CREW SAFETY AND SURVIVAL ASPECTS OF THE LUNAR-LANDING MISSION

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Abstract

Some of the safety and survival aspects of the manned lunar-landing mission are examined. The conditions requiring abort to the earth, lunar orbit, and lunar surface are determined. Some of the possible design requirements to permit abort to lunar orbit or surface are indicated. Lunar orbital and surface survival kits are described, and the stationing of such kits in lunar orbit and at the intended landing site is proposed.

Introduction

A manned lunar-landing mission includes all of the safety and survival problems of earth orbital and lunar orbital missions, plus problems that arise from flight phases peculiar to the lunar landing. For example, the lunar landing involves several additional powered phases and the danger of landing accidents on the moon, with resulting problems of survival. Phases common to other missions, such as boost, earth orbit, translunar flight, lunar orbit, and earth recovery are not considered in this paper, since these areas are covered adequately in other investigations. The lunar-landing mission is considered from the standpoint of the initial exploratory missions; that is, no permanent lunar base is assumed to have been established.

In this paper, the term "safety" refers to the escape and survival of the crew should an emergency or accident occur. The term "survival" refers to the long-term aspects of the crew existence after an emergency. Rescue would be included in the survival area.

An indication of the extent of the problem and the flight phases to be considered is given in figure 1. A small sector of the moon is shown, and the trajectory of a vehicle landing from lunar orbit, then taking off to return to earth is indicated. In general, the four flight phases are, as indicated: phase 1, the lunar deorbit and approach; phase 2, the actual lunar landing; phase 3, lunar residence, which includes all the time spent on the moon; and phase 4, the lunar take-off which extends from the firing of the take-off engines to injection into lunar orbit.

Also included in figure 1 is a list of pertinent items such as the altitude, the characteristic velocity increment involved in each of the four flight phases, and the approximate duration, in minutes, of the flight phase. Phases 1, 2, and 4 are characterized by the operation of the main propulsion system, maneuvering, and possibly staging. Phase 3 is primarily characterized by long duration, while phase 2 has the added problem of lunar impact.

Obviously, any number of emergencies and accidents could occur during a mission such as that illustrated in figure 1 which would result in safety and survival problems. The presence of man in the lunar-landing vehicle both complicates and simplifies the problem because, although the requirements for provision of safety and survival are much more severe, the man can be relied upon to take a personal and active interest in the matter.

Safety

Considerations of safety are limited to phases 1, 2, and 4, inasmuch as these phases involve powered flight. Phase 3 is discussed in the following section on survival.

System Failures

Some of the critical system failures that might occur in phases 1, 2, and 4 are shown in figure 2. A general safety requirement might be to always provide a way out following one failure (preferably two in series). Figure 2 lists how this requirement might be met for several systems. Emergencies are presented in order of increasing urgency: those requiring no immediate abort; those which may require immediate abort, depending on the conditions prevailing at the time of the failure; and, finally, one which requires immediate abort. These, of course, are not all of the systems in the spacecraft, but are representative of the various types. It might be noted that under safety provisions, redundancy and repair are the most important factors for all systems except structure and propulsion, for which repair is the primary provision. Redundancy is generally the only acceptable safety provision for failures occurring during power-on operations such as in phases 1, 2, and 4, but when conditions provide adequate time, it is possible for the crew to take action to perform repairs. Thus, on the surface of the moon or in lunar orbit, the original capability and reliability of the systems may be regained if suitable equipment, parts, and skills are available.

Abort Requirements and Goals

Abort requirements and the goals of abort should also be considered in a discussion of safety, inasmuch as abort is the last resort following emergency. Figure 3 shows the characteristic velocity requirements for abort to each of three possible target areas: the earth, lunar orbit, or the moon. These three locations, of course, have different levels of desirability and attainability, depending on the flight phase when the emergency occurs. For example, if an emergency occurs just as deorbiting is initiated, it is obviously possible to return to the earth or to the lunar orbit with much less expenditure of energy than is required by an abort to the moon. Conversely, if an emergency occurs during the final phases of landing, aborting to the moon involves much less energy than to the earth or lunar orbit. Omitting the earth, the choice between abort to the lunar orbit or surface is dependent upon design, supply, and survival considerations to be discussed.

