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PRELIMINARY SUBSYSTEM DESIGNS FOR THE ASSURED CREW RETURN VEHICLE (ACRV)

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Described herein is a series of design studies concerning the Assured Crew Return Vehicle (ACRV). Study topics, developed with the aid of NASA/Johnson Space Center's ACRV Program Office, include a braking and landing system for the ACRV, ACRV growth options, and the design impacts of the ACRV's role as a medical emergency vehicle. Four alternate designs are presented for the ACRV braking and landing system. Options presented include ballistic and lifting body reentries; the use of high-lift, high-payload aerodynamic decelerators, as well as conventional parachutes; landing systems designed for water landings, land landings, or both; and an aerial recovery system. All four design options presented combine some or all of the above attributes, and all meet performance requirements established by the ACRV Program Office. Two studies of ACRV growth options are also presented. Uses of the ACRV or a similarly designed vehicle in several roles for possible future space missions are discussed, along with the required changes to a basic ACRV to allow it to perform these missions optimally. The outcome of these studies is a set of recommendations to the ACRV Program Office describing the vehicle characteristics of the basic ACRV that lend themselves most readily to adaptation for use in other missions. Finally, the impacts on the design of the ACRV due to its role as a medical emergency vehicle were studied and are presented herein. The use of the ACRV in this manner will impact its shape, internal configuration, and equipment. This study included the design of a stretcher-like system to transport an ill or injured crewmember safely within the ACRV; a compilation of necessary medical equipment and the decisions on where and how to store it; and recommendations about internal and external vehicle characteristics that will ease the transport of the ill or injured crewmember and allow for swift and easy ingress/egress of the vehicle.

LIST OF ACRONYMS

ACLS	Air Cushion Landing System
ACRC	Assured Crew Return Capability
ACRV	Assured Crew Return Vehicle
CERV	Crew Emergency Rescue Vehicle (former designation for ACRV)
JSC	Johnson Space Center
MSFC	Marshall Space Flight Center
NSTS	National Space Transportation System (Space Shuttle)
SPRD	System Performance Requirements Document (JSC-31017)
SSF	Space Station *Freedom*
TPS	Thermal Protection System

INTRODUCTION

Since the beginning of the space program, NASA has been dedicated to the design philosophy of assured crew return capability (ACRC). This philosophy has meant that every manned program in NASA's history has had some method of returning the astronauts safely to Earth in the event of a failure of the primary return system. The commitment to ACRC continues in the design of Space Station *Freedom*. The primary return method for the space station's crew is the National Space Transportation System (NSTS), but NASA has foreseen the need for a dedicated, space-based return vehicle at *Freedom* to act as a "lifeboat" in at least three circumstances: (1) a catastrophic event occurs on the space station, the crew is forced to evacuate immediately, and the shuttle is not at *Freedom*; (2) there is a medical emergency that exceeds the capability of the space station's facilities, and the shuttle cannot respond in time; and (3) the NSTS is forced to halt flights for any reason, meaning it is not available to resupply or transport the station's crew. NASA has begun the design of the Assured Crew Return Vehicle (ACRV) to meet these contingencies.

Through USRA's Advanced Design Program, Penn State became associated with the ACRV Program Office at Johnson Space Center in 1989. Prior to the 1989-90 academic year, several ACRV design topics were identified by Penn State faculty and ACRV Program Office personnel. During the past academic year, 49 seniors in Penn State's Aerospace Engineering Department were divided into 7 project groups and pursued 3 of these topics: the design of a braking and landing system for the ACRV, the investigation of ACRV growth options, and the investigation of the ACRV's role as a medical emergency vehicle and how this impacts its overall design. This report summarizes the results of these three studies.

ACRV BRAKING AND LANDING

For the purposes of this investigation, the braking and landing system of the ACRV was defined as those devices and vehicle characteristics that slow the vehicle upon atmospheric reentry and allow it to land safely on the Earth's surface. This did not necessarily include a propulsion system for a deorbit burn or an attitude control system, but some of the project groups felt it necessary to examine these systems also.

