishment of the required tasks.
- Transparent panels may be subject to etching from micrometeorites or misting.
- Planetary shadows may hide objects requiring the use of floodlights and spotlights.
- The eye, if unprotected, may be damaged by infrared or ultraviolet radiation. Ultraviolet radiation which strikes the eye obliquely may give rise to a fluorescence in the lens.

It is clear that it will be quite difficult for the orbital workman to make accurate decisions on the basis of direct visual inputs alone. However, man's ability to make visual judgments in space can be improved. For example, perception of relative distances may be enhanced through the use of the phenomena of object constancy. This could be accomplished by thoroughly familiarizing the workman with the size and configurations of the elements that he must find and assemble in space. Judgments of relative size and distance could also be improved by providing man with distance cues. This could be accomplished by painting familiar patterns at standard and known distances apart on the surface of the orbital structures. When the orbital operation takes place in a planetary shadow, such cues could be provided by the use of lights. Glare could be reduced by the use of special coatings. These could be removable should the need arise to remove them after the assembly operation had been completed.

Further enhancement of visual judgments could be accomplished by tightly restraining the man to his seat in order to alleviate disorientation produced by vestibular inputs. In this manner, man's perception of the vertical will be referenced to the vehicle. Downward will be toward the floor of the vehicle or, in the case of the anthropomorphic vehicle, in a footward direction.

The effectiveness of such aids to visual judgments is not known. It is to be expected that man will still encounter much difficulty in the interpretation of the visual field under certain situations. For example, the isolated object in space will appear further away than it is actually. It is apparent that the orbital workman must be trained to compensate for and interpret the confusing visual inputs of space prior to the initiation of orbital operations. A simulator of the orbital operation, described in the concluding section of this paper, could be utilized for this type of training.

In some situations, man's visual inputs will have to be augmented or replaced by carefully designed visual displays. In fact these will probably constitute his most important sensory inputs with respect to the status of the external situation. If direct external viewing is provided, the orbital workman's problems will be similar to those of the high altitude pilot. His eyes, when adapted to the highly illuminated exterior field, will be unable to perceive quickly display details in the relatively dark interior of the vehicle. This problem might be reduced by the incorporation of high intensity lighting with a variable control within the assembly vehicle. The man-control-display relationships must be carefully designed. Specific displays that may be required to augment man's capabilities are discussed in a later section.

Kinesthetic Inputs - The orbital workman will also receive and require kinesthetic information in the form of feedback through the vehicle and manipulator controls. It is anticipated that feedbacks, which probably will be largely artificial, may be necessary to prevent overcontrol of the vehicle or manipulators. The specific function of feedback in space, however, is still questionable. In fact, the entire area of vehicle and manipulator control will require comprehensive research prior to the establishment of orbital operations.

The capability of man to manipulate an object directly while under the weightless state is not clear. It may be difficult for him to accomplish tasks of this type due to unnatural kinesthetic cues. For example, it will be difficult for man to perceive or judge the weight of an object in space. Only upon accelerating the object will he be able to perceive mass. Rees and Copeland (9) have demonstrated that mass increments must be at least twice as large as 1 g weight increments to be detected under a weightless condition. It is anticipated that man will require a period of adaptation under the weightless condition before he will be able to manipulate objects effectively by direct contact. The experimental apparatus of Rees and Copeland, which consists of masses supported by compressed air on an air-bearing table, might well be used in the adaptation and training of the orbital workman.

Other Sensory Inputs - Additional inputs are mediated to the man through the tactile and auditory senses. Man's sense of touch in the performance of space tasks will be restricted by a number of factors. First, the external temperature of the components being handled may vary over a wide range, depending on the presence or absence of incident solar energy. Second, man's pressure container will present an impediment to tactile inputs. Third, the use of manipulators as an intermediary between man and the tasks will alter the normal usefulness of the sense of touch.

The vacuum of space, of course, offers no auditory information to man directly from outside the vehicle. However, his auditory senses may be utilized to sense indirectly the status of outside processes. For example, warning signals might be used to advise of excessive forces of manipulator jaws or an excessive rate of closure on another object.

