THE RELATIONS BETWEEN EXPERIMENT REQUIREMENTS, ENVIRONMENTS, AND SPACECRAFT DESIGN

By Robert A. Bruce

NASA Langley Research Center
Langley Station, Hampton, Virginia

Lecture notes of presentation given by Robert A. Bruce at the Bio-Space Technology Training Program conducted at Wallops Island, Virginia, August 1966

GPO PRICE $ ____________

CFSTI PRICE(S) $ ____________

Hard copy (HC) 2.00

Microfiche (MF) .50

ff 653 July 65

N66 39422
(ACCESSION NUMBER)

35
(PAGES)

TMX-57996
(NASA CR OR TMX OR AD NUMBER)

(THRU)

1
(CODE)

31
(CATEGORY)

FACILITY FORM 602

THE RELATIONS BETWEEN EXPERIMENT REQUIREMENTS, ENVIRONMENTS, AND SPACECRAFT DESIGN

In this talk I shall try to show some of the steps thru which an experiment passes from its concept to the time that it is ready for launch. These factors will not be covered in detail, because many of them are subjects of other lectures, but their relation to the design of the experiment and the spacecraft will be discussed. In order to have a central point of focus to keep this discussion together, let us assume a hypothetical biological experiment and follow its progress from the concept on the experimenter's desk to the flight-worthy experiment ready on the launch pad.

The first requirement for the experiment is to have a concept of something which must be done. In order to understand better the effects of prolonged weightlessness on man, let us propose to make an experimental flight of three months duration with two squirrel monkeys as our test subjects. The monkeys will be recovered at the end of this time for comprehensive examination. During flight it will be necessary to make sufficient measurements or observations to be able to determine at what point or at what rate during the flight the final observed changes may have occurred. It is desired to keep the subjects in as near normal environment as possible so that all observed changes may be ascribed to the weightless condition. For this reason, the subjects will be unrestrained and there will be no implanted sensors used. Measurements of body temperature, electrocardiogram, and ability to perform tasks, together with television observation of the monkeys' activities are considered adequate to use as general indicators of the condition of the monkeys during the flight.

Having established the concept of the experiment, the next thing which must be done is to determine the experiment requirements as listed in figure 2. The first requirement is that the experiment be conducted in a zero gravity condition. The requirement of maintaining conditions as near normal as possible dictates the use of normal atmospheric pressure and normal atmospheric gas composition. We will establish the temperature range as 70 - 90°F, a relative humidity in the range of 30 - 70%, and a maximum allowable concentration of carbon dioxide of 1% in the atmosphere. Certain other environmental conditions cannot be defined as readily - illumination is one of these. In order to maintain the most nearly normal conditions for the monkeys, we would have to illuminate on a light and dark cycle for 24 hour periods. However, for television observation, it is far more desirable to have a constant level of illumination. This is one of the areas where a trade-off between convenience of operation and the experimental effect will have to be determined. Radiation presents a similar problem. We have two choices here. We may install sufficient radiation shielding that the radiation dose received by the monkeys during this three month flight will be no higher than that which is received on earth. Or, since this flight will not be at altitudes where high radiation levels are expected, it may be sufficient to monitor the radiation dose and take this into account in the final evaluation of the experiment results. The experimental requirements also include the measurements that must be taken. On the subjects, we have determined that electrocardiogram, body temperature, task performance ability and activity observation by means of television will be adequate. We can meet our requirement of no implanted sensors if we design the task performance panel so that, in order to perform the task and receive food, the monkeys will grasp two levers and manipulate them. The two levers can be insulated from the structure and used as electrodes to make the electrocardiogram measurement. A thermistor sensor implanted in the lever can also determine the body temperature of the monkey. In addition to the measurements on the subjects, we also have to make measurements on the environment. These would include, as a minimum, the atmospheric pressure, temperature, gas composition, and radiation level.

Having established the requirements of the experiment, we can then proceed to the preliminary design. First of all we have to define the system functions which must be performed, as in figure 3. The environmental control system will have the functions of the oxygen and nitrogen supply and control, air circulation, temperature control, carbon dioxide control and humidity control. The life support system will include food supply, water supply, and waste disposal. The third area is that of data management. This will include the measurements which are taken on the subjects and on the environment, data storage and finally telemetry. The television observation of the monkeys' activity during those irregular intervals when the spacecraft is passing over a receiving station will be adequate, but the task performance data and electrocardiograms which are taken at regular intervals during the flight must be stored until a convenient time to transmit them to earth. The fourth system is that of electric power supply. The requirements of our environmental control system, life support system, and data handling system will determine the power level required and a suitable system can be designed. An additional area is that of attitude control for the spacecraft. The attitude control is required in order to orient the panels which receive solar energy, and to orient the spacecraft so that the radiator is not looking at the sun or at the earth, to which it could not radiate its energy, but is looking out towards space. It is also necessary to be able to orient the spacecraft so that it can perform the reentry operation. The next area is reentry and recovery systems. These will provide the necessary deceleration for reentry from orbit, heat shielding from reentry heating, and landing and recovery aids. The final system is the structure which includes the pressure cabin for the subjects and the framework for supporting all of the above systems.

We now have to select the particular subsystems which will perform the system functions which we have described. We shall use the environmental control system for an example. In figure 4 we have shown three different types of systems which could be used to perform this function. The first is the completely open system. Here the oxygen and nitrogen gas from storage is metered out past the test subjects and this gas, containing the carbon dioxide, water and any contaminants, is dumped overboard. The second system, which is somewhat more complex, will take the oxygen and nitrogen from storage, adminster it to the chamber containing the subjects, and then recirculate this gas, by means of a blower, through carbon dioxide removal and water removal subsystems.

Unused oxygen is thus returned to the subjects for reuse. A small amount of gas in the system is vented overboard to get rid of contaminants. The third type of system that could be used is the completely closed system. In this the air from the storage tank is used to pressurize the compartment where the subjects are kept. This air, however, is all recirculated through a blower to the carbon dioxide, water, and contaminant removal subsystems and returned. In addition, the carbon dioxide and water go through the oxygen recovery subsystem and the recovered oxygen is returned to the subjects' cabin. With this system there is no intentional dumping of gas overboard. Some leakage will occur naturally, however, and this amount will be made up from the oxygen and nitrogen stores.

How do we select the optimum subsystems from these different possibilities? If none of these systems would have to be rejected on the basis of unavailability within the required time, or on the basis of excessive cost or power requirements, the selection could be made on the basis of minimum weight. The equivalent weight of a system is the sum of the fixed hardware weight, the weight of the expendables consumed during the period of flight, and a proportional share of any auxiliary systems required. If a particular system we are discussing uses half of the electrical power which is generated, this system would be charged with half of the electrical power system weight. This is referred to as a power penalty. Similarly, a heat rejection penalty would be a proportional share of the weight of the radiation surfaces and controls required for rejecting heat from the vehicle. The various systems may be compared then on the basis of their total equivalent weight as shown in figure 5. The open type system is the simplest and it shows a very low fixed weight. However, it has the highest rate of expendable consumption of any of the systems. The semi-closed system is somewhat more complex and has a higher fixed weight but the rate of consumption of expendables is considerably reduced as shown in the figure. The totally closed system is very much more complex, requires considerable power and therefore, exhibits a very high initial weight, but since the consumption of expendable materials is only that from normal leakage, the curve is very flat. Therefore, it can be seen that for flights of any particular duration one or the other of these systems will be optimum. For the very short duration flights the completely open system is perfectly adequate. For flights of longer duration, the least weight is shown by the semi-closed system. Finally, for very long durations, the completely closed regenerative system shows the optimum total equivalent weight. For our hypothetical experiment, the oxygen consumption by these small monkeys is very low and, for the duration that we are discussing, the semi-closed system with reuse of oxygen and nitrogen after removal of the carbon dioxide and water is optimum. In a similar way, the particular subsystems which will perform the rest of our subsystem functions will be chosen.