The braking and landing system of a reentry craft provides an interesting design challenge due to the large variety of alternatives available to the designers. It also involves some of the most important design decisions, since this system may impose size, shape, and weight constraints on the vehicle's other systems.

The project groups had certain restrictions imposed on their design by the ACRV System Performance Requirements Document (SPRD; JSC 31017). This document, written by the ACRV Program Office, was developed to provide guidelines for the ACRV design, but was intentionally left as vague as possible to allow for the maximum creativity on the part of the designers. Several of the more important requirements are

1. The fully constructed ACRV must be able to be launched in the shuttle payload bay.

2. In its role as a medical emergency vehicle, the ACRV system (including recovery forces) must be able to deliver the returning astronauts to a suitable medical care facility on the ground within 24 hours of the decision to leave the space station. Of this time, no more than six hours may be spent in transit. This allows for up to 18 hours to be spent on-orbit awaiting an appropriate reentry window.

3. Reentry accelerations must be limited to $4g$ for all crewmembers. Impact accelerations and total impulses upon landing must be limited to $15g$ and $3g$-sec for healthy crewmembers, and $10g$ and $2g$-sec for an ill or injured crewmember.

4. The ACRV must be able to be operated by a deconditioned crew.

5. To maximize the reliability of the system, proven "off-the-shelf" hardware should be used whenever possible.

Four of the seven student project groups did preliminary and detailed designs of an ACRV braking and landing system, the first of which incorporates the use of a lifting body reentry shape, an expendable ablative heat shield, a parafoil gliding parachute, and an air cushion landing system (ACLS). The lifting body shape chosen was the M2-F3 configuration (see Fig. 1). This shape provides a number of advantages, including a high lift-to-drag ratio (approximately 1.2), high volumetric efficiency, and a tested prototype with a large database. The high L/D gives the vehicle a large crossrange, enabling it to reach the continental U.S. from a large percentage of its orbits, and also reduces the reentry g-forces to considerably below the limits set forth in the SPRD. The high volumetric efficiency means that even with the size constraints of the shuttle's payload bay, there will be sufficient room for up to eight astronauts (the crew complement of Freedom). The fact that the M2-F3 shape has been extensively tested in the past and has proven reliable also gives it a distinct advantage over other configurations because this reduces the amount of prelaunch flight testing required.

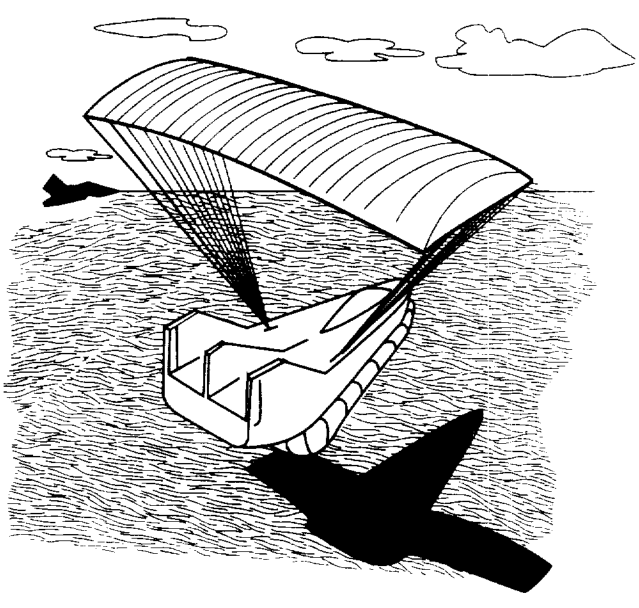


Fig. 1. An M2-F3 lifting body with air cushion landing system

The chosen thermal protection system (TPS) is an expendable, ablative heat shield. The M2-F3 configuration experiences sufficiently high temperatures at its stagnation points to require the higher temperature resistance of an ablative TPS (as compared to ceramic tiles). Additionally, the curved lower surface of the M2-F3 shape, which experiences reentry temperatures low enough to allow the use of the reusable tiles, could not easily be integrated with the tiles' flat surfaces. For these reasons, an ablative TPS was chosen. The desired landing system, described below, required that the heat shield be detachable. While this limits the choice of landing sites, the advantages of the landing system were deemed sufficient to merit a detachable TPS.

