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BICONIC CARGO RETURN VEHICLE WITH AN ADVANCED RECOVERY SYSTEM

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The current Space Exploration Initiative is focused around the development of the Space Station *Freedom* (SSF). Regular resupply missions must support a full crew on the station. The present mission capacity of the shuttle is insufficient, making it necessary to seek an alternative. One alternative is a reusable Cargo Return Vehicle (CRV). The design suggested in this report is a biconic-shaped, dry-land recovery CRV with an Advanced Recovery System (ARS). Liquid rocket boosters will insert the CRV into a low Earth orbit. Three onboard liquid hydrogen/liquid oxygen engines are used to reach the orbit of the station. The CRV will dock to the station and the cargo exchange will take place. Within the Command and Control Zone (CCZ), the CRV will be controlled by a gaseous nitrogen Reaction Control System (RCS). Alternatively, the CRV will have the capability to exchange the payload with the Orbital Maneuvering Vehicle (OMV). The bent biconic shape will give the CRV sufficient crossrange to reach Edwards Air Force Base and several alternative sites. Near the landing site, a parafoil-shaped ARS is deployed. The CRV is designed to carry a payload of 40 klb, and has an unloaded weight of 35 klb.

ACRONYMS

ARS	Advanced Recovery System
CCZ	Command and Control Zone
CRV	Cargo Return Vehicle
FRCI	Fibrous Refractory Composite Insulation
HABP	Supersonic/Hypersonic Arbitrary Body Program
L/D	Lift-to-Drag Ratio
LRB	Liquid Rocket Booster
OMS	Orbital Maneuvering System
OMV	Orbital Maneuvering Vehicle
PLOG	Pressurized Logistics Module
RCS	Reaction Control System
SSF	Space Station *Freedom*
SSRMS	Space Station Remote Manipulator System
TABI	Tailorable Advanced Blanket Insulation
TPS	Thermal Protection System
UPLOG	Unpressurized Logistics Module

INTRODUCTION

Between the years 2000 and 2010, space station *Freedom* (SSF) is projected to be fully operational. Currently, the space shuttle is the only way to resupply the Space Station. However, SSF requires a yearly resupply of 214,000 lb, and since the shuttle can only support 5 missions a year, with a total upcargo of 178,185 lb, NASA is looking at Cargo Return Vehicles (CRVs) as a way to augment the shuttle's capacity. This report outlines the design of a biconic CRV proposed to fill this mission.

Requirements

1. The primary operational period will be between the years 2000 and 2020.
2. The CRV will be unmanned.
3. The primary mission will be to meet the resupply/return needs of SSF (in orbit at 220 n.m. and 28.5° inclination).
4. All payload supplied or returned from SSF will be transported in a Pressurized Logistics Module (PLOG) or Unpressurized Logistics Module (UPLOG).
5. The CRV will use shuttle-compatible payload interface methods.
6. The CRV will have an upcargo capability of 40,000 lb.
7. The CRV will be partially reusable.
8. The CRV will have a dry-land recovery using a runway of not more than 10,000 ft.
9. The primary landing site will be Edwards Air Force Base.
10. The CRV will be able to transfer cargo both by direct docking and using the Orbital Maneuvering Vehicle (OMV).

Design Criteria

The design of the biconic CRV took place in three stages. First a trade study was conducted, then a conceptual design, and finally models were built and tested to verify the conceptual design's results.

As a result of the trade study, it was decided that the the CRV would consist of a bent-axis biconic (see Figs. 1a,b), with a two-stage reentry phase.

The main objective is to achieve a highly reusable vehicle, minimizing weight and size.

During the first stage of reentry, the CRV will be reentering the atmosphere. The split axis serves to provide enough lift to allow the biconic to come to within a few miles of the landing site. At this point the parafoil is deployed.

To minimize the weight, size, and drag, it was decided that the ARS would be nonrigid and internally stored.

Design considerations in the area of propulsion sought to integrate the CRV with an already existing, or planned, launch vehicle. The design of launch boosters was beyond the scope of this project.