It might be noted in figure 2 that only failures of the propulsion system require immediate abort. Various propulsion configurations can be utilized to obtain the 17,000 ft/sec velocity potential required to land on the moon from lunar orbit and return to earth. Figure 4 shows examples of some of these configurations, with comments on the results of propulsion failures. The first configuration consists, essentially, of a single stage for lunar landing and earth return. With this configuration, any failure in phase 1 and 2 results in a crash on the moon. In phase 4, if a failure occurs below orbital velocity, a crash results; whereas, at velocities above orbital speed, the vehicle can remain in lunar orbit. With the second configuration, a separate stage is indicated for earth return and lunar landing. Failure of the lunar-landing stage in phase 1 or 2 permits the use of stage B to abort to the earth, lunar orbit, or the moon, since sufficient velocity potential exists in this stage. If stage B fails subsequent to a stage A failure, there is still a possibility that the vehicle will remain in orbit rather than crashing on the moon. Phase 4, in this instance, is the same as phase 4 for the single-stage vehicle. The third configuration has three stages: lunar landing, lunar take-off, and earth return. In each phase there are two propulsion systems that can fail without a resulting crash. It might be noted that for all three configurations, failures in phase 4 preclude abort to the earth.

Safety considerations of another possible operational technique and group of propulsion configurations for the lunar landing are shown in figure 5. A small vehicle is assumed to leave a mother vehicle in lunar orbit, make a landing on the moon, then take off from the moon to rendezvous with the mother vehicle which will be used for earth return. Three configurations are also shown in this figure. The first again consists of a single propulsion system capable of the 14,000 ft/sec requirement for this mission. Any propulsion failure in phase 1, 2, or 4 with this configuration will cause the vehicle to crash on the moon. In the second configuration, two parallel, independent propulsion systems are utilized which operate throughout the flight. The propellant supply systems can be interconnected at the pilot's discretion, as required. If either propulsion system fails, the mission can be completed or an abort can be made to the moon or to lunar orbit in all flight phases. The third configuration is similar to the second, in that two independent propulsion systems are used. In addition, a second stage is provided having a capability of approximately 3,000 ft/sec, for a total capability of 17,000 ft/sec. Both A and B propulsion systems can fail, and system C will still permit an abort to either the moon or to lunar orbit. If desired, the lander can be designed for a 14,000 ft/sec total capability and lunar surface refueling used to provide the required redundancy.

Considering the various possible configurations and operational techniques presented in figures 4 and 5, selection of the best balance between complexity, reliability, safety, and efficiency is dependent, of course, upon the hardware involved. It would seem that the first configuration in each figure could not be considered because of safety requirements. A choice between the second and third configurations would probably depend upon the relative reliability of the propulsion systems. It would appear that serious consideration might be given to the third configuration in the direct lunar landing and to the second configuration for the lunar rendezvous.

Effects on Design

In all of the foregoing, a tacit assumption has been made that abort to the lunar orbit or the moon is preferable to the emergency being experienced at the given time. However, the effect of such an abort requirement on the design of the actual lunar vehicle must be considered. Some effects have been indicated, such as the additional staging or parallel staging. Again, the possibility of aborting to the moon with a stage that is not the primary lunar-landing stage introduces the necessity of having two lunar-landing gears on successive stages, or a single landing gear capable of two landings mounted on the lunar take-off stage. Although it might also be possible to build sufficient shock-attenuation capability into the capsule itself to withstand lunar-landing impact, this capability does not appear to be a solution because of the danger of fire and explosion. Safety considerations would appear to require that the lunar take-off engines not only be extremely reliable but also be throttleable or otherwise capable of performing emergency lunar landings. The capability of emergency landing, of course, would be inherent in the parallel propulsion configurations mentioned previously.