A high-payload ram-air inflated parafoil was chosen as the preferred aerodynamic decelerator. High-payload parafoils are currently being researched by Pioneer Aerospace Corporation and NASA's Marshall Space Flight Center; flight tests have already been conducted with a 10,000-lb payload. These tests have proved successful, even when the parafoil suffered minor canopy and suspension-line damage. Further tests will increase the payload to 60,000 lb. The landing system chosen imposed a sink rate at landing of 12 ft/sec. This rate can be achieved for a vehicle weighing 12,500 lb (the estimated weight of the ACRV) by using a 300-ft parafoil wing span. Parafoils of this size have successfully been deployed by Pioneer and MSFC.

The chosen landing device is an air cushion landing system (ACLS). This system is composed of an inelastic cushion that is inflated from the underside of the ACRV. When inflated, it forms an isosceles triangular shape along the perimeter of the ACRV's lower surface, with the tip of the triangle at the front of the vehicle and the base at the rear. After inflation, air flows out of small holes in the lower surface of the cushion, creating a clearance height (typically 1 in). When in ground effect, this flow creates a higher pressure within the cushion cavity, supporting the vehicle and reducing friction between the trunk and the ground. This device has been tested and proven reliable on aircraft weighing up to 41,000 lb and over a large variety of landing surfaces (water, sand, concrete, grass, and rough land with small tree stumps).

Additionally, the ACLS has also proved able to perform satisfactorily with significant damage to the cushion (tests were performed by cutting a 3500-sq-in hole in the cushion surface).

The second proposed design differs from the first in several ways. First, it does not impose a vehicle shape on the ACRV, but instead suggests a heat-shield shape. The heat shield suggested is ablative, and its shape is the same as an aerobrake being studied at Johnson Space Center (JSC) as part of an Aeroassist Space Transfer Vehicle. This shape was chosen due to its design for a low heating rate and integration into the shuttle's payload bay. Additionally, researchers at JSC have already performed experiments on the aerobrake, so its aerodynamic and heating effects have already been studied, and a future test flight on the shuttle is planned. Since a vehicle shape is not imposed on the ACRV, the shape can be optimized for the other onboard systems, providing a significant advantage. Using this shield, the ACRV will reenter using a hybrid lifting-ballistic trajectory similar to that used by the Apollo spacecraft. This means the crew will experience *g*-forces near but below the SPRD requirements mentioned above.

After reentry, a set of drogue parachutes is deployed to slow and stabilize the ACRV, after which the heat shield is separated from the vehicle proper (see Fig. 2). The shield is connected to the main body of the craft by four aluminum struts that are joined using pyrotechnic bolts. These allow the heat shield to be detached from the rest of the vehicle at the appropriate time. The heat shield has its own parachute, which is deployed after separation, allowing a more controlled descent into the ocean.

Once the heat shield has been separated, the ACRV deploys a high-payload parawing. This device works similarly to a hangglider, and allows the ACRV to have a slow, controlled descent to a runway landing. Such a device has already been tested using a Mercury capsule for a payload. The parawing will be triangular, with a length of 86 m and a width of 75 m.

On approach to the runway, landing gear will be lowered from the bottom of the craft to allow for a conventional-type landing. The landing gear is similar to that used on a Learjet 24. A study was performed to show that parawing velocities and estimated vehicle weight would allow the use of such gear. To accommodate a deconditioned crew, the ACRV will have a control system that can be remotely piloted throughout its flight.

The third braking and landing proposal comprises a lifting-body design with a lift-to-drag ratio near 1.0, a thermal protection system, a set of conventional canopy chutes, and a water landing. Rather than employing a previously used shape for its vehicle, this design contains a new lifting body shape with an L/D near 1.0 (see Fig. 3). The aerodynamic characteristics of this shape are defined such that it will meet all SPRD requirements with regard to size and *g*-loading.

While a specific thermal protection system was not included in the design, the desired properties of the vehicle's TPS were specified as high specific heat, high emissivity, and low thermal conductivity. Given these desired characteristics, a TPS can be designed that is adequate for the ACRV's needs.