After the systems have been chosen, the next step in our process will be to make our preliminary weight estimates. For illustration here, I have chosen the breakdown of the weights of the environmental control system, as shown in figure 6. For oxygen and nitrogen supply, we have a requirement of 18 pounds of gas. If we store this gas in the liquid state, we may estimate a tank weight of 10 pounds and controls at another 10 pounds, or 38 pounds total for this system. Similarly, carbon dioxide removal by lithium hydroxide sorption will require 15 pounds of lithium hydroxide in an approximately 1 pound container, and we may proceed the same way down the weights required for water removal, air circulation, and waste removal. When we sum up these weights, we find approximately 110 pounds for the weight of the environmental control system. Proceeding through the rest of the systems in the same manner, we can get the estimated weights that are shown on figure 7. The total of these weights gives us our preliminary estimate of weight for the complete experimental spacecraft.

Once the weights have been determined, it is necessary to select a booster which will put our spacecraft into the desired orbit. We have no requirement for orbit altitude as far as the experiment is concerned with the exception that we require a flight duration of three months. For any given spacecraft there is a maximum duration of orbital flight before its velocity decreases to the point that it will reenter the earth's atmosphere. This orbit "lifetime" is a function of the initial orbit altitude and the "ballistic coefficient" of the spacecraft, which depends on the spacecrafts' weight to effective drag area ratio. From our preliminary design, we may estimate a ballistic coefficient of 100, and the relation between orbit altitude and orbit life time will be as shown on figure 8. Our requirement of a 90 day flight indicates that we will need an orbit of approximately 142 nautical miles. With this orbit requirement and our preliminary estimate of spacecraft weight, we can now select a potential booster. The curves shown in figure 9 show the performance of several boosters in terms of the altitude of the circular orbit can be obtained with any given payload weight. The two lower curves are those of two configurations of the Scout vehicle - a four stage solid fuel rocket. The two upper curves are two of the Delta launch vehicle configurations. These are 3 stage rockets using liquid fuel rockets for the first two stages and the same solid fuel rocket as the Scout B for the final stage. Our requirements of orbit altitude and payload weight come out to a point that could be obtained by a Scout B configuration. It should be noted here that this would not be a sound selection in practice since experience has shown that the weight of the final spacecraft usually exceeds the preliminary weight estimates by about 20 percent, and a weight-growth margin should be included in the weight estimates. However, let us be optimistic as well as hypothetical in this discussion and assume that the Scout B is a suitable choice.

Let us now look at the environment to which the payload on the Scout B launch vehicle would be exposed. In figure 11a, we see the acceleration as a function of time during the flight. The burning of the first stage motor produces an acceleration of the vehicle approximately 5 times greater than the normal earth gravity (or 5 "g"). As the first stage burns out, the second stage is ignited at approximately 75 seconds into the flight, and produces a maximum acceleration of about 8 "g". The third stage produces a still higher acceleration with a peak of about 9 "g". After the burning of the third stage, the vehicle goes through a coast until it reaches its orbital altitude. The fourth stage is ignited at that point and provides the necessary velocity to insert the payload in its circular orbit. The maximum acceleration that the payload experiences is during the fourth stage burn, and, for the particular payload and launch vehicle that we have assumed, would be approximately 10 times normal gravity. The effect of this acceleration is that all of the components of the spacecraft, including the monkeys themselves, are reacting on their supports with a force of 10 times their normal earth weight. The structure must be designed to withstand these forces, and it will be necessary to determine whether special supports will be necessary to protect the monkeys during this launch environment.

During the burning of the first two stages, the vehicle is being accelerated to a high velocity through the atmosphere and aerodynamic heating as shown in the figure 11b becomes quite important. This shows the temperature at the "stagnation point", or the maximum temperature on the nose of the vehicle, as a function of time during flight. This curve was taken for the maximum heating trajectory and is somewhat more severe than what we would encounter in the particular flight which we have chosen. The heat shield is designed to tolerate this high temperature and minimize the heat coming into the payload compartment. The lower line on this curve shows the temperature rise in the inside of the heat shield under the point of maximum external temperature. We see that at the time when the outside of the heat shield is over 800°, the inside has risen from approximately 80° at launch to about 100°. After the second stage has burned and just before third stage ignition, the heat shield is separated from the vehicle and discarded. At this point the vehicle is high enough that aerodynamic heating is no longer a problem. Just as the capability of the booster to lift weight into orbit limits our payload weight, the dimensions of the heat shield limit the volume and the relative dimensions we can have for the payload.

The third environment to which our payload is subjected is that of spin during burning of the fourth stage motor, as shown in figure 11c. In the previous three stages the vehicle was stabilized by means of attitude control motors, however, the fourth stage is stabilized by spinning the vehicle around its longitudinal axis at a fairly high rate to balance out the effect of any thrust misalignments. The minimum spin rate is determined by the accuracy required for orbit injection. Our particular payload would be spun up by means of four small solid motors to a rotational speed of approximately 134 revolutions per minute. This spin-up is accomplished in about 1-second of operation, creating a very high angular acceleration. It may be necessary to protect the test subjects from this violent acceleration and this could be accomplished by mounting the cage about a pivot point so that it is free to turn relative to the spacecraft itself. When the spacecraft is spun up in this maneuver, the cage will remain relatively still and just start to spin slowly as friction in the bearings imparts a torque to the cage. After the fourth stage burn has been completed, the spacecraft has been injected into orbit. The spacecraft can then be de-spun and the cage can be locked into its required position relative to the spacecraft. The payload may be de-spun by means of the attitude control motors of the spacecraft, or by use of what is called a yo-yo de-spin system. In the yo-yo system, the angular momentum of the spacecraft is imparted to two weights which fly out on cables wrapped around the spacecraft. The tension in these cables provides a braking torque to the spacecraft. When the spacecraft rotation stops, the cables are released, and the attitude control system completes the required stabilization.