Survival and Rescue

In speaking of survival, it is assumed that the crew have escaped the immediate emergency and have been able to attain a place of relative safety. In this paper, this safety area is considered to be lunar orbit or the surface of the moon. Each of these survival locations offers a number of survival supply and rescue possibilities, as shown in figure 6. Each survival area has different requirements in regard to launch rates, vehicle development problems, and operational feasibility. Some of the particular problems and operational considerations are discussed in the following sections.

Lunar Orbit

The lunar orbit might be considered desirable as a location for long-term survival because less expenditure of energy is required for rescue; that is, a vehicle in lunar orbit is in a much more shallow energy well than it would be on the lunar surface. Also, as indicated in figures 4 and 5, it is frequently the only survival area available.

If it is assumed that a survival type of emergency has occurred, that is, the living module of the vehicle is essentially undamaged but cannot leave lunar orbit, the basic problem is that life must be sustained until a successful rescue attempt can be mounted. As indicated in figure 6, rescue may be by a vehicle already in orbit, which would present no supply problem, or by a vehicle from earth, which would require sufficient supplies on the lunar lander or a lunar orbital supply ship. It is, of course, preferable that sufficient supplies be contained in the lunar lander, if possible, thereby avoiding the necessity of providing a second vehicle; however, the amount of supplies required depends upon the time for rescue and may be excessive for the lunar lander.

Consideration of the supplies required indicates, as discussed in reference 1, that the provision of atmosphere is most critical for survival, because the crew can survive from 30 to 40 days on the supplies of food and water carried on a 14-day lunar mission, but can survive only a few minutes without breathing. Thus, from a survival standpoint, any excess payload capability should be used for atmospheric supplies: oxygen and CO_2 absorbent. A minimum of about 110 pounds of oxygen and lithium hydroxide (plus container weight) per man would be required to match the total survival period possible with the food and water carried on a 14-day lunar-landing mission. This weight does not appear to be too great a penalty to pay for the increase in survival potential.

Another hazard, however, precludes reliance solely upon supplies stored in the lunar lander. This is the high probability of encountering a major solar flare. Normally, insufficient shielding would be carried on the lunar mission for solar-flare protection, reliance being placed, instead, on prediction and statistics. Thus, lunar-orbit survival will require the provision of additional shielding by a supply ship or rescue in a very short time. The improbability of being able to launch a rescue ship in a short time makes the provision of a supply ship in lunar orbit quite attractive. Such a supply ship would be capable of carrying sufficient shielding and supplies to permit survival in lunar orbit for a period of several months until a rescue ship from earth could arrive. This orbiting supply ship is discussed further in the next section.

Rescue can be performed by providing a manned or unmanned rescue ship in lunar orbit (fig. 6); however, it appears that the manned ship is undesirable because its duration on station is limited. An unmanned ship, it is believed, would be much less reliable than the simpler supply ship discussed above. Therefore, it is felt that the provision of a supply ship in a permanent lunar orbit is to be preferred to the orbiting rescue ship.

The third rescue possibility, that of using a lunar-launched rescue vehicle, will not be practical until a permanent base with sufficient facilities exists on the moon. At that time, it may be the preferred base for rescue operations because a velocity of only 10,000 ft/sec will be required to perform the rescue and proceed to earth, or 14,000 ft/sec to rescue and return to the moon. An earth-based rescue would require about 41,000 ft/sec velocity.

It might be noted that all of these procedures for rescue in lunar orbit involve the assumption that the problems of orbital rendezvous have been solved and that rendezvous is essentially a normal operational technique. It is believed that this capability will probably have been achieved during the time period under consideration.

One final point might be mentioned with regard to rescue in lunar orbit by an orbiting rescue vehicle. This is the normal procedure of operation if the lunar landing has been made by means of a special vehicle, as discussed previously (fig. 5); thus, a special rescue vehicle is not required, since the mother vehicle fulfills this role.

Lunar Survival

Problems resulting from an accident or emergency late in the lunar landing, during the lunar residence, or immediately after lunar take-off (phases 2, 3, and 4 of fig. 1) could eliminate the possibility of attaining a lunar-orbit condition. Therefore, survival on the moon itself must be considered.