The lifting characteristics of the chosen shape for this design will slow the ACRV to approximately Mach 1.5 before any supplemental braking devices are used. After this velocity has been achieved, two conical ribbon drogue parachutes will be deployed to slow the ACRV to subsonic speeds; then, three 88-ft triconical canopy chutes are used to slow the vehicle for landing. This design calls for a water landing, which greatly simplifies the design and lowers the cost.

The fourth and final braking and landing proposal differs in several ways from the others. The proposed system is composed of a lifting body, ceramic tiles for thermal protection, conventional parachutes for further deceleration, and an aerial recovery. Additionally, this project group

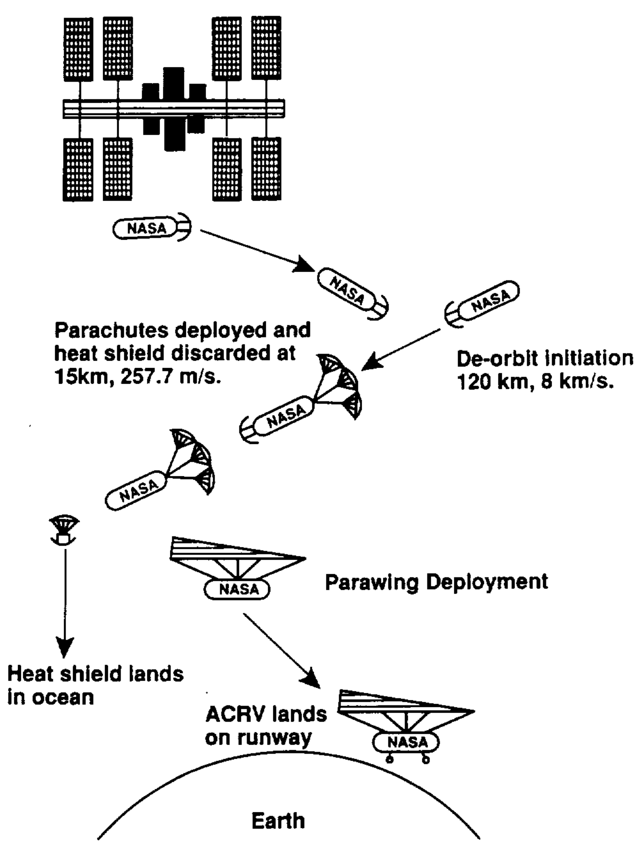
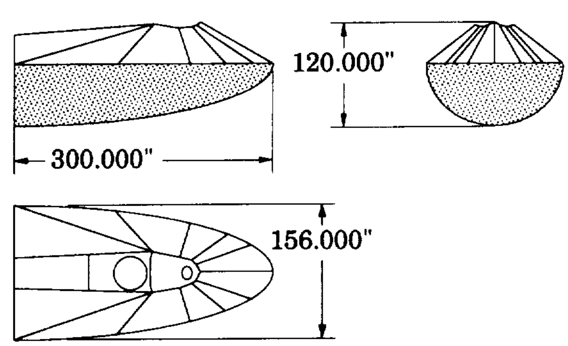


Fig. 2. A parawing and detachable heat shield configuration



Approximate Surface Area:	800 (ft^2)
Approximate Volume:	1500 (ft^3)
Predicted L/D:	1.0
Predicted Ballistic Coefficient:	55 to 75 (lb/ft^2)

Fig. 3. An alternative lifting body shape with L/D ≈ 1

investigated the use of a tether to aid in the deorbit maneuver. While a tether proved not to be sufficiently effective in reducing required propellant mass to justify the additional complexity, it did provide an interesting design challenge.

One difference between this proposal and the rest is that no shape was specified for the vehicle or its heat shield. Instead, a rather extensive analysis was performed to find an optimal lift-to-drag ratio given the desired *g*-loadings, crossrange, heating effects, time of flight, and velocity at 10 km altitude. The recommendation is for an L/D of 1.8. This L/D will result in *g*-loads less than 1.3 *g*, reentry heating rates and temperatures low enough to allow the use of shuttle tiles, a velocity below Mach 0.5 at 10 km altitude, sufficiently high crossrange to reach a large number of landing sites in the continental U.S., and a reentry flight time under the three-hour limit imposed by NASA.