System Outputs

The fundamental outputs of the orbital assembly system will consist of vehicle motions and man-machine mechanical operations. In some instances man may be capable of producing the required motions or operations without the assistance of equipment. However, in most instances, man will require augmentation of his abilities in order to accomplish a prescribed task. It follows that the design of an orbital assembly system will require a rather concise definition of man's capabilities to perform envisioned tasks both alone and in combination with equipment of various degrees of complexity.

Assembly Vehicle Motion - In the absence of other bodies in space, man is incapable of initiating linear motion unassisted. When in contact with a body, man can initiate a motion perpendicular to its surface, but motion parallel to the surface of the body requires some means of producing a perpendicular interbody force before a tractive force can result. In each case, man's motion is attained by an exchange of momentum with the body. Motion by these means may be useful for a limited number of space tasks.

When man must move for appreciable distances out of contact with other bodies, such as in the retrieval of components which are in a slightly different orbit, man's capabilities must be augmented by a propulsive device. The total amount of energy to be supplied by this device will be dependent on the following considerations:

- The total distance to be traveled
- The number of starts and stops
- The time in which the maneuvers must be accomplished
- The mass of the propelled body

Since energy represents weight, the minimum expenditure of energy will result when a minimum quantity of propellant is carried by the assembly vehicle. This suggests the use of a central storage area to which the vehicle can frequently return for refueling.

Having shown the need for a jet system for providing the forces for movement, it is necessary to determine if the man is capable of controlling the vehicle motions and, if so, to establish the characteristics of the supplemental display devices that may be required. Undoubtedly, extensive research will be needed to determine man's ability to produce the required motions associated with the orbital assembly operation.

Several studies illustrating this type of research are described below. These are concerned with the specific problem of man's ability to control a space intercept. The data from these studies indicate that the supplemental display equipment required for space interception is a function of distance between the vehicles and the closure rate.

Simulator studies conducted by Wolowicz et al. (12) for ranges of one-half mile, established that "direct-visual observation interceptions can be performed effectively without the aid of range and rate-of-closure-of-range meters at speeds up to approximately 50 feet per second; however, higher speeds of interception require the use of these instruments." They further indicate that "the use of longitudinal-translation and attitude controls alone is inadequate. Use of translation controls alone, parallel and normal to the axis of the interception vehicle, is effective; the addition of attitude control enhances intercept effectiveness, provided the control is used discriminately." The study covered both on-off and proportional-type controls. For the on-off system the longitudinal control produced two acceleration values (initially); 1.29 feet per second^2 and 5.15 feet per second^2 selected at the pilot's option. The normal (to axis of vehicle) control had an acceleration of 5.15 feet per second^2 based on initial weight; and the pitch attitude had an angular acceleration of 2.1 degrees per second. The proportional controls, which had a small dead band, were linear and had maximum accelerations corresponding to the maximums of the on-off system. Results showed that pilot performance was essentially identical for both type controls as applied to the longitudinal thrust, but that a slight reduction in fuel expended was attained by use of proportional controls. Two side-arm type control sticks were used as the input devices. The left stick controlled longitudinal acceleration, while the right stick controlled pitch rotation and, by means of a thumb-actuated switch, normal acceleration.

Kurbjun et al. (2) conducted studies beginning at a range of 50 miles and a velocity up to 875 feet per second. They concluded that: "The following information is required on the pilot's instrument panel:

"o Elevation and azimuth line-of-sight angles and rates

o Range and range rate

o Vehicle attitude relative to the line of sight and the attitude rates."

The disposition of simulated thrust units gave three-axis attitude control and longitudinal thrust. The maximum control moments gave angular accelerations of 2.8 degrees per second^2 in yaw, 2.3 degrees per second^2 in pitch, and 4.5 degrees per second^2 in roll. Several values for longitudinal thrust were tried. Their final recommendation was to provide two levels: 3.2 feet per second^2 and 6.4 feet per second^2. Control input devices consisted of a pencil-type side-arm controller on the right for control of pitch and roll, rudder pedals for yaw control, and a throttle on the left for longitudinal thrust control.