The high level of energy expenditure required for a lunar landing creates complex supply and rescue operation problems; therefore, it might be well to regard survival on the moon operationally in the same light as survival during polar expeditions. In the past, it was not considered catastrophic or even unexpected if the return of an arctic or antarctic expedition was delayed 6 months to a year by their ships being frozen into the ice. Similarly, it would seem that if adequate preparation were made, a lunar accident which prevented immediate return of the crew should not be considered a catastrophe or cause extreme concern. Six months' survival potential would probably be adequate if the planned second lunar-landing mission had rescue capabilities. This second mission would probably be scheduled for launch 2 months after the first. Thus, allowing for failure of this mission, 2 months to launch a third, and a 50-percent safety margin, a 6-month survival time should probably be provided.

Two general survival areas must then be considered, as shown in figure 6: the intended landing site, and a remote site. First, consider survival following accident or emergency at the intended landing site. Accidents and emergencies are most likely to occur in this area, since it is here that landing impact is made and the long-duration lunar residence occurs. As indicated in figure 6, there are four possibilities for supply at the lunar-landing site. In this instance, it would appear to be advantageous to place the supply vehicle at the landing site before the lunar landing was attempted. This can be done during vehicle development just prior to the landing attempt. Although, as will be discussed later, supply by a ship in lunar orbit is also attractive, it offers somewhat less assurance of success. The supply ship could fail to operate properly when called down, then reliance would have to be placed on supply from earth.

The first requirement for long-term survival on the moon is adequate shelter for protection from radiation, micrometeorites, temperature extremes, and vacuum. Since the stay on the moon is to be possibly as long as 6 months, there is a virtual certainty of encountering multiple solar flares of sufficient intensity to be hazardous. Similarly, micrometeorites of appreciable size can be expected. Although no detail design has been made, a possible form of shelter to provide adequate protection against these hazards is shown in figure 7. This shelter would be buried under 8 to 10 feet of lunar rock for protection from radiation and extremes of temperature. At this depth, the rock is estimated to have a constant temperature of -40° F. With proper insulation, the internal heat generated by the occupants and equipment will maintain a comfortable temperature. Burial of a lunar shelter of this type would be performed by blasting out a hole, installing the shelter, then mounding the lunar debris over the shelter. It is possible that good fortune would provide a crevice or cave in the vicinity of the landing and thus greatly reduce the effort required. In figure 7 the astronauts have been fortunate to find sufficient loose soil to bury the shelter without an excavation. The shelter illustrated has two air locks; one is normally used for a sanitary facility, but provides also an emergency air-lock capability. The general dimensions are: length, 22 feet; width, 9 feet; height, 7 feet; and volume, 1,070 cubic feet. It might be of interest to compare these dimensions with those of the hut in which Admiral Byrd spent 6 months alone in the antarctic. This hut[2] was 9 by 13 by 8 feet high, was designed for three men, and was similarly buried for protection from the environment.

The supplies and systems required for the proposed shelter are listed in the following table:

Supplies for Lunar-Landing "Survival Kit"
(Six-month duration, three-man crew, pressure - 7.5 psia)

	Weight, lb
Breathing atmosphere:	
Oxygen (2 lb/man/day, 10 shelter cycles, 500 air-lock cycles, 10 percent leakage, 400 lb for space suits)	2,050
O_2 storage	1,280
Nitrogen (10 shelter cycles, 500 air-lock cycles, 10 percent leakage)	900
N_2 storage	680
CO_2 absorption (LiOH)	2,040
Atmosphere decontamination (catalyst burner, charcoal, fuel)	430
Food (2 lb/man/day)	1,100
Water	300
Water reclamation (condenser, 2 stills, filters, etc.)	320
Sanitary facilities (fixtures, storage, etc.)	200
Electric power 1 kw (2 fuel cells, 1 photo voltaic system, battery)	500
Hydrogen	216
Hydrogen storage and system	200
Oxygen	1,944
Oxygen storage	1,200
Shelter	1,560
Miscellaneous supplies (suits, communications, tools, recreational equipment, etc.)	3,000
Total	18,900