After reaching 10 km altitude, the parachute system is deployed. The first chute is a ringslot drogue parachute. This will further slow and stabilize the vehicle for the deployment of the main chute, a ringsail parachute with a surface area of 2410 m^2. This combination of parachutes will allow the ACRV to achieve a velocity of less than 10 m/sec at 5 km altitude. This value was desired for the recovery system detailed below.

Rather than use a conventional landing, this design calls for an aerial recovery of the ACRV (see Fig. 4). This method has been used in the past to recover unmanned satellites, but a modified system should be able to safely recover and transport the ACRV before it reaches the ground. This design uses a modified Sikorsky CH-53E helicopter to retrieve the ACRV after it has slowed to a descent rate under 10 m/sec. Using an aerial recovery will greatly reduce the time needed to get the crew to land facilities without increasing the complexity of the ACRV itself. When performing a medical emergency mission, the ACRV could be flown directly to a hospital helipad and detached from the helicopter there, providing swift transport to medical facilities for an ill or injured crewmember.

ACRV GROWTH OPTIONS

Growth options are the future missions that an ACRV or a similar vehicle might undertake. A study of ACRV growth options includes investigating proposed or suggested future

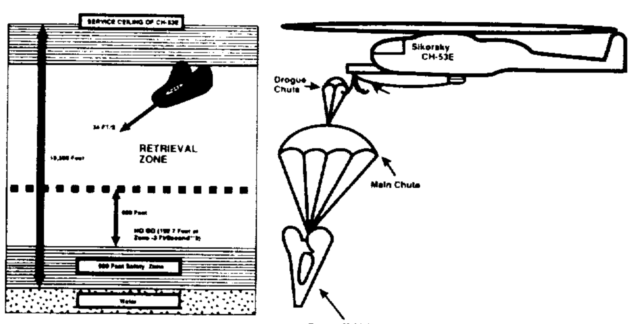


Fig. 4. Aerial recovery of the ACRV using a modified CH-53E helicopter

missions in space to determine whether an ACRV-based vehicle might be able to perform or contribute to these missions. Once this preliminary investigation is done, modifications to the ACRV enabling it to perform these missions optimally are determined, and these modifications are then used to recommend the vehicle characteristics of the basic ACRV that lend themselves most readily to adaptation for use in these future missions. A growth options study is essential for good design in this sort of circumstance, where planning now could mean significant cost reductions in the future due to the availability of a vehicle that can be easily modified to perform many tasks.

Two of the seven project groups participating in this program chose to examine growth options for the ACRV. The two groups were able to determine some fundamental characteristics of an ACRV by knowing about its mission and by examining the SPRD (for example, the structure of the ACRV must be designed to take the high stresses of an atmospheric reentry). From these characteristics, they were able to perform a growth options study. In addition, both groups examined a more detailed aspect of the ACRV growth options. A summary of the results of these two studies is presented below.

The first growth options study proposes the use of a modified ACRV to perform the following missions: shuttle and international space vehicle rescue; space station crew rotation; space station cargo transfer; satellite boosting; satellite servicing; and lunar operations. The report also investigates using a modified ACRV boosted on an expendable launch vehicle (ELV) to accomplish some of these missions. The shuttle and international space vehicle rescue would be a mission to rescue the crew of a disabled spacecraft in Earth orbit. The modified ACRV would leave *Freedom*, rendezvous with the spacecraft, transfer the crew to the ACRV, and transport them either back to *Freedom* or down to Earth's surface. The growing number of existing and proposed manned spacecraft make this a viable mission. Figure 5 shows the increasing levels of structural complexity and subsystem requirements for these missions.

Space station crew rotation and cargo transfer missions are fairly self-explanatory. Using the ACRV for these missions would help reduce the station's dependence on the shuttle. The satellite boosting and servicing missions are also fairly self-explanatory. Having an on-orbit vehicle to aid satellite operations in this manner could greatly extend the life of many existing satellites, significantly reducing replacement costs.

