# Critical Soft Landing Technology Issues for Future U. S. Space Missions

## J. M. Macha, D. W. Johnson and D. D. McBride

Parachute Systems Division
Sandia National Laboratories
Albuquerque, NM 87185

Prepared for:

National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Houston, TX 77058

## Sandia National Laboratories

(NASA-CR-185673) CRITICAL SOFT LANDING
TECHNOLOGY ISSUES FOR FUTURE US SPACE
MISSIONS Final Report (Sandia National
Labs.) 26 p

N92-26894

Unclas
G3/16  0091354

# Abstract

There has not been a programmatic need for research and development to support parachute-based landing systems since the end of the Apollo missions in the mid-1970s. Now, a number of planned space programs through the year 2020 require advanced landing capabilities for which the experience and technology base does not currently exist. New requirements for landing on land with controllable, gliding decelerators and for more effective impact attenuation devices justify a renewal of the landing technology development effort that existed all through the Mercury, Gemini and Apollo programs. A study has been performed to evaluate the current and projected national capability in landing systems and to identify critical deficiencies in the technology base required to support the Assured Crew Return Vehicle and the Two-Way Manned Transportation System. A technology development program covering eight landing system performance issues is recommended.

## Acknowledgements

# Table of Contents

# 1.0 Introduction

A number of planned and contemplated NASA space programs through the year 2020 require the capability to soft land manned and unmanned vehicles or other hardware on earth, the moon, or Mars. Where there is sufficient atmosphere, it is anticipated that landing systems using some type of deployable aerodynamic decelerator will receive strong consideration. Because there has not been a programmatic need for research and development to support parachute-based landing systems since the end of the Apollo missions in the mid-1970s, the soft landing experience and technology base within NASA and the U. S. as a whole has stagnated. Future programs have new requirements for landing on land rather than water, the use of controllable gliding decelerators and more effective landing impact attenuation that cannot be satisfied with existing technology. The NASA Johnson Space Center (JSC) intends to establish a Soft Landing Technology Initiative to ensure that the necessary new technology is developed in a timely manner. The objectives of the initiative are to 1) improve NASA's ability to support new programs that require the landing or recovery of spacecraft and reusable launch vehicle hardware, 2) offer hands-on experience to NASA engineers and redevelop NASA's in-house landing systems knowledge base, and 3) contribute to the general advancement of soft landing technology.

NASA/JSC awarded the Parachute Systems Division of Sandia National Laboratories a contract to evaluate the current and projected national capability in landing systems and to recommend a technology development plan that will support the broad objectives of the Soft Landing Technology Initiative. The following four-part approach was used to accomplish the study:

1. Assess the current and projected technology base in aerodynamic decelerators and landing impact attenuation devices.
2. Review the soft landing requirements of planned NASA space missions.
3. Identify apparent technical barriers to the development of landing capabilities to support these future missions.

4. Recommend specific actions that would provide the technical base necessary to perform intelligent trade studies among various landing system options and/or perform final system designs.

This final report documents the issues addressed in the study and the recommendations made for future technology development.

## 2.0 General Approach

The space programs identified by JSC as relevant to this study included the Assured Crew Return Vehicle (ACRV), the Two-Way Manned Transportation System (MTS), LifeSat, the National Launch System, and various missions for Lunar and Mars Exploration. Except for the National Launch System, Sandia was briefed by JSC personnel on the overall objectives and soft landing requirements for each of these programs during a meeting at JSC on July 26, 1991. JSC also made available to Sandia documentation on the Advanced Recovery System (ARS) program performed for the Marshall Space Flight Center by Pioneer Aerospace Systems, Inc.

During a second meeting at JSC on October 17, 1991, Sandia presented an interim progress report. The material presented was focused on soft-landing considerations for the two more immediate manned missions, ACRV and MTS. It became obvious from the discussion that the task of identifying *critical* landing technology issues for these missions was hindered by unresolved questions about vehicle configuration and choice of landing site. For example, a final decision on water landing versus land landing for ACRV probably would not be made before January 1992. And three entirely different spacecraft configurations are still under consideration for the MTS.

Following the meeting, JSC recommended that a more hypothetical approach be taken toward identifying critical landing technology areas. Sandia was to assume there are valid requirements for both a water landing and a land landing of a vehicle in the ACRV weight class, and for land landings of reusable vehicles in the weight classes of the ACRV-D and biconic versions of MTS. It was also suggested that some consideration be given to landing issues that might be unique to the space exploration missions. Because of limited resources, Sandia's effort remained focused on ACRV and MTS.