No attempt has been made to optimize this "survival kit;" therefore, considerable weight reduction would probably be possible, particularly in the electrical power system. A heat-engine system operating on the temperature difference between the lunar surface and subsurface might replace the fuel cell required for night-time power with a considerable saving in weight. Similarly, the life-support system assumes no regeneration of oxygen, but future developments will probably make this feasible. Only a small water reserve is supplied because regeneration of waste water and the additional water resulting from the fuel cell will insure an adequate supply. The total payload weight of the shelter and all supplies would thus be about 20,000 pounds. Most of these supplies would not be stored within the shelter, but, instead, would be stored above ground in a shelter provided by the nose cone of the supply ship.

The survival shelter would be shipped to the moon in two parts for ease of assembling and handling. As mentioned previously, it would probably be best to land the supply vehicle on the moon prior to the manned landing so that the supplies would be available for use at that time. If the supplies were not required by the lunar-landing party, they would be available for the next landing crew in the same manner in which supplies have been left by antarctic expeditions for use by later expeditions.

Survival in a landing away from the primary landing site, that is, immediately after take-off in phase 4, poses special problems. The distance may be too great to permit the crew to return to the landing site and use the stored supplies at that point. Although this is, perhaps, the most difficult of all lunar survival problems, the probability of an emergency in this area requiring survival provisions is fairly remote. Most malfunctions requiring abort can be expected to occur in the first few seconds of powered operation when the ship is still very close to the base. For example, if the emergency occurs at less than 1,000 ft/sec, the landing will be made within about 20 miles of the base, probably within walking distance. An emergency occurring at a later point requires that a survival kit be provided at the emergency landing site within the time during which survival is possible with the stored atmosphere on board the lunar-landing vessel. Survival, in this case, is critically dependent upon having a supply vessel ready for launch on earth, or in orbit about the moon to be called down to the proper landing site. It would probably be preferable to have a survival supply ship in lunar orbit for call down to the emergency landing site. This vehicle would contain essentially the same "survival kit" described previously and would thus serve as a back-up for the normal landing site. The vehicle would probably be most accurately and favorably positioned if it were landed by radio control from the lunar lander. Thus, it could be landed at a location near suitable shelter locations and still sufficiently remote from the lunar lander to avoid damage from flying rocks and other debris dislodged by the supply ship landing rockets.

Proper design of this survival vehicle would enable its use as the supply ship for aborts to lunar orbit. To perform this function, it would be necessary for the survival vehicle to incorporate adequate rendezvous capability and the addition of the large amount of shielding for solar-flare protection. As indicated in references 3 and 4, water shielding weights on the order of 5,000 pounds to 10,000 pounds may be required for protection. This shielding could be provided in an auxiliary compartment which could be jettisoned if the "survival kit" is to be landed on the moon, thus not interfering with the lunar-landing performance. Having the kit already in orbit rather than on the earth would greatly increase the chances of successful supply as well as reduce the time required for supply.

The orbiting supply ship might be used for emergencies occurring at the normal landing site and remote sites, thus requiring only one survival vehicle rather than two. However, it would appear to be much more effective to have the supplies on the moon at the intended landing site as discussed previously, particularly when the probability of a malfunction at this location is considered.

One final point that might be discussed is the possibility of a form of lunar-surface rendezvous being utilized to improve the safety and survival potential of the mission. A rendezvous of this type could take the form of a duplicate mission vehicle landed automatically at the intended landing site prior to the mission. This is particularly attractive if the lunar-orbit rendezvous technique is employed because of the extremely small vehicle required and the fact that the mother ship is already waiting in lunar orbit. Similar possibilities exist to provide propellants to avoid marginal fuel conditions at lunar take-off. The best combination of facilities, supplies, and equipment in the survival kit will vary greatly, depending on the chosen lunar-mission flight procedure and will require extensive study and evaluation.

Concluding Remarks

This study of the lunar-landing mission indicates that abort to lunar orbit and the lunar surface is probable as a result of emergencies in various phases of the mission. These emergencies may result in considerably longer orbital or lunar residence time than originally planned for the mission. Consequently, external supplies and assistance will be required for survival and ultimate rescue.