The last environment introduced by the launch vehicle is that of vibration. During the burning of the last stage, the longitudinal vibrations produced by the motor are transmitted to the payload. These vibrations may be represented as shown in figure 13a. A vibration level of approximately $\pm$ 1 "g" exists between 20 and 50 cycles per second. From 50 to 500 cycles per second approximately $\pm$ 4 "g" accelerations are experienced, and from 500 to 2000 cycles per second there are vibrations with approximately $\pm$ 8 "g" level. This curve is not to be interpreted as being the instantaneous level of the vibrations present with the sharp variations in magnitude, however, this will be an envelope of the vibrations which are produced and would represent the probable maximum for vibrations which would be experienced in the particular frequency ranges. The effects of vibration may be combatted by mounting very critical components on special vibration dampening mounts, and throughout the rest of the spacecraft by ensuring that the natural frequency of the structure does not fall within a critical vibration area. Let us consider a simple weight suspended on a beam. If we assume that this has a natural frequency of 1000 cycles per second, we would have a possible vibration effect indicated in figure 13b. As we can see, vibrations near the natural frequency of the 1000 cycles per second can produce accelerations of approximately $\pm$ 40 "g" on the weight. If we redesign the structure so that the same weight is supported by two struts, each of which having the same cross-section as above, the natural frequency of the system will be increased to 2800 cycles per second. This is outside of the range of exciting vibrations and the maximum acceleration would be approximately $\pm$ 16 "g" at the weight. Taking into consideration the range of exciting freq-uencies and the possible amplifications that may result in the structure, it is necessary to design all of our structure for adequate strength at these possibly high vibration levels. It is also necessary to ensure that any mounting screws or connectors are adequately secured so that they will not become shaken loose by these vibrations.

Another set of environmental conditions will be those encountered during reentry. Figure 14a shows two possible reentry profiles. The dotted line represents a lifting type reentry where the maneuver consists of a series of dips and climbs. This extends the time of the reentry, and as can be seen in figure 14b, reduces the maximum deceleration from more than 5 "g" to less than 2 "g". These accelerations are less severe than those encountered during launch, but, since they occur in a different direction than the launch accelerations, the structural design must be checked for adequate strength during the reentry conditions. Let us assume that we will select the lifting reentry in order to minimize the reentry stresses on the monkeys after their period of weightlessness.

A very severe environment is that of aerodynamic heating during reentry. As shown in figure 15a, the surface of the heat shield at the point of maximum heating reaches a temperature of 4000°F. These high temperatures require the use of an ablative type of heat shield, rather than the insulated metal shield that was suitable for protection during launch. The ablation of the heat shield during reentry is shown in figure 15b. At the conclusion of the reentry, only one-inch of the original $2\frac{1}{2}$-inch thick heat shield remains. The temperature of the interior surface of the heat shield rises to approximately 400°F by the time the reentry is complete. This will require the incorporation of an active cooling system for control of the temperature within the monkeys' compartment.

So far we have discussed some of the conditions for which we would have to design concerning the active phases of the space flight. Another area which must be taken into consideration is that of prelaunch requirements. This covers the time period from the insertion of the subjects into the spacecraft until the actual launch is accomplished. While the spacecraft and launch vehicle are sitting on the launch pad, some of the spacecraft systems will not be operating. If we use solar cells for power, no electrical power will be generated in this condition. No heat can be rejected from the space radiator, and, with the normal atmospheric pressure on the outside of the spacecraft, there will be no ventilation flow of gas from inside the cabin to the external atmosphere. It will be necessary, therefore, to design ground support equipment and provide connections to the spacecraft for electrical power, for ventilation, and for cooling as long as the spacecraft remains on the pad. Another factor which must be considered is the effect of any launch delay. This might be due to weather conditions unfavorable for launching or due to some mechanical malfunctions. For our particular experiment, it is not particularly critical that the launch be accomplished within a specific time interval or "launch window" since we are just going into earth orbit and are not planning to accomplish a rendezvous with any other objects. Another point which would be critical in some experiments would be the effect of launch delay on the state of development of the test subjects, but this is not a problem in our case either. The main effect of launch delay on our particular experiment will be that we will have to be sure that the ground support equipment is designed to carry the necessary loads for whatever period of delay might reasonably be encountered.

At this point we have established the experiment requirements and environment for our spacecraft and are ready to proceed into the detailed design. We must produce a design which will not only satisfy these requirements, but will offer a high probability of success. Experimentation in space has several unique characteristics. The first of these is the inability to perform any maintenance on the spacecraft once it has left the launch pad and the second is the high cost of the launch vehicle. The failure of a ten-cent resistor resulting in loss of the experiment data may cost more than a million dollars. It is obvious, therefore, that one of the most important factors throughout the design and manufacture of the spacecraft is the necessity of producing a highly reliable device. The design phase must include not only the preparation of drawings and specifications, but also the establishment of reliability provisions and test plans. The effects of failure of each of the components must be considered and critical failure modes minimized by the selection of components of demonstrated suitability for the application and by providing redundant or "back-up" systems as needed. Throughout the manufacturing phase it is essential to maintain stringent controls to ensure that the item produced meets all of the requirements of the design. The verification of successful design comes in the test program. Functional tests, performed during the development phase and on the finished hardware, verify that the design adequately fulfills the experiment requirements. These tests should include operation of the spacecraft in a thermo-vacuum chamber with the monkeys on-board to test all systems in a normal operating environment. The thermo-vacuum chamber has liquid nitrogen cooled surfaces to which the spacecraft can radiate heat as it would to space and arc lamps to simulate solar energy. Qualification tests are performed on prototype components or spacecraft to prove that the design is adequate to survive the environment to which the spacecraft will be subjected. These tests include, as a minimum, acceleration, vibration, and shock. The qualification tests are usually run at levels about 50% more severe than those expected in flight to expose any marginal areas in the design. Items which have been exposed to these high qualification test levels are not used for flight. The final set of tests are the flight acceptance tests. These tests, acceleration, vibration, etc., are conducted at the levels anticipated in flight and serve to expose any flaws in material or workmanship in the actual flight items.

I have not tried to make any definition of the individual responsibility of the experimenter or the spacecraft designer in this talk, but rather to attempt to point out the things that must be done. Close contact and understanding is essential to ensure that proposed solutions to design problems are compatible with the experiment, and conversely, that experiment requirements are compatible with practical engineering design.

EXPERIMENT CONCEPT

DETERMINE EFFECT OF PROLONGED ZERO-GRAVITY EXPOSURE ON A PRIMATE.

ENVIRONMENT AS NORMAL AS POSSIBLE TO AVOID EXTRANEOUS EFFECTS.

USE TWO SQUIRREL MONKEYS AS TEST SUBJECTS.

NO RESTRAINTS OR IMPLANTED SENSORS TO BE USED.

RECOVER LIVE AFTER FLIGHT FOR DETAILED EXAMINATION.

Figure 1

EXPERIMENT REQUIREMENTS

DURATION: 90 DAYS

ENVIRONMENT

- ZERO GRAVITY
- PRESSURE: 14.7 PSIA
- TEMPERATURE: 70° - 90°F
- HUMIDITY: 30 - 70%
- O_2 CONCENTRATION: 20 - 50%
- CO_2 CONCENTRATION: 0 - 1%
- ILLUMINATION LEVEL ?
- RADIATION LEVEL ?