Mechanical Operations - The mechanical operations produced by the man-machine system may be classified into the following types:

- o Maintenance of linear or angular position
- o Maintenance of velocity (movement)
- o Developing acceleration along or about three reference axes

In the apparent absence of gravitational forces in space, the maintenance of the position of a mass will not require a force output by man or the system. Force is required to maintain position, however, when a mass is acted on by another moving mass such as might occur in the aligning of two structural components. Likewise, no force output is required to maintain a velocity, unless frictional forces exist where two structural components are held in contact. If an articulate device such as the arm or a manipulator is used to maintain the linear velocity of a mass, force will be necessary for the acceleration of individual segments. All of these forces, however, are relatively small and will certainly fall within man's capability without augmentation.

On the other hand, operations involving the development or cessation of movement of mass, such as the positioning of structural segments, require careful consideration. It must be remembered that in space, although a weightless condition exists, the mass remains the same as on earth. It requires just as much force to overcome inertia in space as on earth. It is in this respect that man's capabilities may require augmentation by special equipment. For example, if man is to move a 20,000-pound component and desires to accelerate it at 0.3 foot per second^2, a force of approximately 200 pounds is required. Normally, man is capable of producing a force of this magnitude when properly supported. However, if he must also control his assembly vehicle as well as attend to the guidance of the component, a marginal, if not impossible, situation will result.

The alternative for supplementing man's capability in this respect is to use manipulators. As mentioned earlier, a pressure shell must be placed around man's gaseous environment. Thus, if circumstances are such that a flexible container can be used, man's inherent capabilities with respect to the magnitude of force available will be reduced. A rigid container has the potential advantage of being less susceptible to accidental penetration or rupture. When such advantage is to be exploited, some mechanical means for transmitting man's mechanical movements to the outside of the pressure shell is mandatory.

IV. THE ORBITAL TASK

Each envisioned orbital mission will present a unique matrix of operational tasks and perhaps different space environments; and, the system design requirements will vary with each mission. Envisioned tasks range from the assembly of small detail units and the performance of simple maintenance to the manipulation and joining of massive structural units. For this reason, orbital assembly vehicles and equipment must be designed to the requirements dictated by each specific mission.

Analyses of design tradeoffs must be made early in each design, at which time available information concerning man's capabilities, alternatives of vehicle and equipment design, and the space environment will be used to establish the ground and space operations. A detailed analysis of the space operations will determine the best tradeoffs between space vehicle design and assembly vehicle and equipment design. For example, if large components are assembled into a space vehicle or structure and the joining process is largely automatic, the weight penalty to the space vehicle will be at a maximum, but the number and complexity of tasks to be accomplished by man, as well as the weight of the supporting equipment needed by man, will be reduced to a minimum. On the other hand, if the space vehicle is assembled from small components by standard welding, bolting, or riveting operations, a lighter weight vehicle can be designed; however, the tasks to be performed by man will be more complex and the supporting equipment heavier.

It is apparent, then, that the characteristics of the orbital task will also depend on the type of assembly methods used. Space assembly may well require unique fastening methods. Thus, it appears important that the designer give his imagination free reign, rather than being bound to the conventional terrestrial fastening methods, since these may not be compatible with the environment and dynamics of the space operation.

Since the task is dependent upon the other system elements and on the mission requirements, only representative tasks that may be required of the orbital workman and his equipment can be described. These are listed below:

- o Locating components in space
- o Retrieving components and moving them to the assembly area

- o Unpackaging and disassembling packaged components
- o Securing parts not needed immediately to prevent drift
- o Positioning or indexing parts to be assembled
- o Holding parts relative to each other during assembly
- o Joining parts by means of welding, belting, or other means
- o Performing sealing, wiring, and plumbing operations
- o Orienting components with respect to the sun

V. ASSEMBLY VEHICLE CONCEPTS

It is anticipated that future space missions will require the development of a number of different orbital assembly vehicle concepts. A spectrum of potential concepts is described in this section. These vary in the number and complexity of the supplementary systems provided, and their capabilities vary with respect to three factors:

1. The length of time of independent operation away from larger vehicles, as represented by the capacity of the life support systems

2. The size of assembly components that can be moved about and handled safely as a result of thrust and manipulator characteristics

3. The distance and speed that can be utilized relative to the components and vehicle being assembled

The heavier and more complex assembly vehicles have the greater capabilities, of course, in terms of these factors. In the following descriptions, the weight noted for each vehicle includes fuel but not the man.