It appears that the most practical supply vehicle combination for all the conditions discussed would consist of:

a. An unmanned supply ship at the planned primary landing site and

b. An unmanned supply ship in orbit capable of orbital rendezvous for orbital supply and capable of lunar landing for supply of unplanned remote landings.

In each of these cases rescue would be performed by a rescue ship sent from earth.

Provisions of increased safety potential may place unusual requirements on various spacecraft systems, particularly for the propulsion system and the landing gear where safety requires some form of redundancy. Additional important design requirements are the provision of rescue capability in the basic lunar lander and extension of automatic lunar-landing capabilities to large payloads.

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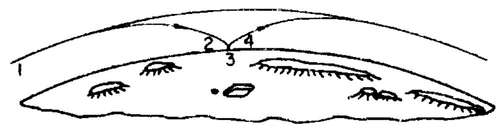
PHASES OF LUNAR-LANDING MISSION



FLIGHT PHASE	ALTITUDE, FT	CHARACTERISTIC VELOCITY INCREMENT,* FT/SEC	DURATION, MINUTES
1. LUNAR DE-ORBIT AND APPROACH	50,000 TO 1,000	6,400	7 TO 20
2 LUNAR LANDING	1,000 TO 0	400	1
3 LUNAR RESIDENCE	0	0	1 TO 10,000
4. LUNAR TAKEOFF TO LUNAR ORBIT	0 TO 50,000	6,500	5 TO 6

*INCLUDES 10° ORBITAL-PLANE CHANGE AND 1 MINUTE OF HOVERING

Figure 1

SYSTEM FAILURES AND SAFETY PROVISIONS

SYSTEM	SAFETY PROVISIONS	REQUIRED ACTION
GUIDANCE	REDUNDANCY, REPAIR	NO IMMEDIATE ABORT
ENVIRONMENT CONTROL	REDUNDANCY, REPAIR	
COMMUNICATIONS	REDUNDANCY, REPAIR	
CONTROL SYSTEM	REDUNDANCY, REPAIR	MAY REQUIRE IMMEDIATE ABORT
AUXILIARY POWER	REDUNDANCY, REPAIR	
STRUCTURE	REPAIR	
PROPULSION	PARTIAL REDUNDANCY, REPAIR	IMMEDIATE ABORT

Figure 2

CHARACTERISTIC VELOCITY REQUIREMENTS FOR ABORT

FLIGHT PHASE	VELOCITY, FT/SEC		
	ABORT TO –		
	EARTH	LUNAR ORBIT	MOON
DE-ORBIT	3,500 TO 10,500	0 TO 7,000	6,500 TO 100
LANDING	10,500	7,000	100
RESIDENCE	10,500	7,000	0
TAKE-OFF	10,500 TO 4,000	6,500 TO 0	0 TO 6,500