MEASUREMENTS ON SUBJECTS

- BODY TEMPERATURE
- ELECTROCARDIOGRAM
- TASK PERFORMANCE
- ACTIVITY OBSERVATION

MEASUREMENTS ON ENVIRONMENT

- PRESSURE
- TEMPERATURE
- GAS COMPOSITION
- RADIATION LEVEL

Figure 2

SYSTEM FUNCTIONS

ENVIRONMENTAL CONTROL SYSTEM

- AIR SUPPLY
- AIR CIRCULATION
- TEMPERATURE CONTROL
- HUMIDITY CONTROL
- CO_2 REMOVAL
- CONTAMINANT CONTROL

LIFE SUPPORT SYSTEMS

- FOOD SUPPLY
- WATER SUPPLY
- WASTE DISPOSAL

DATA SYSTEMS

- MEASUREMENTS ON TEST SUBJECTS
- ENVIRONMENT MONITORING
- DATA STORAGE
- TELEMETRY

POWER SYSTEM

ATTITUDE CONTROL SYSTEM

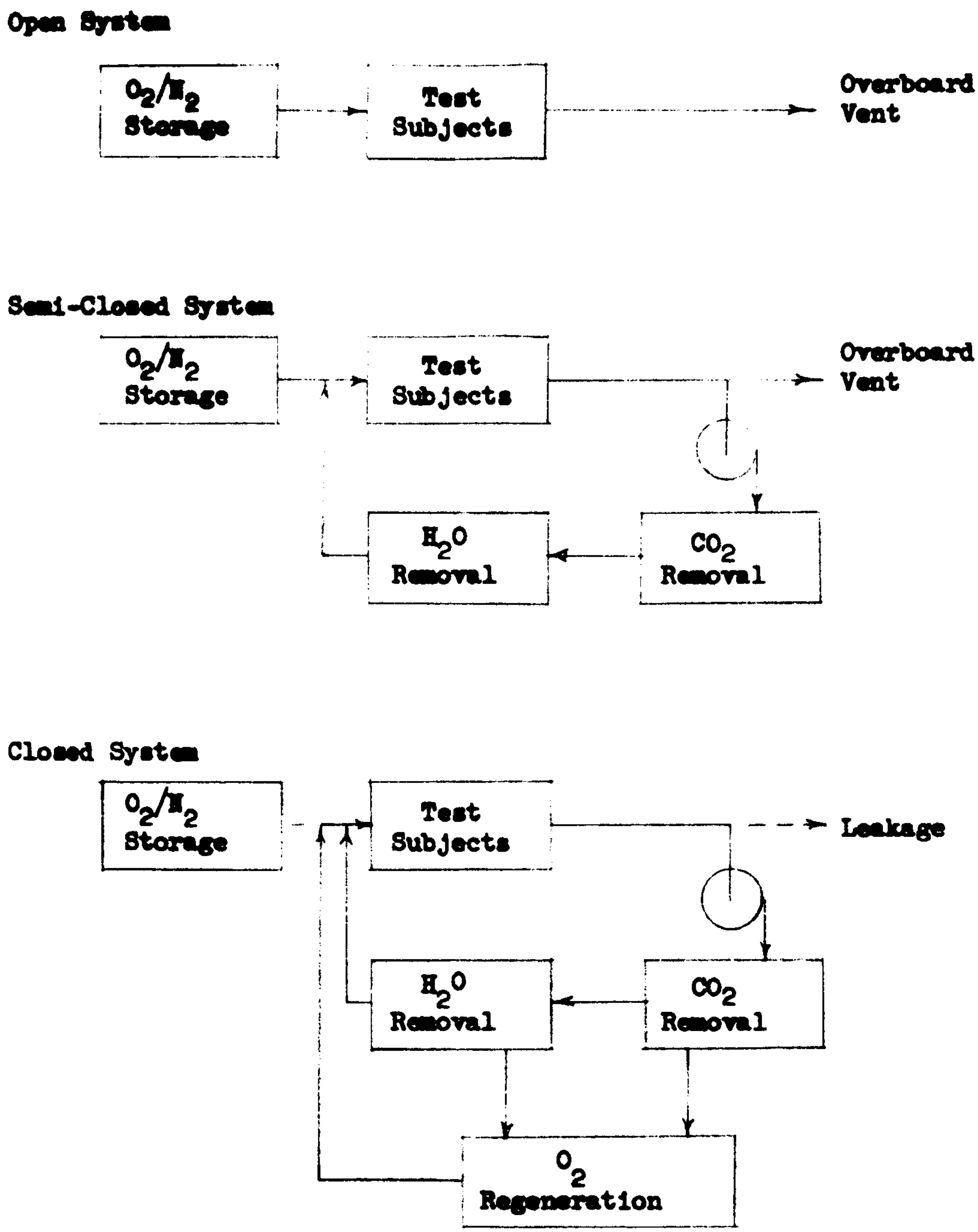
- SOLAR ENERGY
- HEAT REJECTION
- REENTRY