Anthropomorphic Concept

Figure 3 represents a vehicle concept contoured to follow closely man's body shape. This concept is principally applicable to tasks performed in close proximity to a larger vehicle or space station where fuel and life support systems can be replenished after a period of several hours. This concept also permits maximum use of limbs for moving about by handholds or magnetic shoes when in direct contact with large space components.

The supplemental devices, which are kept to a minimum while still permitting man limited movement in free space, consist of a pressure container, a gaseous environmental system, and a reaction jet control system. As shown by the figure,

Figure 3. Anthropomorphic Vehicle Concept

the pressure container is essentially the shape of a suit. The workman's arms and legs are housed within flexible shells. Bellows in the area of the limb joints provide added flexibility for freer movement. The man's torso is housed within a rigid shell. A helmet which can rotate about the body's longitudinal axis completes the pressure container.

The gaseous environment consists of pure oxygen at 5 psi. The environmental control system is contained within the back pack which is rigidly attached to the shell protecting the torso.

The propulsion system consists of a number of small jet nozzles, a control unit, and stored fuel. The jet nozzles are all interconnected rigidly by the torso-pack assembly to provide an orthogonal three-axis control system which is fixed relative to the man. Representative nozzles are shown forward of the man for yaw control and on his helmet for pitch control.

The control unit is located in front of the man's chest. Three control input levers are located on each side of the control unit to permit operation of the control system with either hand. The motion of each input unit corresponds with the desired output motion of the vehicle. The upper unit controls fore-and-aft motion and pitch, the center unit, lateral motion and yaw; and the lower unit, vertical motion and roll. Fuel for propulsion and control is contained within the back pack.

The weight of this vehicle concept is estimated to be 115 pounds.

Cylindrical Concept With Fabric Armpieces

In the concept shown in Figure 4 man is housed in a cylindrical vehicle. This configuration is intended primarily for movement in free space; however, movement along a space structure may be accomplished by the use of handholds or lines.

The supplemental equipment provided is the same as that listed for the anthropomorphic concept; i.e., pressure vessel, life support system, and control system. However, in this vehicle concept, the life support system and the control system permit more independence of operation than in the anthropomorphic concept.

The cylindrical pressure vessel offers the following advantages over the anthropomorphic concept:

- The simpler shape is easier to fabricate.
- Temperature control is facilitated by reducing the surface area and the number of individual air passages.
- A larger part of the container can be made of rigid-type material and is less subject to puncturing and tearing from contact with other bodies.
- If radiation or meteoroids present a real hazard, protection can be provided more easily.

Though man is deprived of the use of his legs, they are of questionable utility in many situations encountered in space. As stated earlier, even when in contact with other space structures, a synthetic perpendicular interbody force such as magnetic attraction is required before movement along the structure can be accomplished. Acquisition of this artificial force may impose undesirable design constraints. The magnetic force, for example, necessitates the use of a space body material of high iron content.

Fabric armpieces are provided in order to permit man to use his hands for accomplishing the mechanical operations of assembly. He can withdraw his arms into the main compartment when desired.

The life support system is located in the lower section of the cylinder and beneath the man's feet. Temperature control makes use of an internal source and sink.

Larger propulsion jets and more fuel are provided in this vehicle than in the anthropomorphic vehicle, in order to permit larger payloads to be towed for greater distances. The general aspects of the control system are similar to those described for the anthropomorphic vehicle. A controller of essentially the same arrangement as that shown by Figure 3 is provided, although it is not shown in

Figure 4. A single set of three control levers is provided inside of the cylindrical shell to permit control when the arms are withdrawn from the fabric armpieces. Fuel for the system is stowed below the floor in the cylindrical compartment.

The weight of this system is estimated to be approximately 175 pounds.