Figure 3

PROPULSION CONFIGURATION EFFECTS ON SAFETY
FOR DIRECT EARTH RETURN TECHNIQUE

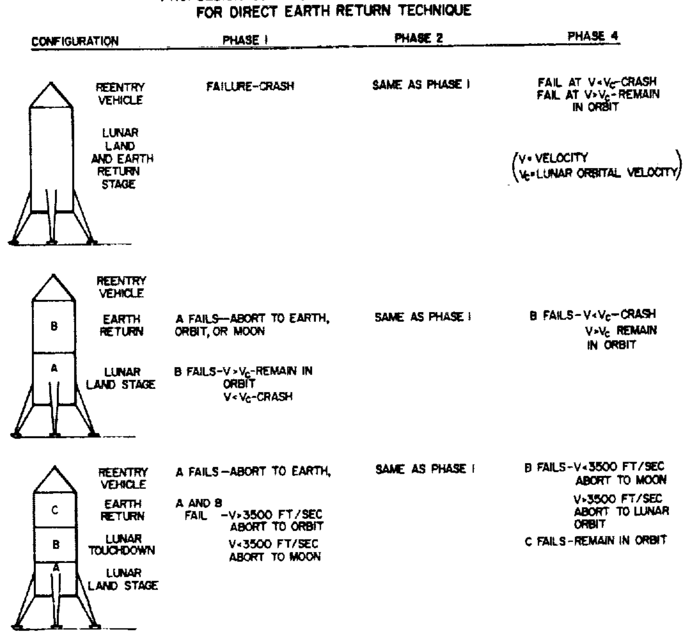


Figure 4

PROPULSION CONFIGURATION EFFECTS ON SAFETY
USING LUNAR RENDEZVOUS TECHNIQUE

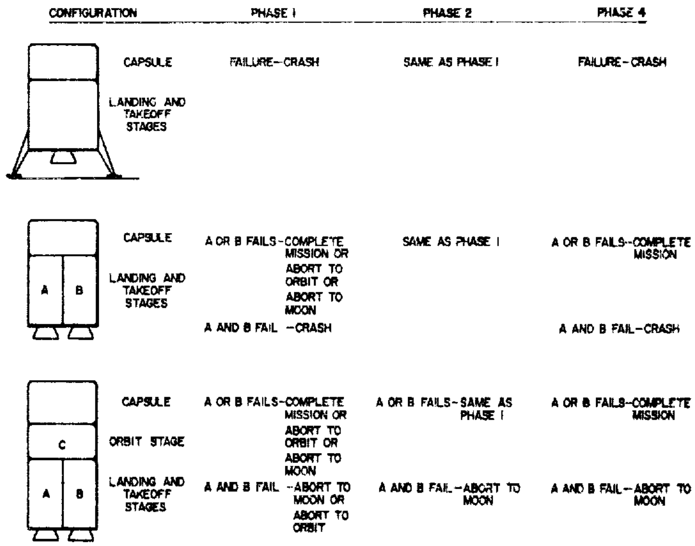


Figure 5

SURVIVAL AND RESCUE POSSIBILITIES

SURVIVAL LOCATION	SOURCE OF SURVIVAL SUPPLIES	SOURCE OF RESCUE VEHICLE
LUNAR ORBIT	LUNAR ORBIT LANDER (STORED) EARTH	LUNAR ORBIT EARTH MOON
MOON (LANDING SITE)	LUNAR ORBIT LANDER (STORED) EARTH LANDING SITE	LUNAR ORBIT EARTH MOON
MOON (REMOTE SITE)	LUNAR ORBIT LANDER (STORED) EARTH	LUNAR ORBIT EARTH MOON

Figure 6

LUNAR SHELTER AND SUPPLY SHIP

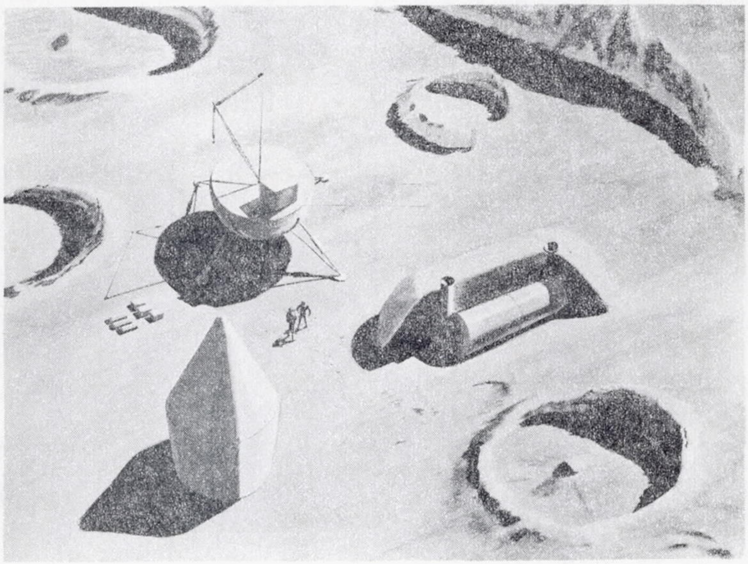


Figure 7