Lunar operations cover a variety of topics. The modified ACRV could be used as a "command module," similar to that used during Apollo missions, for transferring either crew or cargo to the Moon when U.S. space activities turn in that direction. It could also act as an ACRV for a Moon base, giving the crew of the base the same benefits as it does the space station's crew.

As part of a more detailed look into how these growth options might be executed, this project group examined the necessary hardware infrastructure to accomplish the above missions. The resulting options were (1) to build an individual, ACRV-based spacecraft to accomplish each mission; (2) to

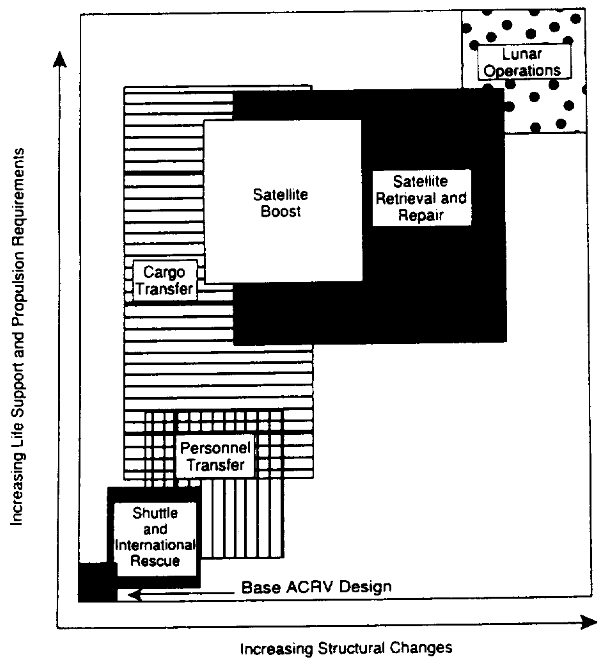


Fig. 5. Increasing structural and subsystem complexity for alternative ACRV missions

build multimission spacecraft, still ACRV-based, which could perform two or more of these missions; and (3) to build a modular ACRV. The recommendation was to use the third option—a modular ACRV (see Fig. 6). This means that the ACRV would be designed with the ability to be attached to modules that would enhance its systems. For instance, there might be a propulsion module that provides extra fuel and a larger thrust engine. When performing its mission of crew return, the ACRV would have no modules attached, but when traveling to geosynchronous orbit to repair a spacecraft, the propulsion module would be attached due to the increased fuel and thrust requirements of the mission.

A modular design would have several advantages over the other solutions. First, the basic ACRV, whose only mission is space station crew return, can be designed and built now, with a little modification to allow for expansion. As other missions become desirable, modules can be designed and built to be compatible with the ACRV's systems. This allows the basic vehicle to remain relatively simple, with the added complexity coming in the form of modules, not revisions to the old design. This type of system also provides for future, unforeseen needs. If an unforeseen mission becomes necessary, a new module can be built to allow the ACRV to perform it. Also, a breakdown in a module may cause the ACRV to be unable to perform a specific mission, but it would not disable the entire vehicle. The modular design does have its disadvantages, though, such as the need for storage space at Freedom and the necessity of connecting and disconnecting all the modules needed for a given mission. It was felt, however, that the significant advantages of a modular design far outweigh the disadvantages.

To execute a modular design, several characteristics in the basic ACRV are desirable. First, a ballistic-type design more readily lends itself to exterior modifications and additions. For this reason, a ballistic ACRV is desirable. Second, a removable heat shield would allow large mass savings when the ACRV is performing missions not requiring atmospheric reentry. Additionally, an active life support system more readily lends itself to expansion, and will be required on some of the longer-duration missions mentioned above. While the basic crew return can be accomplished with a passive system, using an active system now will simplify changes in the future. It is also recommended that the power, life support, and computer systems be designed with the possibility of requiring external additions in the future. Some of the modules will augment these systems, so the current design must be done with expansion in mind. Lastly, the computer should have the ability to accommodate "black box" additions, where mission-specific commands can readily be added to the basic capabilities of the control mechanisms.