# 3.0 Soft Landing Issues for ACRV

The primary mission of the Assured Crew Return Vehicle (ACRV) is emergency return to earth of crew from Space Station Freedom. ACRV is to be operational in 1999, coinciding with permanent manning of the space station.

The design philosophy for ACRV is that it is to be simple, low-cost, and based on existing technology. While it is expected that cost and schedule will favor a water landing, strong consideration will be given to a land landing because it facilitates the timely recovery and transport to a medical facility of ill/injured crew. Acceleration limits for an ill/injured crew, which are lower than for any previous NASA manned space mission, are a major driver in the design of the landing system. Current medical recommendations for maximum accelerations of ill/injured crew are 10 g eyes in/out, 5 g eyes left/right, and 4 g eyes up/down. Because the crew may be deconditioned or ill/injured, automatic control capability is required for all flight phases including landing.

Our assessment of soft landing technology issues for ACRV is based on a JSC in-house design named SCRAM (Station Crew Return Alternative Module). Sized to transport 8 crew members, the reentry configuration of the SCRAM is a low L/D capsule with a hypersonic cross range of 50 miles. The landing weight of 11,000 lb is approximately the same as that of the Apollo capsule. Like Apollo, the seating position of the crew for landing is reclined, with the spine parallel to the base of the capsule.

In the interest of an orderly discussion of landing technology issues for ACRV, the two primary options -- water landing and land landing -- will be presented separately. However, it will be obvious that many of the landing subsystems and associated technology requirements may be applicable to either a water or a land landing.

## 3.1 Water Landing

It is instructive to first review the landing system used with the Apollo crew module which weighed approximately the same as the proposed SCRAM. The cluster of three 83.5-ft-diameter ring sail parachutes used with Apollo provided a vertical velocity at

impact of 25-30 ft/s. The Apollo program demonstrated that landing impact accelerations below the limits for a healthy crew (i.e., 15 g eyes in/out, 10 g eyes left/right, and 8 g eyes up/down) can be achieved at this descent velocity and for a wide range of horizontal wind drift velocities simply by suspending the capsule below the parachutes at a fixed, nominal pitch attitude. Test data from a quarter-scale model of the Apollo crew module suggest that the lower, ill/injured crew acceleration limits of ACRV could be marginally met if the geometric relationship between the capsule axes and the water surface is more restrictive. However, that geometry is a complicated function of capsule rigging angle, wind drift direction, capsule/parachute roll attitude and pitch oscillation, and wave slope. Because these factors are not controllable with the recovery system used on Apollo, meeting the lower ill/injured crew acceleration limits of ACRV cannot be guaranteed with a similar system. Thus, soft landing technology beyond that used on Apollo is required for a water landing of the SCRAM concept of ACRV.

There are three basic approaches to reducing the impact accelerations below those experienced by Apollo: 1) decrease the vertical and/or horizontal capsule velocities, 2) control the attitude and orientation of the capsule at impact, or 3) isolate the ill/injured crew from the capsule structure.

It is possible to decrease the vertical velocity for an Apollo-like landing by increasing the size or number of ballistic parachutes. However, if a large reduction in velocity is required, the weight and storage volume of the additional canopy area may become prohibitive. Past experience and trade-off studies have shown that a landing system combining parachutes with retro-rockets is a more efficient use of weight and volume to obtain vertical impact velocities below about 20 ft/s. Although landing rockets have not been used previously for U. S. manned systems, the technology has been developed and demonstrated. JSC propulsion specialists designed and developed "qualifiable" rocket landing systems for both the 2900 lb Mercury and 5000 lb Gemini spacecraft. A later study considered the feasibility of installing the Gemini rocket motors in the Apollo spacecraft to provide a land landing capability. In addition to NASA's efforts directed toward man-rated systems, the Army's Natick Research, Engineering and Development Center has sponsored the design, development and test of various rocket-assisted cargo landing systems. The only alternative to larger ballistic parachutes or rockets to

achieve a low vertical velocity for a water landing of ACRV is a deployable decelerator with a high lift to drag ratio (L/D). Because of the lift force, a gliding decelerator is smaller and lighter, and requires less storage volume than a ballistic parachute for the same descent velocity. Existing gliding decelerator designs have little or no capability to vary their L/D during flight. Thus, use of a high L/D device implies a high forward flight speed. Under low wind conditions, ACRV would be subjected to a high horizontal speed at water impact with a strong tendency to upset and tumble. One means to reduce the horizontal velocity caused by wind drift with a ballistic parachute or by forward flight with a high L/D decelerator is a horizontally firing rocket system like that proposed by Pioneer in the Phase I Advanced Recovery System (ARS) trade-off study. To be effective over a wide range of wind conditions, the rockets should be throttleable and pointable in the direction of capsule motion.