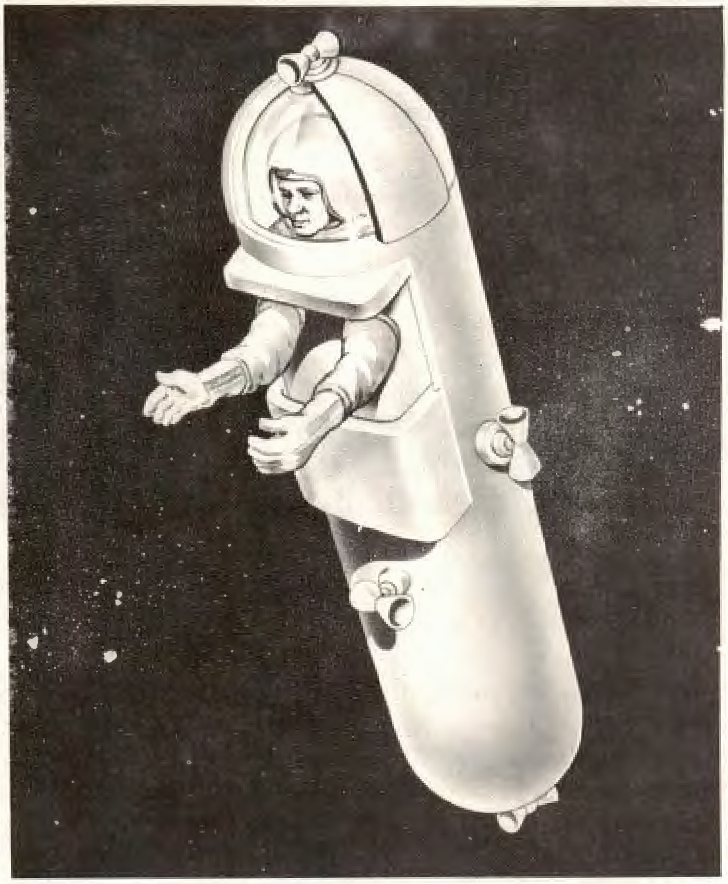

Figure 4. Cylindrical Concept with Fabric Armpieces

Cylindrical Concept With Manipulators

Figure 5 represents a refined version of the concept just described. The major differences are the addition of manipulators in place of fabric armpieces, a torus near the lower end of the cylinder, and external lights.

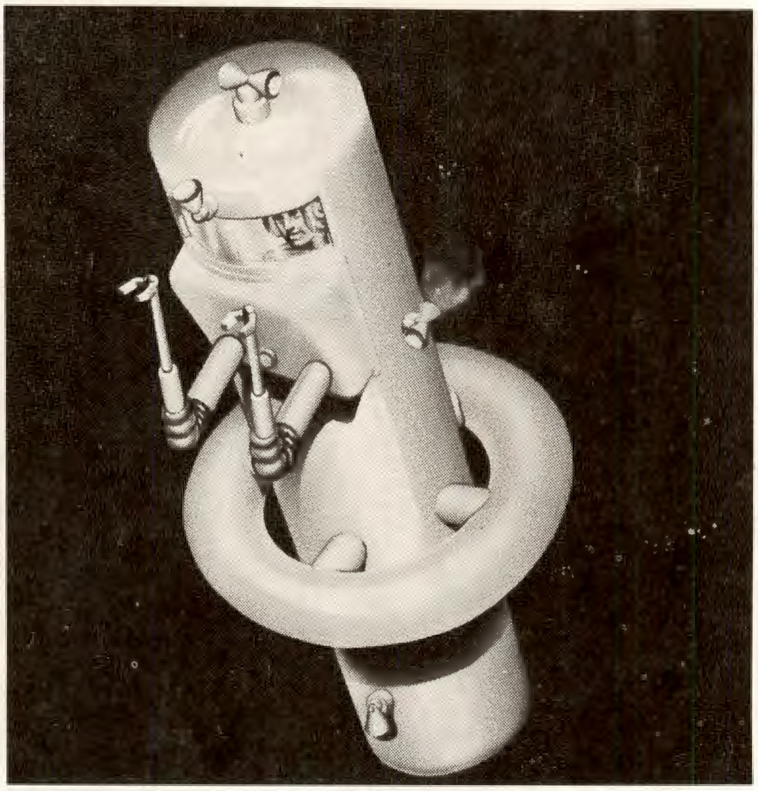

Figure 5. Cylindrical Concept with Manipulators

Locking devices on the manipulators free the man's hands for controlling the vehicle when moving from place to place with an assembly component in tow. The manipulators also give a greater reach than is available in the other two configurations and thereby reduce the need for small movements of the entire vehicle.

The torus provides a high-temperature element for radiating heat away from the vehicle. The other two concepts depended completely on internal sources and sinks for maintaining the required internal temperature. This was necessitated by a deficiency in radiating area and in the radiating temperature that could reasonably be used. The torus used here adds radiating area and permits a higher temperature since it is not close to the man. Heat-generating equipment and heat exchangers are located within the torus.