The second of the growth options studies had several similarities to the first. It also considered using a modified ACRV for the satellite servicing, lunar operations, space station crew and cargo transfers, and international rescue missions. In addition, this study examined the use of the ACRV as a portion of a Mars mission vehicle, and as an unmanned asteroid miner. On a Mars mission vehicle, the ACRV would serve much the same purpose as a command module. One proposed design for a manned Mars mission vehicle includes the use of a small

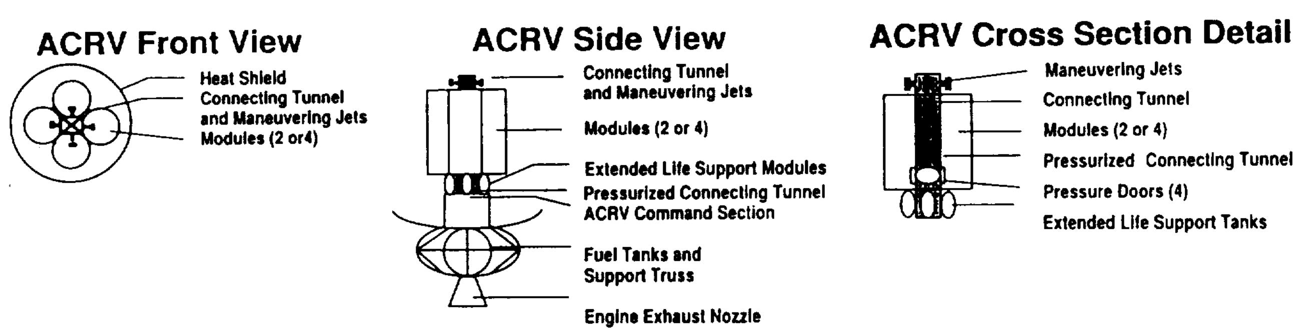


Fig. 6. A modular ACRV design for alternative missions

crew vehicle that would be detached from the main ship upon Earth approach and would decelerate using an aerobraking maneuver. A modified ACRV could perform well in this role. As an unmanned asteroid miner, the ACRV would fly to a near-Earth asteroid that was chosen for mining operations. There, it would load itself with ore mined from the asteroid and would return to Earth, reentering the atmosphere to deliver its cargo.

A quantitative approach was taken to assess the ability of an ACRV to perform each of the missions by estimating the deviation of the major subsystems from the norm of the crew return mission requirements. Using this method, the most compatible growth options were found to be the space station crew and cargo transfer missions, the international space vehicle rescue mission, and the lunar operations missions. Based upon this analysis, recommendations for the basic ACRV configuration include a ballistic shape, a detachable heat shield, and the ability of the subsystems to be readily expanded to handle long-duration missions. Figure 7 depicts the results of this study.

As part of a more detailed look into the growth option possibilities for the ACRV, this project group did a preliminary design of an ACRV-based lunar operations vehicle. The base ACRV is an Apollo-like command module, which is supplemented by a transfer vehicle and a landing platform. The crew remains in the command module for the entire mission. During trips between low Earth orbits and low lunar orbit, the unmanned transfer vehicle provides the propulsion for the command module. The landing platform stays in low lunar orbit. Following rendezvous of the command module/transfer module vehicle with the platform, the command module detaches from the transfer vehicle, attaches to the lander, and proceeds to the lunar surface. On the return trip, the lander transports the command module to lunar orbit, where it docks with the transfer vehicle, and then returns back to low Earth orbit, where it may either reenter Earth's atmosphere or dock with the space station. A preliminary design of the subsystems of the command module was also performed.

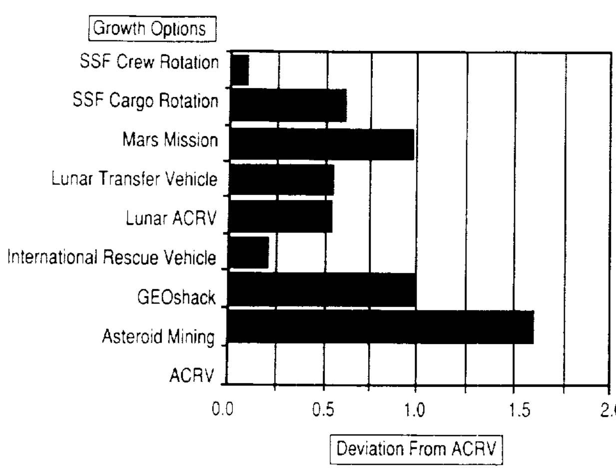


Fig. 7. Deviation of major subsystems from baseline ACRV design for alternative missions