The second general approach to reducing the impact accelerations during a water landing of the SCRAM vehicle is to optimize the geometry and kinematics of the vehicle/water contact surface. In the case of the Apollo crew module, it was possible to meet healthy crew acceleration requirements by suspending a capsule shape optimized for reentry performance at the best pitch attitude as determined from sub-scale model drop tests. It is possible that refinements in the shape of SCRAM could guarantee meeting ill/injured acceleration requirements at water impact with Apollo-like ballistic parachutes, without compromising reentry flight performance. The necessary methodical investigation of the effect of changes in capsule shape on water entry dynamics would require development of an appropriate computer simulation and follow-on experimental verification. Optimization of capsule shape for low impact accelerations would be much easier and more effective if the roll and directional attitudes of SCRAM were controllable. For example, one might desire to align the axis of symmetry of the SCRAM with the direction of horizontal motion. With ballistic parachutes, the orientation of the capsule could be controlled by a motor driven swivel and appropriate ground track sensors. This concept and the associated technologies were addressed in the study to upgrade Apollo to a land landing capability. If a gliding decelerator rather than a ballistic parachute is used with SCRAM, the inherent capability to steer the decelerator/capsule system negates the requirement for a controllable swivel. For this purpose, a gliding

6

parachute with a low or moderate L/D might provide adequate maneuverability and present lower technical risk than a high L/D device.

The third approach to ensuring that the ill/injured acceleration limits are observed during a water landing of the SCRAM vehicle is to isolate the crew and/or crew compartment from the outer vehicle structure. Historically, crew couches have been supported by energy-absorbing struts and crushable honeycomb has been used to protect the crew compartment. In the case of Apollo, the couch struts would seldom stroke during a normal water landing (i.e., all three parachutes inflated) depending on the orientation and motion of the capsule at impact. The Apollo impact attenuation system served primarily as insurance against injury in the event of failure of one of the parachutes. In the case of SCRAM with a terminal descent velocity of 25-30 ft/s, an impact system would be the keystone for meeting the lower ill/injured acceleration limits under normal landing conditions. The effectiveness of couch support struts as a primary impact attenuation device will be limited to the maximum stroke achievable within the confines of the crew compartment. If the directional and roll attitudes of the SCRAM are controlled, either by a swivel mechanism for ballistic parachutes or by a steerable gliding decelerator, the couch struts could be optimized to provide adequate impact attenuation along predictable lines of action.

## 3.2 Land Landing

Compared to a water landing, limiting crew accelerations to an acceptable level on land presents a substantially greater technical challenge. Without the cushioning effect of the deformation and penetration of a water surface, a lower vertical descent velocity and/or a more capable impact attenuation system is required. A land landing is further complicated when a significant horizontal velocity is present, because of the greater tendency for the capsule to upset and tumble and because of the possibility of striking an obstacle. Nevertheless, it is possible to reliably recover space crews on land as demonstrated by the Soviet Soyuz program. While few details of the Soviet landing system are known, it is expected that impact accelerations are greater than ACRV's limits for ill/injured crew.

There is a long history of domestic involvement with land landing system concepts that is relevant to at least a trade-off study for ACRV. The one-man Mercury capsule had an inflated gas bag behind the heat shield that was designed to limit the impact acceleration of the 2,900 lb vehicle to 15 g in the event of an errant land landing. No operational experience with the air bag was obtained since all Mercury landings were in water. Throughout the Mercury and Gemini programs, the NASA Johnson Space Center (JSC) maintained a land landing technology development and demonstration effort. During Mercury, a marginal system combining a steerable, gliding parachute (L/D of 0.5) and a retrorocket was tested at full scale. Subsequently, a landing system based on a controllable parasail parachute (L/D of 1.0) and a sophisticated impact attenuation scheme using skid landing gear and rockets was developed for the 5000 lb Gemini spacecraft to the point of being "qualifiable". Both JSC and the Langley Research Center were involved in the definition and preliminary design and demonstration of a land landing capability upgrade for the Apollo crew module. These studies evolved the consensus that a successful land landing system should include a steerable, high L/D (i.e., greater than 2.0) gliding decelerator for obstacle avoidance and wind penetration capability, rockets or an effective flare technique to reduce descent velocity at impact, and a shock-absorbing landing gear appropriate to landing site terrain to handle the potentially high horizontal velocity under light wind conditions. In the more recent Phase I ARS study by Pioneer, land landing systems based on ballistic and low L/D parachutes in combination with retrorockets were compared to a system based on a high L/D device. While that study was directed to payload weights much greater than the SCRAM version of ACRV, the ballistic and low glide parachute options were judged to have relatively low technical risk. Such systems might meet the technology readiness level constraints for ACRV.