The addition of the external light permits illumination of the work areas in the absence of sunlight.

The weight of this vehicle concept is estimated to be 300 pounds.

Spherical Concept

Figure 6 represents a further step in complexity and attendant man-vehicle capability. This concept is capable of operating for several days without outside assistance. The supplemental equipment consists of the pressure vessel, the life support system, manipulators, a control system, a radar system, and instrumentation. The crew consists of two men; one man controls the vehicle motion while the other operates the manipulators.

The spherical pressure shell permits a maximum internal volume for a given shell weight. The vehicle is fabricated from a thin aluminum skin with rigid plastic foam back-up for stiffness and insulation. The function of the torus is the same as that described for the previous configuration; i.e., to provide heat-radiating surface area at a high temperature. All high heat output equipment is stored within this area.

Capacity of the life support system is adequate for several days operation without replenishment. The oxygen is stored in liquid form to reduce system weight and volume.

The manipulators and the control system are essentially the same as those described earlier, except a larger supply of fuel is provided.

The radar system provides for detection of unilluminated bodies and provides range data. The instrumentation includes those inputs referred to earlier as essential. These are range and range rate, elevation and azimuth relative to a pre-set line-of-sight, and vehicle attitude. Three-dimensional television and environmental and acceleration (linear and angular) displays complete the instrument complement.

The weight of this vehicle concept is estimated to be 700 pounds.

VI. SIMULATOR CONCEPT

The environment within which man must function during the space assembly operations is both widely different from his natural environment and quite hazardous. Because of the risks and costs involved, it is necessary to provide for ground simulation of the space environment and of the orbital mission. A simulator with this capability could be used to determine the adequacy of system designs for accomplishing the mission and to train the orbital workman for safe and expeditious performance of his tasks.

The essential elements of simulating the space assembly operations are as follows:

- Six-degree-of-freedom undamped motion of two or more bodies under the influence of inter-body and control forces
- The gaseous environment to which man is to be subjected
- The visual environment internal and external to the vehicle.