ACRV MEDICAL MISSION

The medical mission of the ACRV arises if a space station crewmember becomes ill or injured requiring time-critical medical treatment beyond the capability of the space station's facilities, and the shuttle cannot respond in time to transport the crewmember. This mission places special restrictions on the ACRV design because, as stated earlier, the ACRV is required to perform this mission within 24 hours of the decision that the trip is necessary, and the portion of that time spent in transit cannot exceed 6 hours. Additionally, there are different impact impulse requirements for healthy and ill or injured crew. For the purpose of this analysis, it was determined that the ACRV itself met only the restrictions for healthy crewmembers, and that special equipment was necessary to protect the ill or injured occupant.

The assignment for the project group performing this study was to assess the impacts that the medical mission makes on the ACRV. This mission will affect the shape, internal configuration, and equipment of the entire vehicle. Additionally, the group was asked to design the actual stretcher-like system for transporting the crew member safely.

First, the decisions on what medical equipment to include were made by examining the current state of the art in medical emergency care and transportation. To this end, the group investigated the medical equipment currently used in ambulances and medical helicopter transports. This led to an extensive list of necessary medications and devices for proper care of an ill or injured individual. This list included special devices for dealing with the fluctuating gravity environment and devices that could transmit data on the ill or injured crew member to Mission Control for evaluation by the on-duty flight surgeon.

The next task was the design of the stretcher mechanism. It was decided that the optimal design would comprise two parts: a base and a substretcher (see Fig. 8). The base is

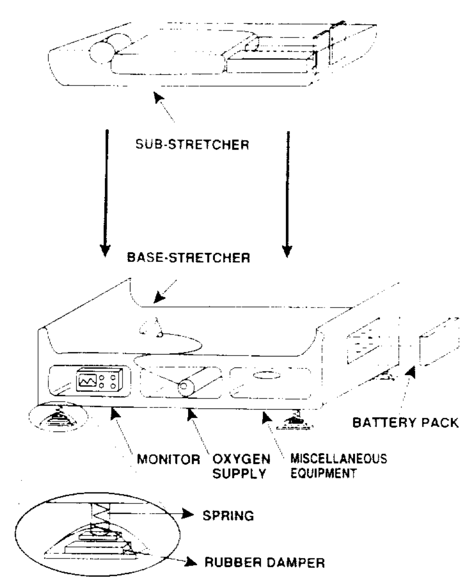


Fig. 8. Base and sub-stretcher for the medical mission

permanently mounted to the floor of the ACRV, and contains within it shock absorbing mechanisms to protect the patient during impact. Additionally, the base contains storage space for the above-mentioned equipment and pharmaceuticals. The substretcher consists of a device called a vacuum splint. This device is a bag filled with flexible beads. When inflated around a patient, the splint conforms to his or her shape. The air is subsequently evacuated, and the vacuum splint becomes rigid, immobilizing the patient's entire body. Most of the anterior side of the patient is still exposed, to allow for the connection of monitoring equipment and/or IV tubing. This procedure is performed on the space station, and the patient remains in the splint until reaching the ground-based medical facility. This allows easy, safe transport of the patient from the space station to the ACRV, to the surface transport vehicle, and to the hospital. Onboard the ACRV, the vacuum splint is placed in the base, and a number of restraints will keep the splint firmly in place. The top of the base is concave to allow easy and secure positioning of the patient.

Several recommendations on the design of the rest of the vehicle were also made. Due to the low reentry forces, a gliding or lifting-body reentry shape was recommended. A runway or similar type of landing was also recommended due to the lower impact loads experienced by the crew in such a landing. Additionally, this study showed that a hatch should be installed on the top surface of the ACRV, and that this hatch should be large enough to allow an immobilized patient to be evacuated in a horizontal position.