In all of these previous land landing initiatives, the objective was to safely recover healthy crew, or in the case of the ARS program, reusable hardware. The lower ill/injured acceleration limits of ACRV make it almost certain that any existing spacecraft landing technology will have to be supplemented by a more capable impact attenuation system. Besides the strut couch supports discussed earlier, a wide range of devices have been developed mainly for hardware recovery that could possibly be installed external to the crew compartment. Air bags and crushable materials such as paper or

8

aluminum honeycomb have been used in a variety of vehicle recovery and cargo drop applications. Recently, the Natick Research, Development and Engineering Center has carried out a small program to investigate improved air bag performance by controlling vent area and internal pressure. A notable, operational man-rated air bag system is the one used on the F-111 crew escape module. While air bags are typically the device of choice for sensitive payloads, horizontal drift during impact is a major concern for structural integrity and effectiveness. Directional control of ACRV during landing might facilitate the design of air bags and crushable material attenuators capable of withstanding sliding in a predictable direction. As discussed for the water landing option, this controllability could be accomplished by a swivel mechanism for ballistic parachutes or by the inherent steerability of gliding decelerators.

It was stated earlier that it is generally perceived that a high L/D decelerator is the best option for a land landing. The rationalization for this position is based on the desirable capabilities of such a device to penetrate strong winds to reach a specific landing site and to avoid local obstacles if it is necessary to land at some unprepared site. The technical risk and development time for a gliding decelerator depend in large part on the size of the decelerator and its L/D. The size, in turn, is dictated by the payload weight. Personnel size gliding decelerators (e.g., parasails and parafoils with canopy area of 200-600 ft²) are easy to pack, deploy, manage inflation loads, steer, and flare upon landing. The wing loading (i.e., payload weight/canopy area) is less than 1.0 lb/ft². The successful parasail-based demonstration system for the Gemini capsule described earlier had canopy area and wing loading on the order of 2500 ft² and 2.0 lb/ft², respectively. If a wing loading of 2.0 lb/ft² is maintained for the 11,000 lb ACRV, the required canopy area is doubled at 5000 ft². Packing, deployment, inflation, etc. of a low L/D decelerator (e.g., a parasail) of this size is probably feasible. On the other hand, the largest high L/D device successfully deployed is the 3600 ft² parafoil during the ARS program. The inflation and loads management technique used on that system appears promising based on a few flight tests, but it is too early to assume there will not be problems with a significantly larger system.

While the forward velocity of a gliding decelerator can be used to advantage to nullify vehicle drift under windy conditions, it is a source of unwanted additional kinetic

energy under windless landing conditions. A high ground speed at touchdown will require a complicated landing gear system and prepared landing surface to prevent capsule upset. The capability to tailor L/D (and thus, the forward velocity) to suit wind conditions at the landing site is an attractive idea, but very little work has been done in this area.

## 4.0 Soft Landing Issues for MTS

The primary mission of the Two-Way Manned Transportation System (MTS) is regular rotation of the crew of Space Station Freedom. MTS is scheduled for operation after the space station is permanently manned (2000-2005 time frame).

The design requirements and philosophy for MTS are that it will accommodate 8 passengers and a crew of two. All subsystems shall be man-rated and two-fault tolerant for safe return to earth. It will use technology which will be at least at Level 6 readiness by 1992. Normal landing will be on land with an emergency water landing capability. Emergency crew escape and recovery from the launch pad and during ascent is required. The spacecraft shall be reusable to the fullest extent possible.

Currently, there are three candidate concepts for MTS: 1) a derivative of the SCRAM assured crew return vehicle (ACRV-D), 2) a moderate L/D biconic shape, and 3) a winged lifting body (HL-20). The different weights and hypersonic/subsonic lifting characteristics of these three vehicle types have a strong influence on how the requirement for a normal landing on land is addressed.