REENTRY AND RECOVERY SYSTEMS

- DECELERATION
- HEAT SHIELDING
- LANDING
- RECOVERY AIDS

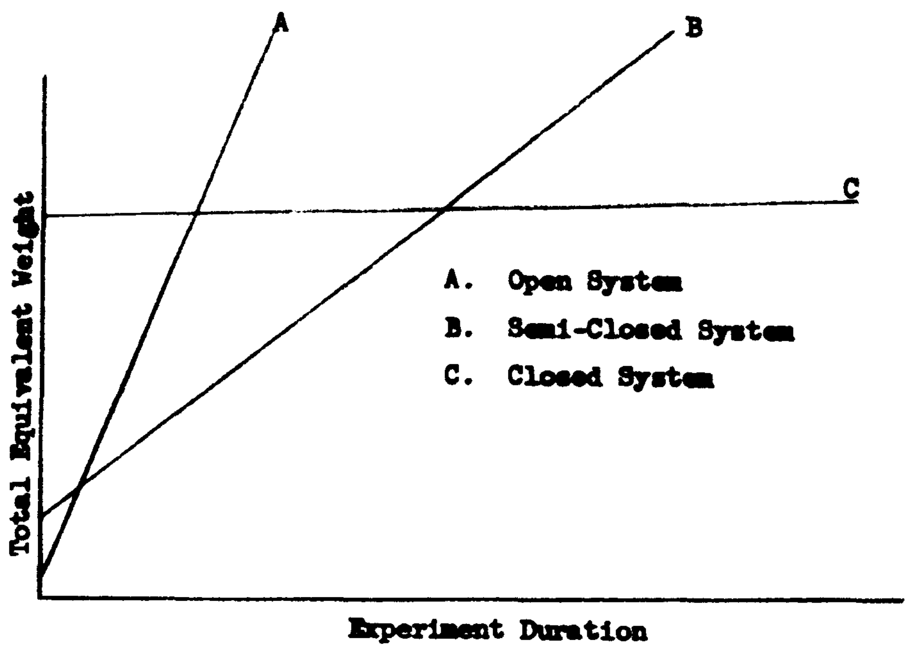
STRUCTURE

Figure 3



TYPES OF ENVIRONMENTAL CONTROL SYSTEMS

Figure 4



SELECTION OF ENVIRONMENTAL CONTROL SYSTEM

Figure 5

PRELIMINARY WEIGHT ESTIMATES

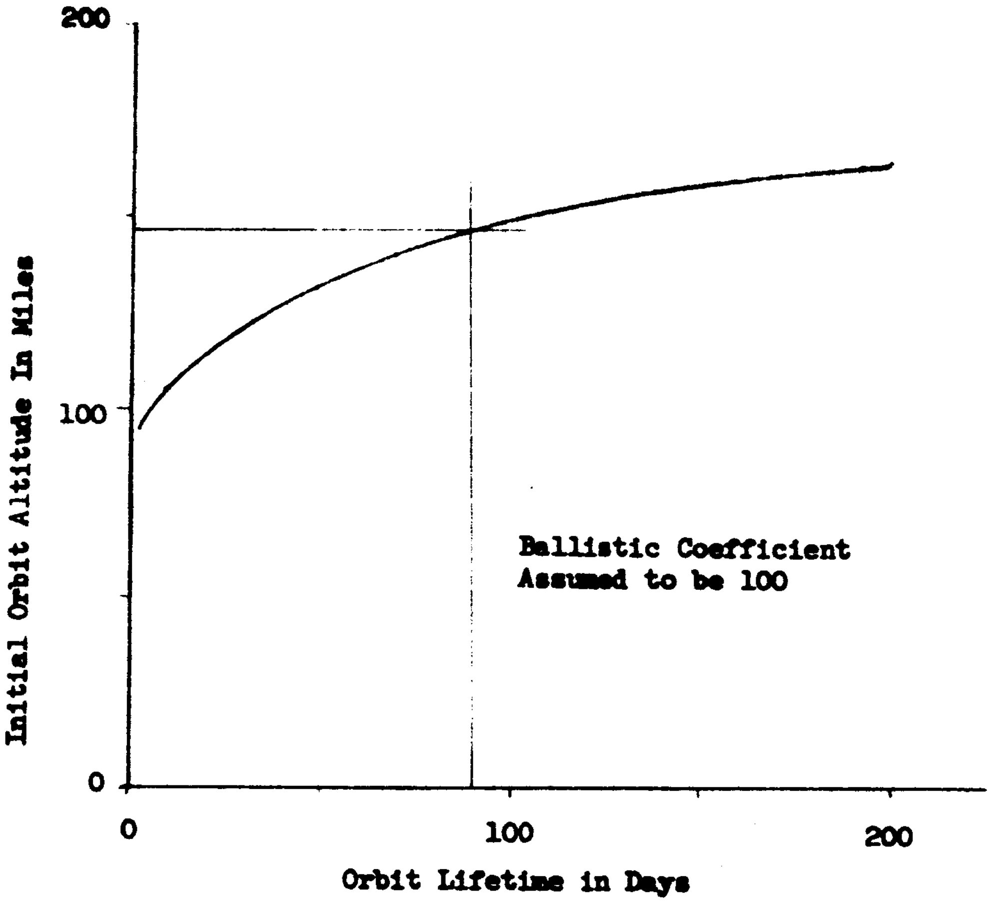
ENVIRONMENTAL CONTROL SYSTEM		
O_2/N_2 SUPPLY		
GAS WEIGHT	18	
TANK WEIGHT	10	
CONTROLS	10	38
CO_2 REMOVAL		
LITHIUM HYDROXIDE	15	
CONTAINER	2	17
H_2O REMOVAL		