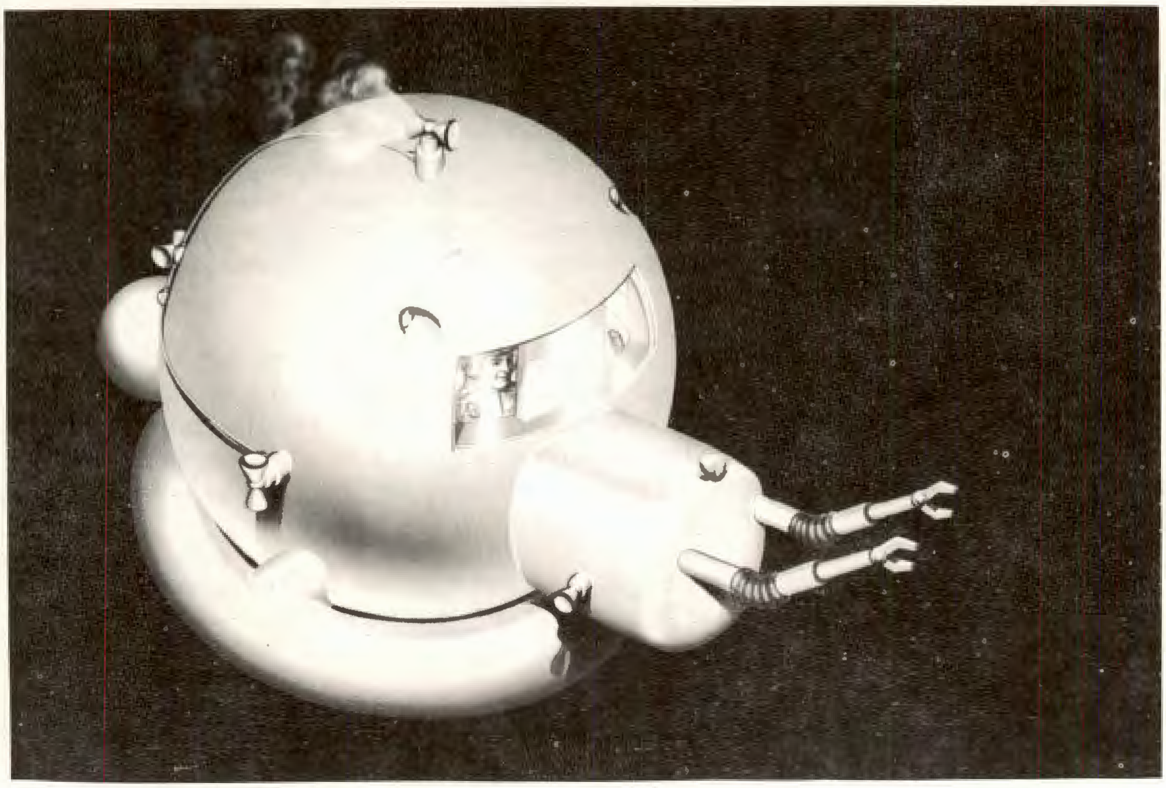

Figure 6. Spherical Vehicle Concept with Manipulators

A simulator concept fulfilling these general requirements is shown in Figure 7. Two suspension systems are supported by overhead tracks; a third suspension system is supported by tracks near the ground level. In the figure, the lower suspension system is shown supporting a manned assembly vehicle, while the upper suspension system supports the two halves of c cylindrical compartment to be assembled.

Each suspension system provides for movement of the supported body in three degrees of translation and three degrees of rotation. Each of the six degrees of motion is controlled in velocity and position by a positive drive system which receives its control signals from the computer system. The longitudinal travel of the suspension systems is provided by movement of each assembly along tracks running the full length of the building. The lateral movement is provided by a trolley which moves along a cylindrical bridge. One end of a telescoping tube, which affords vertical movement of the suspended body, is attached to the trolley. The telescoping tube is supported at one side of the trolley so that the two bodies suspended from the overhead systems can make contact before the corresponding bridges engage. The tube is composed of three hydraulic cylinders in tandem.