### 4.1 ACRV-D

Considering the 28.5 deg inclination of the orbit of Space Station Freedom and the 50 mile reentry cross range capability of ACRV-D, the only possible land landing sites in the U. S. are in south Texas and south Florida. It is likely that the designated landing zones will be in or near at least sparsely populated areas and that the terrain will have scattered topographic features and obstacles that should be avoided. As is the case for SCRAM, landing accuracy and impact force mitigation are the overriding technology issues for ACRV-D. With a weight only 3000 lb greater than the SCRAM, the previous discussion of SCRAM is fully relevant to ACRV-D.

With a ballistic parachute system, landing accuracy is determined by wind conditions during terminal descent. As an example, for a descent velocity of 30 ft/s from 10,000 ft in a uniform 25 knot wind, the lateral displacement of the capsule is

approximately 2.3 nautical miles. If operational considerations for the landing of the ACRV-D demand less dispersion, strong consideration should be given to a decelerator system with some capability for wind penetration and steerability. With current technology, L/Ds between 0.5 and 3.5 are possible for various types of controllable gliding decelerators. The ability of a gliding decelerator to penetrate the wind depends not only on L/D but also on the magnitude of the descent velocity (i.e., on the wing loading of the decelerator). Therefore, a very high value of L/D may not be necessary nor represent the most efficient gliding decelerator for a specific mission. For example, a 25 knot wind can be penetrated with an L/D = 1 decelerator at a descent velocity of 42 ft/s or with an L/D = 3.5 decelerator at a descent velocity of 12 ft/s. If a moderate dispersion of landing accuracy is tolerable for the ACRV-D (say, hundreds of meters), then the typically lower heading change rates of moderate L/D decelerators are probably adequate. Development factors such as schedule and overall technical risk would also favor a moderate L/D concept.

There are some differences between ACRV-D and SCRAM that may significantly influence the design of a landing system. These differences derive from the additional requirements of reusability and two-fault tolerance for MTS. The issue of reusability will surely affect the design of the capsule's impact attenuation system. Reusable or economically replaceable devices should be developed to minimize refurbishment cost and time between flights. The decision on whether to design the parachute system for single or multiple uses must be based on initial component costs, expected refurbishment costs, and system weight as influenced by structural factors of safety and material degradation.

Extension of the two-fault tolerant requirement to the landing system is a major concern and difficulty if a gliding decelerator is used. Unlike the ballistic parachute system for the Apollo capsule that used a cluster of three independently deployed parachutes, existing gliding concepts use a single deployable device. At present, there is not enough flight experience with large gliding decelerators to quantify the reliability associated with deployment, inflation and loads management. Because predictive models for gliding decelerator behavior are still in their infancy, determining reliability will have to be based on an adequate number of future flight tests. Greater technical risk

and more questions about reliability exist for high L/D devices than for low or moderate L/D devices. Also, there is little past experience to suggest how to handle redundancy for gliding decelerators and their control systems.

For an emergency escape while on the launch pad, the ACRV-D is separated from the booster and lifted by rocket motors to an altitude of a few thousand feet. A parachute system is deployed and the capsule descends to a water landing. The low altitude of the capsule dictates that a decelerator with positive, rapid deployment characteristics be used. There is no advantage to using a gliding decelerator over a ballistic parachute for emergency escape in the ACRV-D, since precision landing and obstacle avoidance are not relevant factors for a water landing.

## 4.2 Biconic

The biconic vehicle has a recovery weight of 24,000 lb. Hypersonic cross range is adequate to reach additional landing sites at the Kennedy Space Center and at White Sands, New Mexico. The baseline design calls for a fully automatic landing system that uses a controllable, high L/D parafoil and a shock-absorbing skid landing gear. There are four key areas of technology development required to establish the feasibility of this concept: 1) loads management during inflation, 2) design of an effective autonomous flight control system, 3) understanding the control-input/aerodynamic-response characteristics of a large parafoil during the touchdown phase, and 4) effective attenuation of the remaining horizontal and vertical kinetic energy of the vehicle.

The most relevant experience with controlled parafoils is from the ongoing NASA/Pioneer ARS program, during which a 3,600 ft² wing with a 13,900 lb payload has been flown. The optimum size of a parafoil for the nearly two-times heavier biconic is influenced by the requirement to penetrate a specified wind as well as the desire to minimize the descent velocity. For example, to penetrate a 25 knot wind, the maximum allowable wing area is approximately 10,000 ft². By coincidence, the full-scale parafoil built by Pioneer for the ARS program but not yet flown is approximately this size. At a relatively low wing loading of approximately 2.0 lb/ft², the flying qualities of this large wing with the biconic as its payload might not be too different from the flying qualities of

personnel size parafoils. Assuming an L/D of 3, the resulting sink rate and forward speed in steady glide are 14 ft/s and 42 ft/s, respectively.