LITHIUM CHLORIDE	23	
CONTAINER	10	33
AIR CIRCULATION		
BLOWER	5	
DUCTING	10	15
WASTE REMOVAL		
CHARCOAL	2	
FILTERS	2	
FRAME	3	7
		110

Figure 6

PRELIMINARY WEIGHT ESTIMATES

ENVIRONMENTAL CONTROL SYSTEM	110
LIFE SUPPORT	50
DATA ACQUISITION AND HANDLING	25
POWER	40
ATTITUDE CONTROL	30
REENTRY AND RECOVERY	80
STRUCTURE	65
	400

Figure 7



ORBIT LIFETIME

Figure 8

TYPICAL LAUNCH VEHICLE CAPABILITY

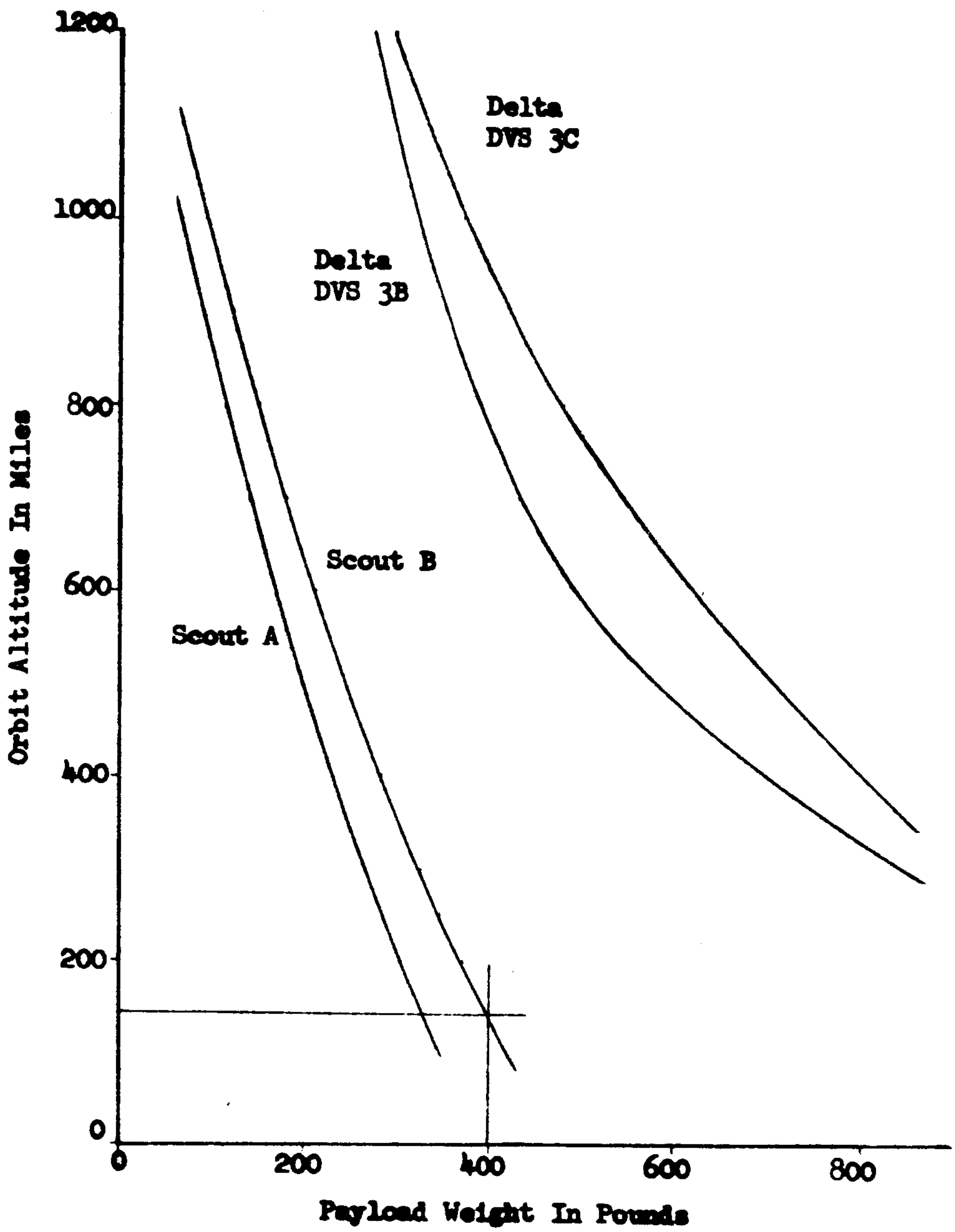
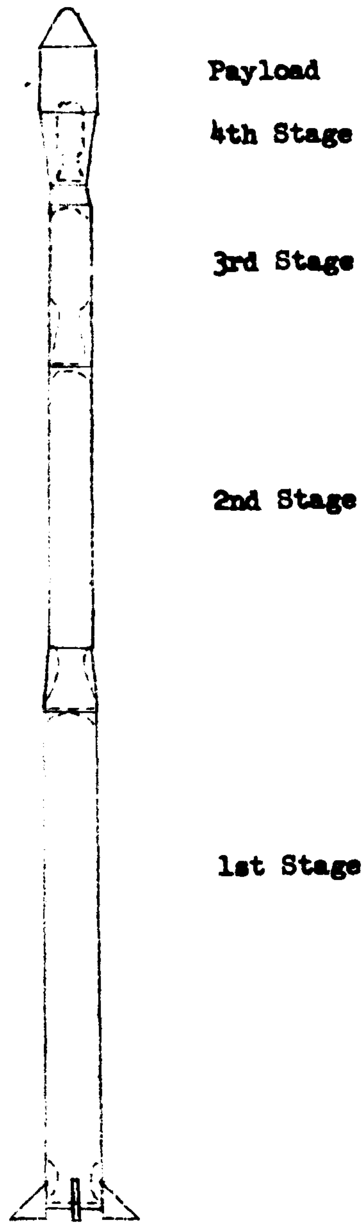