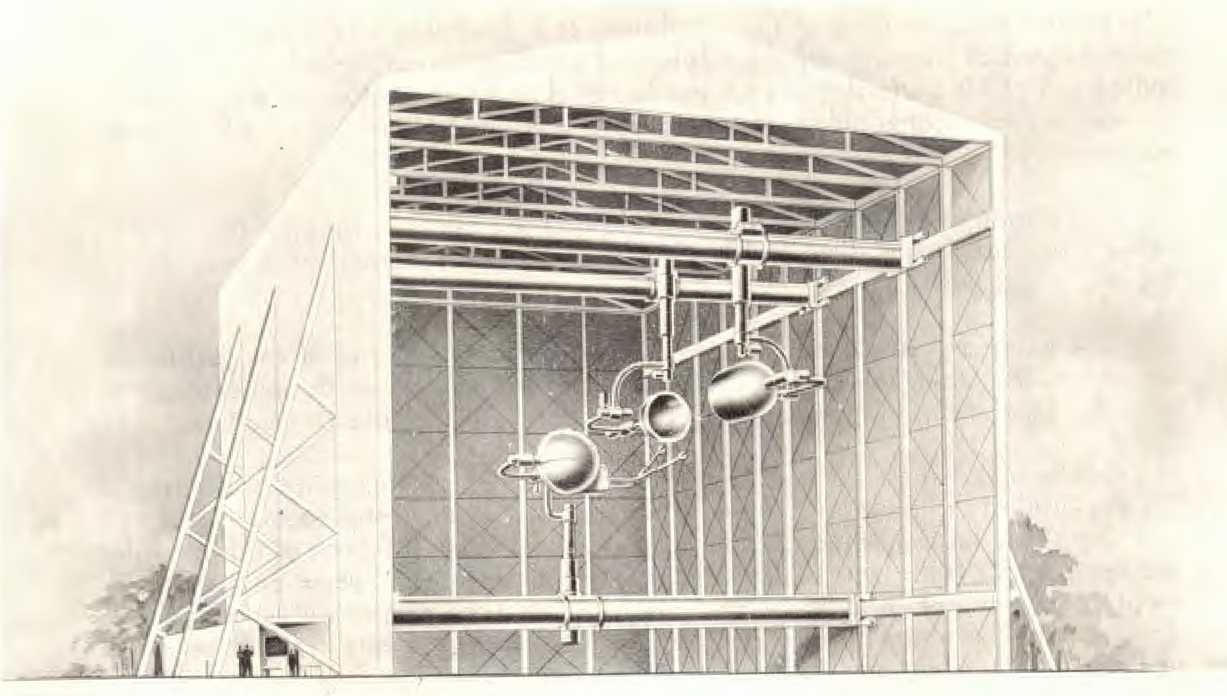

Figure 7. Orbital Space Operations Simulator Concept

A gimbal system which permits rotation of the suspended body through 360 degrees about three axes is attached to the telescoping tube. Each of the gimbal axes is driven by an electric motor and gear train. When the gimbal axes are normal to each other, yaw in the conventional sense results from rotation of the outer gimbal about an axis coincident with the telescoping support. Pitch is provided by rotation of the inner gimbal about the end of the outer gimbal. The roll axis is supported at one end of the inner gimbal. Cantilever-type gimbals are used in order to reduce the vehicle area blocked by the gimbal system.

Vehicle motions can be initiated by the application of an external force to the vehicle. The direction and magnitude of such forces are determined by six sets of strain gages which are installed in such a manner as to pick up the torque at each of the three gimbal axes and the thrust along each of the three gimbal axes.

The test subject can be provided control of all motions of his vehicle. Provisions are made for bringing out independent control signals for each degree of freedom so that various configurations of control systems can be simulated.

The computer system calculates the velocities and accelerations which would result in space from both the interbody forces and the vehicle operator inputs to the control system. Signals are then transmitted to the appropriate servosystems to result in representation of the proper motions. The computer also makes the coordinate transformations which are necessary and limits the translational velocity and the collision velocity between bodies.

During the operation of the simulator, it is desirable to communicate with the occupant of the suspended vehicle and to observe and record information indicative of his performance. A number of data-transmission channels from the vehicle to a convenient stationary observation post are provided for these purposes.

Only the power supply to the vehicle and the control signals from the vehicle are carried by direct wiring. Slip rings at the gimbal axes provide the electrical path.

The external visual environment may be composed of any of the following elements: (a) other vehicles or man-made bodies, (b) the earth and associated objects, (c) the sun, (d) the moon, and (e) more distant celestial bodies.

Representation of the earth may be achieved by photographic projection of the required visual field on the walls or floor of the simulator room. The sun and moon may be simulated by appropriate focusing or diffusing of a high-intensity arc light. This light may be fixed at some point within the room or it may be supported by one of the suspension systems. The more distant celestial bodies may be represented by a large number of small, low-intensity lights scattered about the room or by projection on a screen.

The simulators and the interior of the building will be painted dull black in order to minimize scattered light.

The aural environment may easily be provided by use of recorded noise when such is desirable. The exclusion of undesirable external noise will require soundproofing of the vehicle.

SUMMARY

The accomplishment and scope of envisioned space missions are largely restricted by the weight of payload capable of being launched. However, this restriction can be overcome by the establishment of operations involving the orbital assembly of structures or vehicles whose size, weight, and/or structural limitations prevent their being launched as a single unit.

The spacemen assigned to orbital assembly missions will be called upon to perform unique and complex tasks under the stresses and restrictions of the space environment. It is readily apparent that the orbital workman will require special vehicles and associated equipment to accomplish the required tasks effectively.

The development of orbital equipment requires the consideration of four basic elements: (a) the space environment, (b) the man, (c) the tasks, and (d) the vehicle and associated equipment. Orbital equipment must be developed in terms of the tradeoffs presented by the characteristics and problems as related to each specific mission.

A spectrum of conceptualized manned orbital vehicles is described. These range from an anthropomorphic suit to a complex spherical vehicle including manipulators. The design and operation of such vehicles will require careful planning, research, and training of personnel prior to actual launch. For this purpose a ground simulator capable of simulating the elements of the orbital assembly operation has been investigated and is described in this paper.

The orbital operation contains many of the elements of the nuclear laboratory. Man is required to interact or manipulate objects existing in a hostile environment from which he must be isolated. The orbital workman, in addition, must accomplish his tasks from within a life-supporting pressure vessel. Thus, the grips and claws that have served the nuclear scientist may well become standard and highly important tools for the accomplishment of future orbital operations.

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