As stated above, one of the key technology areas needing attention for the biconic version of MTS is the deployment and inflation loads management of very large parafoils. The ARS program has made significant progress to date by demonstrating a successful method of inflation loads management (i.e., reefing) for the 3,600 ft$^2$ parafoil. It is extremely relevant and important to the MTS that the ARS program demonstrate successful deployment and inflation of the 10,000 ft$^2$ wing for a wide range of wing loadings (e.g., 0.5-5.0 lb/ft$^2$).

The second key area identified above is the development of an experience base with which to design an autonomous automatic flight control system for a large parafoil. Alternative guidance and control methods should be evaluated for a range of wing sizes and wing loadings. The precision with which touchdown location and heading can be controlled has a significant effect on the choice and required preparation of landing sites. Landing accuracy with an autonomous control system, in turn, depends on how well the aerodynamic and inertia characteristics (static and dynamic) of the parafoil/vehicle system are modeled, as well as on the sophistication of the control logic and positioning information. The data base for these models must come from appropriately designed flight and wind tunnel tests. Both the ARS program and the recently begun JSC/Dryden Flight Research Facility program are important to this end.

The third key area involves the aerodynamic behavior of a parafoil at touchdown. Currently, considerable speculation exists about the possibility of achieving a greatly reduced sink rate at touchdown as the result of a precisely executed flaring maneuver. Experienced sport jumpers routinely perform such a maneuver. However, the ARS program has not been able to reproduce comparable large changes in descent velocity with the 3,600 sq-ft wing. Other than wing size, the notable difference between the ARS flights to date and personnel parafoils is the wing loading. Future testing in the ARS and JSC/Dryden programs should include an investigation of the influence of wing loading on the effectiveness of the flaring maneuver. Obviously, whether or not this type of maneuver is effective will significantly influence the design of the skid landing gear and

associated impact attenuation devices. There is an immediate, critical need to investigate and understand, through flight test, wind tunnel test and numerical aerodynamic simulation, the practical possibilities for dynamic modulation of parafoil lift and drag through trailing edge deflection.

The last key technology area identified for the biconic version of the MTS involves the effective attenuation of remaining horizontal and vertical kinetic energy at touchdown. A successful flaring maneuver might be expected to reduce the vertical velocity to a level manageable with telescoping shock absorbers (i.e., less than about 10 ft/s). However, the skid landing gear must still dissipate the horizontal energy associated with a ground speed of at least 40-50 ft/s by sliding friction without causing the vehicle to upset. Some landings with the vehicle in a yawed attitude should be anticipated because of limitations of the flight control system under windy conditions. Therefore, the skid system must be designed to accommodate a currently unspecified range of yaw angles. The characteristics of the landing gear, in turn, directly affect the required degree of ground leveling and other preparations at the landing site.

Present planning calls for an emergency water landing capability for the biconic following a rocket-assisted escape from the launch pad or following an abort during the boost phase. The landing would be performed at a nose-down attitude with the landing gear retracted. For the parafoil to be effective in this emergency scenario, it must be capable of being deployed and completely inflated from an altitude of only a few thousand feet. This requirement may place additional difficulties on developing and qualifying the method used for inflation loads management.

## 4.3 HL-20

The winged HL-20 has adequate hypersonic L/D to reach landing sites at Kennedy, White Sands or Edwards Air Force Base. With its subsonic L/D of approximately 4, the HL-20 would maneuver and glide to a runway landing under the control of an automatic flight system. At a weight of 24,000 lb, the requirement for an emergency water landing

15

during the launch phase might be handled by a cluster of five of the 83.5-ft ballistic parachutes used on the Apollo recovery system.

# 5.0 Summary of Critical Soft Landing Technology Areas and Recommendations for Action

Sections 3 and 4 above examined the soft landing issues relevant to the various design and landing site options for the Assured Crew Return Vehicle and the Two-Way Manned Transportation System. The required performance characteristics of the landing subsystems were analyzed in terms of past experience and the current technology base. Several areas were identified that are critical to meeting performance goals but for which the required technology base does not currently exist. The following recommended actions are necessary to make possible valid trade studies among the various landing system options, as well as to provide basic information for the design and qualification of the selected systems.