Figure 9



SCOUT LAUNCH VEHICLE

Figure 10

LAUNCH ENVIRONMENT PRODUCED BY SCOUT B

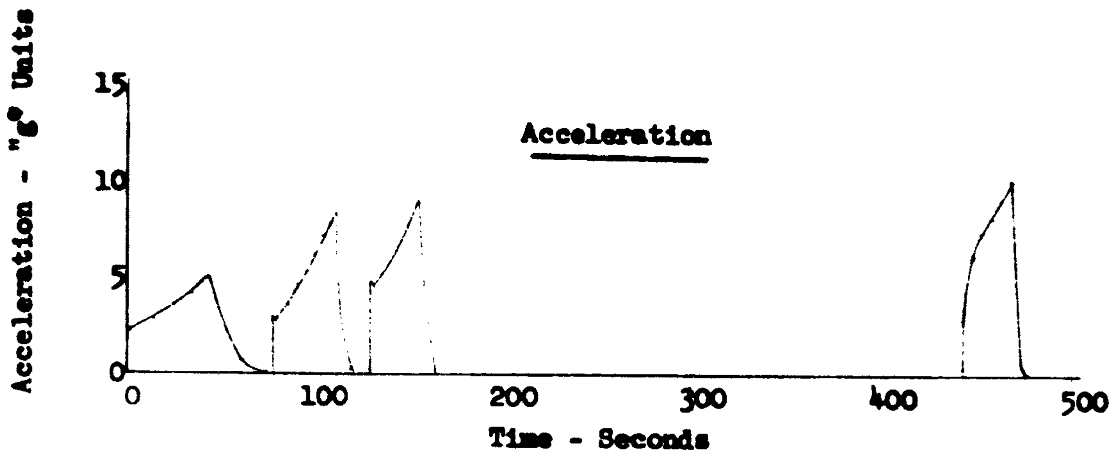


Figure 11a

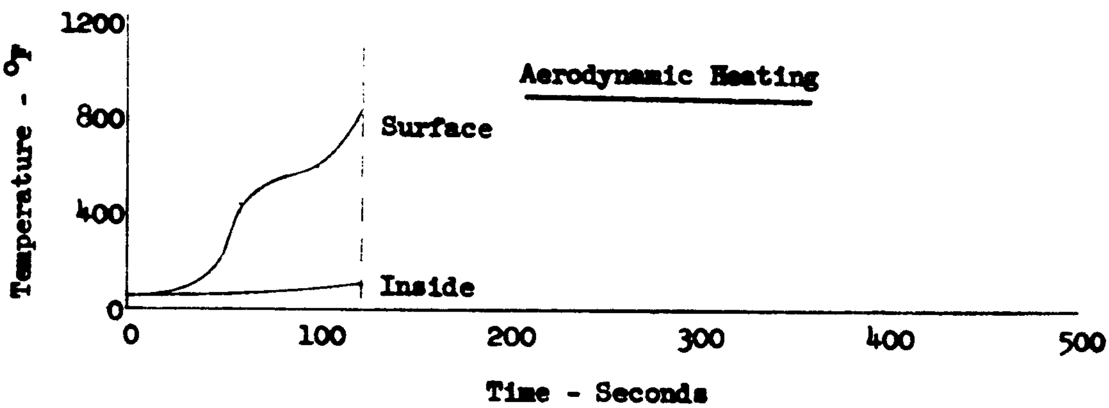


Figure 11b

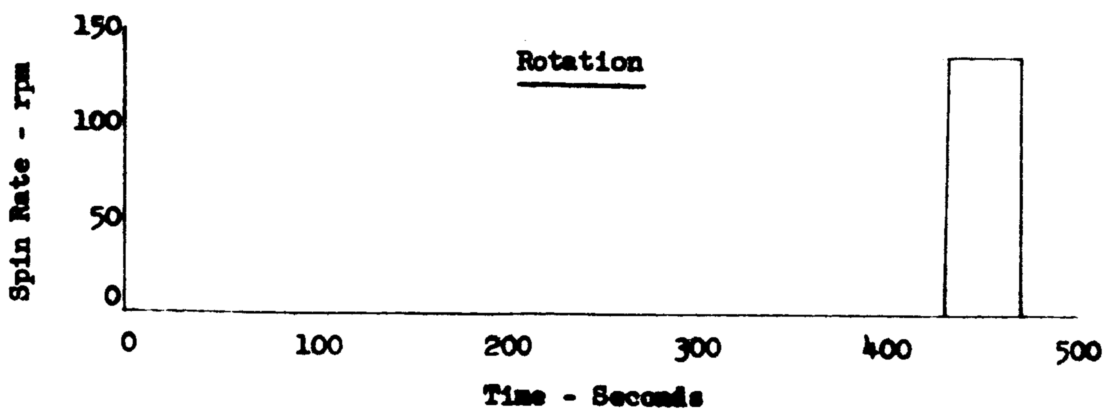
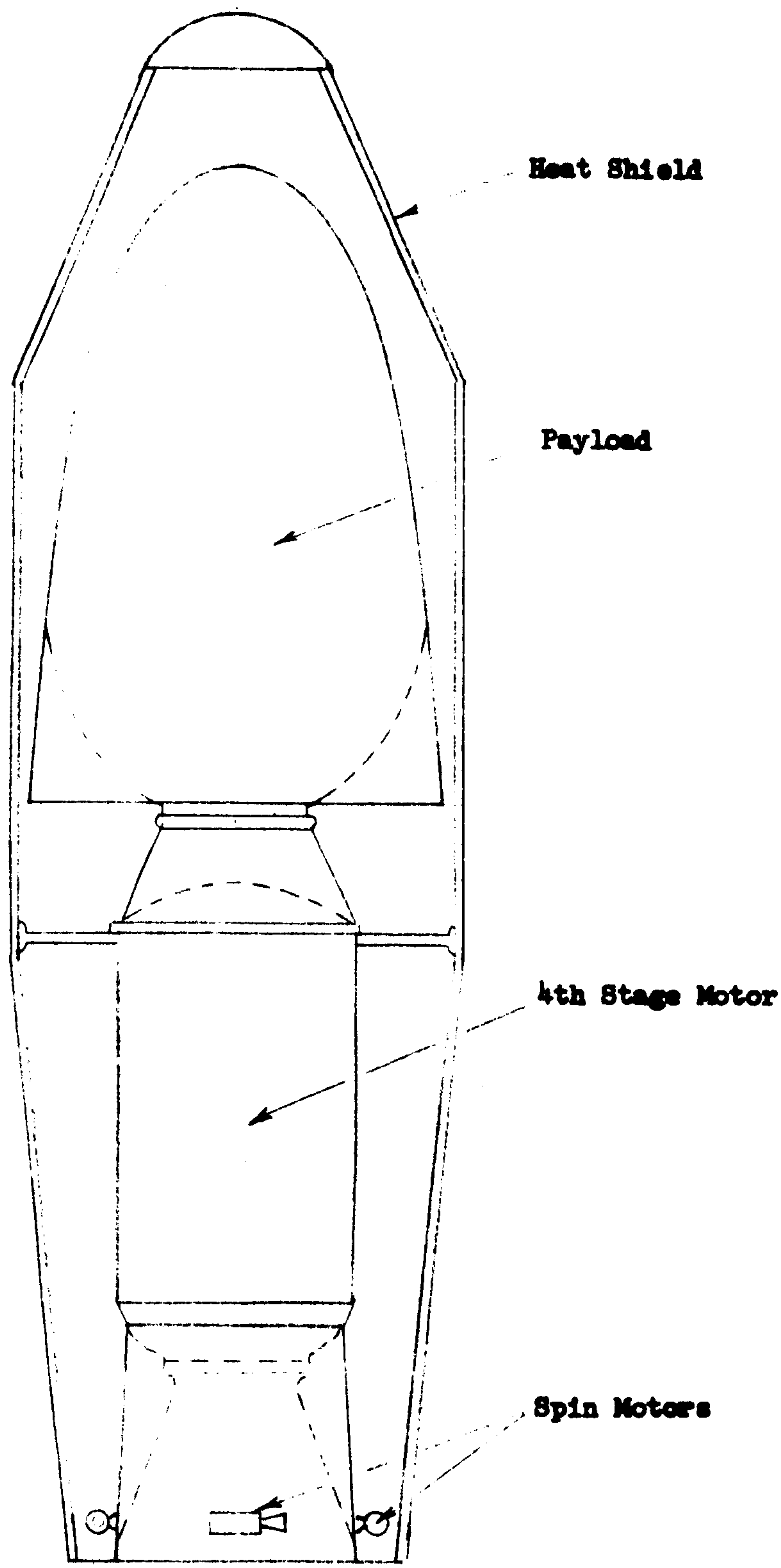