## 5.1 Computer Modeling of Decelerator Deployment and Inflation

There should be a continuing effort to improve the accuracy of decelerator force predictions during deployment and inflation, for all three categories of decelerators (i.e., ballistic, low L/D, and high L/D). Peak loads occur during inflation, and the force history applied to the vehicle must not exceed structural or physiological limits. Accurate modeling of the effects of canopy reefing/disreefing is an essential element of the numerical simulation. Because of the complexity of the fluid dynamics involved, a variety of approaches varying in theoretical sophistication and reliance on experimentally based correlations should be pursued simultaneously.

## 5.2 Structural Analysis of Decelerator Canopies

Weight and storage volume are critical factors in the design of all spacecraft systems, including the decelerator. Knowledge of the loads within the canopy is required to make the most efficient use of available fabric materials. The structural analysis of conventional, round, ribbon-type parachutes under steady state conditions is fairly well developed. This capability should be extended to include biaxial stress analysis of solid and semi-solid canopies. Continued efforts to formulate a truly dynamic

analysis of round parachutes during the inflation phase should be pursued. An accurate computer simulation of stress distributions and load paths for parafoils is also needed.

## 5.3 Impact Shock Mitigation for Water Landing

Since a water landing presents the lowest technical risk for ACRV, work should proceed immediately to drive that particular technology to a state of readiness. A three-dimensional computer simulation of water impact, including wave motion, should be developed and experimentally verified in appropriate test facilities (e.g., the Naval Weapons Center Water Impact Facility). This analysis tool would be used to optimize the shape and orientation of the SCRAM vehicle to keep impact accelerations below the limits set for ill/injured crew. Once a water landing capability has been demonstrated for SCRAM, technology development toward a land landing capability could proceed with lower programmatic risk.

## 5.4 Deployment and Inflation Loads Management of Large Parafoils

Through the ARS program, Pioneer Aerospace, Inc. has devised a promising method of reefing to control inflation loads for a large parafoil. The three-stage reefing method has been successfully demonstrated on five flight tests of the 3,600 ft² parafoil. To establish the feasibility of the biconic version of the Two-Way Manned Transportation System, it is particularly important that reliable deployments of the full-scale, 10,000 ft² ARS wing be demonstrated in the near future. If necessary, the ARS program should be expanded to include additional flights relevant to MTS (e.g., payload weights the same as the biconic.) The ARS program will also provide necessary information on the issues of ground handling and packing a very large parafoil.

## 5.5 Autonomous Control of Gliding Decelerators

Advanced technology development in the areas of guidance, navigation and control (GN&C) is required for any mission where a gliding decelerator must be directed to a landing site. Both the ARS and JSC/Dryden programs are necessary to provide an adequate background for the design of operational, self-contained autonomous control

systems. Major problem areas are expected to include the following: power requirements of the control mechanism, precise performance of the landing flare maneuver, acquisition of adequate wind knowledge, and the combining of Global Positioning Satellite (GPS) and Inertial Navigation System (INS) information for accurate guidance of the decelerator.

## 5.6 Flare Performance of Large Parafoils

Demonstrating the effectiveness of the parafoil landing flare maneuver under relevant conditions (i.e., at an appropriate wing loading and by the authority of an automatic or remotely operated flight control system) is critical to establishing the feasibility of the SCRAM-based and biconic versions of MTS. Both the ARS program and the JSC/Dryden Autoland program are necessary elements of this demonstration. Extrapolation of the JSC/Dryden data to a large wing will require a better understanding of geometric scaling effects than currently exists. It is also imperative that an accurate model of the parafoil's aerodynamic characteristics during the flare maneuver be developed. Considering the wing's flexible structure and the unsteady nature of the maneuver, developing this model will be a difficult undertaking. However, the model is a necessary part of the flight control system; its accuracy will directly affect the precision and reliability of the flare maneuver.

## 5.7 Impact Energy Attenuation and Rockets for Land Landing

Any land landing system designed for the missions addressed in this study will require landing impact attenuation capabilities beyond current demonstrated technology. Effective shock attenuation is especially important to meet the ill/injured acceleration limits of ACRV and the requirement for reuse of the MTS. Resources should be applied to improving the performance and structural integrity of air-bag concepts and their incorportation into skid landing gear. A related issue is the use of rocket systems to reduce vertical and/or horizontal velocities before touchdown. Effort should be put into developing a demonstration subsystem that integrates rocket motors with ground tracking sensors and controls to point the rocket into the direction of vehicle motion.

## 5.8 Moderate L/D Decelerator Concepts

The potential of autonomous landing systems based on moderate L/D (i.e., 1.0-2.0) decelerators should be throughly investigated. While the reduced glide capability means that the highest expected winds cannot be penetrated, a lower L/D system will still significantly reduce the dispersion in landing point accuracy. Furthermore, there should be adequate control authority and responsiveness to preferentially orient the vehicle at landing to benefit the design of landing gear and/or impact attenuation devices. Generally, the deployment and inflation characteristics of moderate L/D decelerators are well understood and the overall technical risk of a landing system development program should be low. Compared to a parafoil, a moderate L/D decelerator may be more amenable to modulation of L/D to suit a range of landing site wind conditions. It may also be possible to identify concepts that use clusters, thereby offering some redundancy for the landing system.

## 6.0 Bibliography

Butler, M. C., "In-Flight Ejection Seat Test Using the Aircrew Gliding Escape System (AGES) Parachute," TP 6741, Naval Weapons Center, China Lake, CA, Sept. 1986.

Eichblatt, D. L., Moore, R. H. and Barton, R. L., "Experimental Verification of Scale Factors for Parawing Opening Characteristics," TN D-4665, NASA, Washington, D. C., Aug. 1968.

Eiden, M. J., "Aerodynamic Decelerators for Future European Space Missions," Paper 89-0879, 10th Aerodynamic Decelerator Systems Technology Conference, American Institute of Aeronautics and Astronautics, Apr. 1989.

Ewing, E. G., Bixby, H. W. and Knacke, T. W., "Recovery System Design Guide," TR-78-151, Air Force Flight Dynamics Laboratory, Wright Patterson Air Force Base, OH, Dec. 1978.

Hinson, J. K., "Application of Gliding Parachutes to the Space Station Crew Emergency Return Vehicle," JSC-22820, NASA Johnson Space Center, Houston, Texas, Dec. 1987.

Lee, C., Rosato, N. and Lai, F., "An Investigation of Improved Airbag Performance by Vent Control and Gas Injection," Paper 91-0892, 11th Aerodynamic Decelerator Systems Technology Conference, American Institute of Aeronautics and Astronautics, Apr. 1991.

Lingard, J. S., "Gliding Parachutes," Lecture Notes, University of Minnesota Parachute Systems Technology Short Course, Framingham, MA, June 1990.

Macha, J. M., "Similarity Parameters for Model Parachutes," Lecture Notes, University of Minnesota Parachute Systems Technology Short Course, Framingham, MA, June 1990.

Moeller, J. H., Linhart, E. M., Gran, W. M. and Parson, L. T., "Free Flight Investigation of Large All-Flexible Parawings and Performance Comparison with Small Parawings, Final Report," CR-66918, NASA, Washington D.C., March 1970.

Nicolaides, J. D. and Tragarz, M. A., "Parafoil Flight Performance," TR 71-38, Air Force Flight Dynamics Laboratory, Wright Patterson AFB, Ohio, June 1971.

Norman, L. C., et al, "Gemini Land Landing System Development Program, Vol. I, Full Scale Investigations," TN D-3869, NASA, Washington, D. C., March 1967.

Norman, L. C., et al, "Gemini Land Landing System Development Program, Vol. II, Supporting Investigations," TN D-3870, NASA, Washington, D. C., March 1967.

Pioneer Aerospace Corp., "Advanced Recovery Systems Phase 2, Final Report, Vol. I, Executive Summary," ARS-DR-12-01, Oct. 1990.

Pioneer Aerospace Corp., "Advanced Recovery Systems Phase 2, Final Report, Vol. II, Demonstration Test Results and Analysis," ARS-DR-12-02, Oct. 1990.

Pioneer Aerospace Corp., "Advanced Recovery Systems Phase 2, Final Report, Vol. III, Advanced Controls Systems," ARS-DR-12-03, Oct. 1990.

Pioneer Systems, Inc., "Final Study Report for Advanced Recovery Systems Development, Vol. II, Study Results," ARS-DR-4-02, Sept. 1987.

Stubbs, S. M., "Dynamic Model Investigation of Water Pressures and Accelerations Encountered During Landings of the Apollo Spacecraft," TN D-3980, NASA, Washington, D. C., Sept. 1967.

Ware, G. M. and Hassell, J. L., "Wind-Tunnel Investigation of Ram-Air-Inflated All-Flexible Wings of Aspect Ratios 1.0 to 3.0," TM SX-1923, NASA Langley Research Center, Hampton, VA.