Figure 11c



PAYLOAD MOUNTED IN SCOUT HEAT SHIELD
Figure 12

VIBRATION PRODUCED DURING BURNING OF LAST STAGE

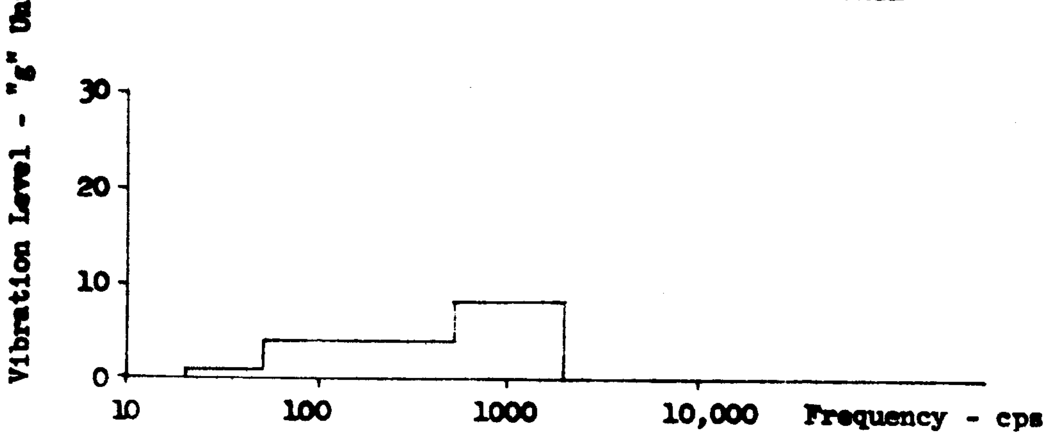


Figure 13a

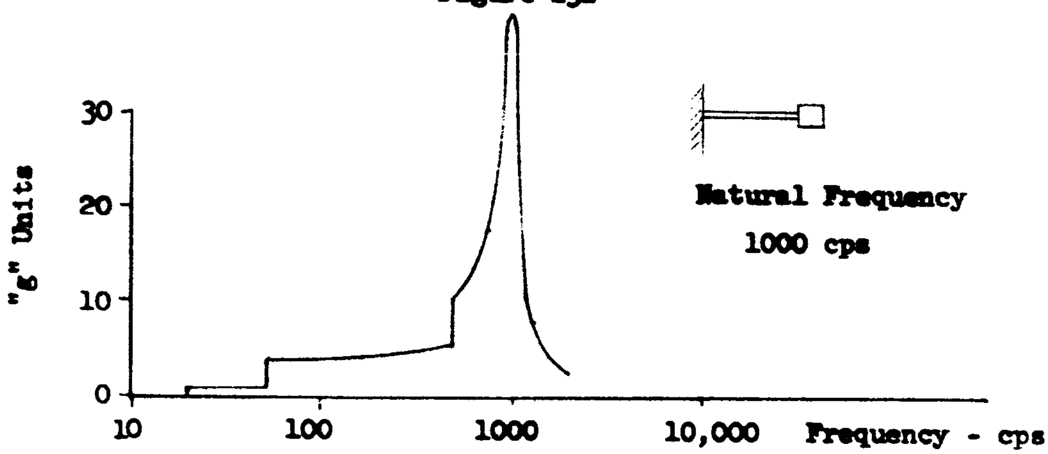


Figure 13b

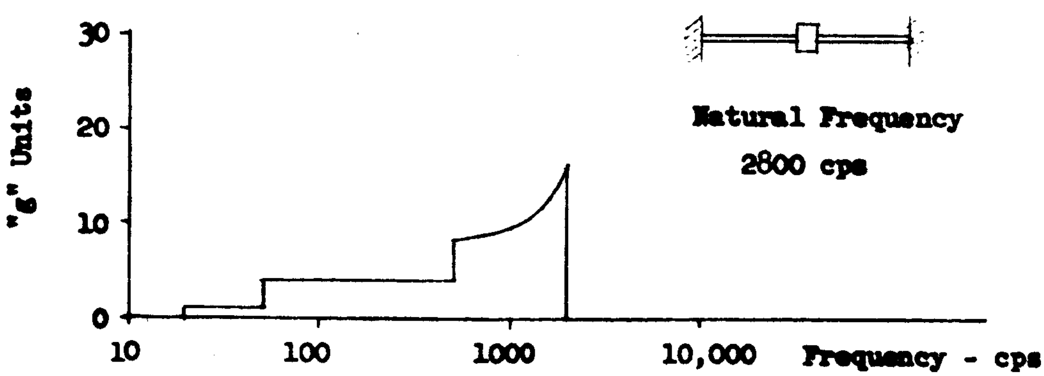


Figure 13c

REENTRY ENVIRONMENT

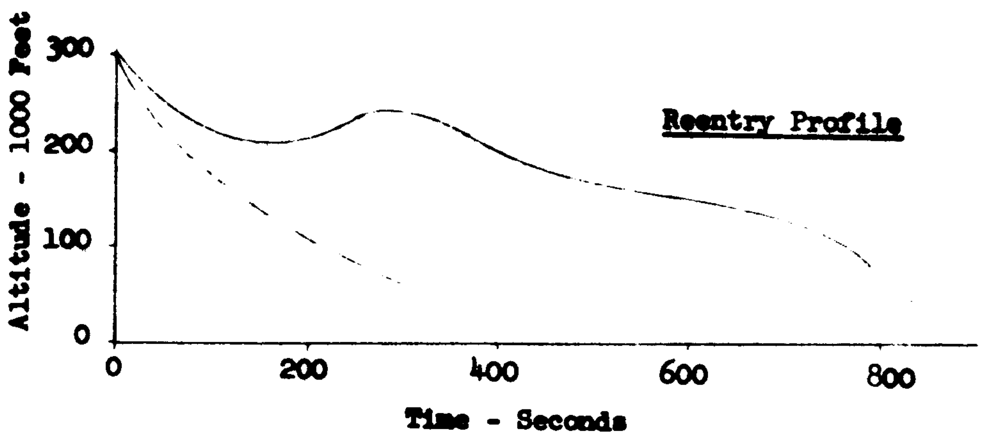


Figure 14a

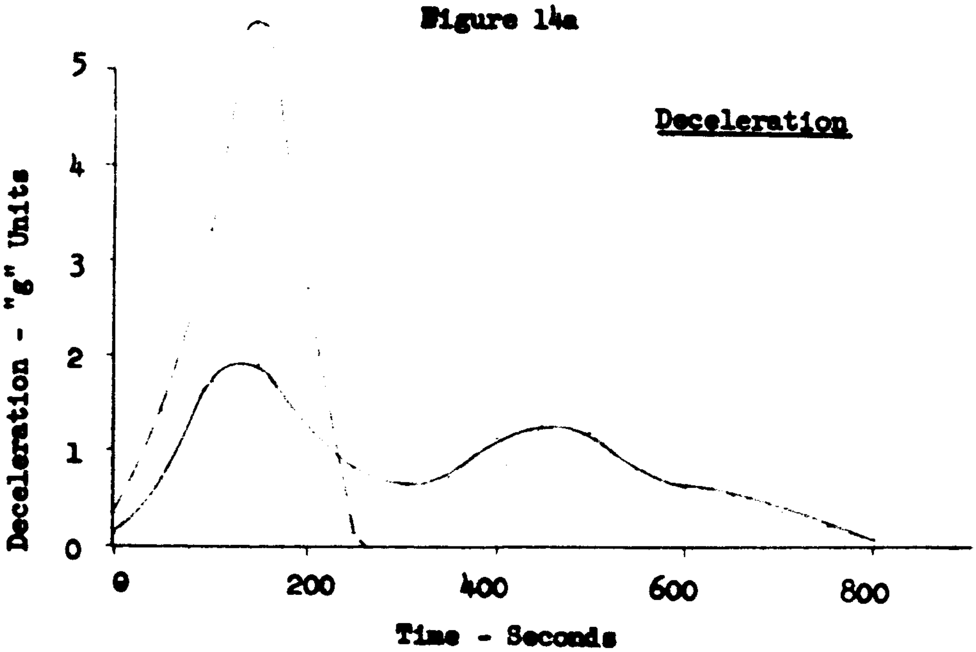


Figure 14b

REENTRY ENVIRONMENT

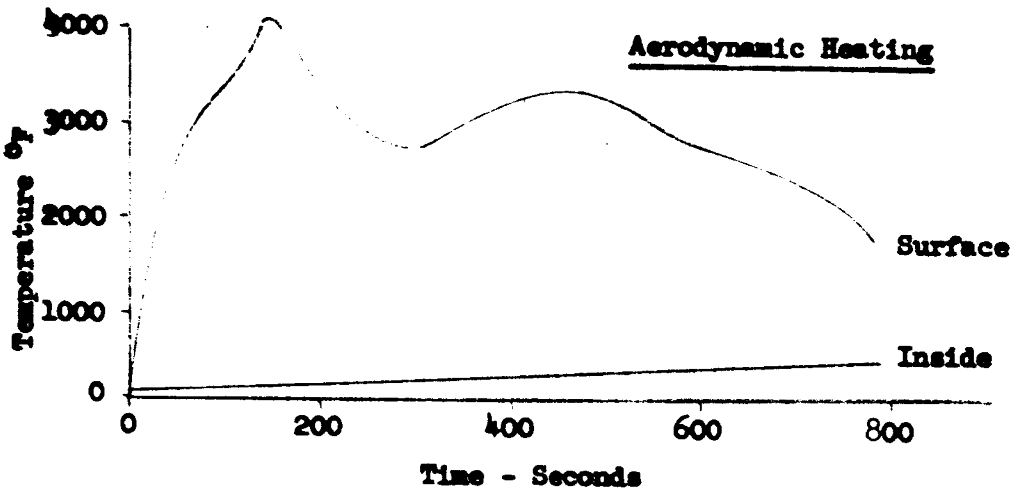


Figure 15a

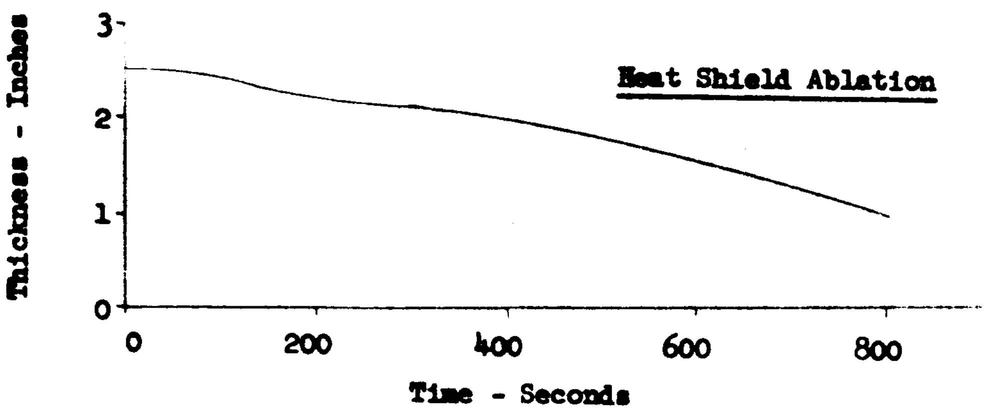


Figure 15b