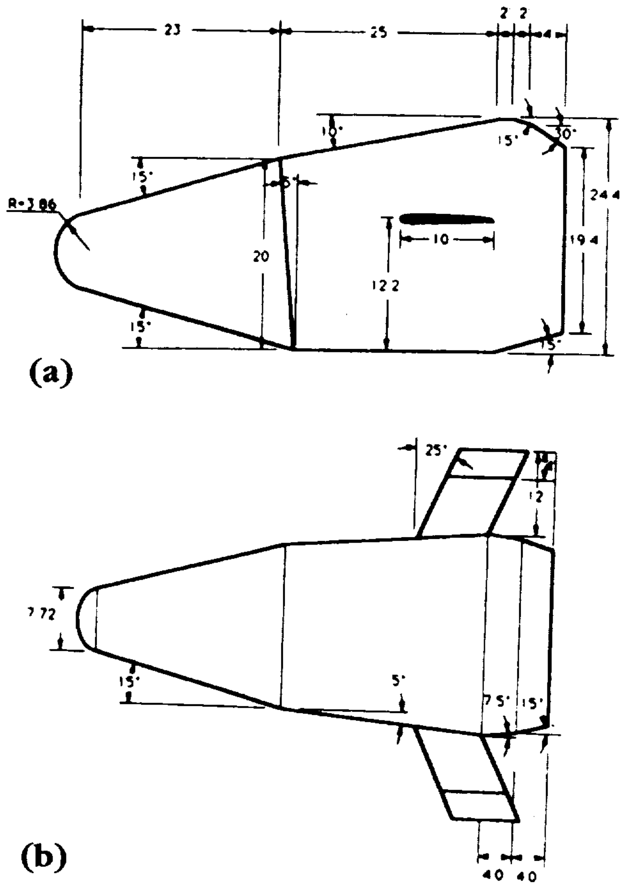

Fig. 1. Dimensions of the CRV. (a) Side View of the CRV; (b) Top View of the CRV

MISSION OPERATIONS

The nominal mission scenario for the CRV is a rendezvous and cargo exchange with Space Station *Freedom* at its orbit of 220 n.m. with an inclination of 28.5°. The CRV will launch from Kennedy Space Center.

The Launch

A number of assumptions about the dynamics of the CRV had to be made. The Earth-to-orbit phase was modeled as a standard two-body problem. Further, the assumption that velocity changes (ΔVs) are instantaneous, was made. Since the burn times are small compared to the duration of the maneuvers achieved, the assumption is legitimate.

In determining the magnitude and time of the ΔVs necessary to reach the station's orbit, two factors had to be weighed against each other: mission time vs. fuel consumption. Because fuel is heavy and one of the CRV design objectives is to minimize weight, minimizing the ΔVs at the expense of time is a good trade in most cases (if the time is too long the weight of the batteries required to maintain the vehicle may offset the benefit derived from the reduced fuel consumption).

With this in mind, the Hohmann transfer was selected for this mission. While it is a lengthy transfer operation, it is also most energy efficient. Here the craft is set into an elliptical orbit. When this orbit brings the CRV closest to a circular orbit, a burn takes place to reach and maintain the latter orbit. The problem with time, then, is that in order to enter the desired orbit at the appropriate place, there has to be a certain waiting period while the two orbits are out of phase.

The liquid rocket booster (LRB) will deliver the CRV into a 50×100-n.m. elliptical orbit; then four more burns, using the CRV's Orbital Maneuvering Systems (OMS) engines, will bring it to the SSF (see Table 1).

Table 1. Orbit Burns.

Maneuver	ΔV (ft/sec)
50×100-110 transfer	100
110-210 transfer	180
210 circularize burn	180
210-220 transfer	20
220 circularize burn	20
Proximity maneuvers (non-OMV)	58
Proximity maneuvers (OMV)	40
220 deorbit	317
Total	895 (non-OMV) 877 (OMV)

To avoid out-of-plane burns, the CRV will have phasing waits. Ignoring phase delays, there is one launch opportunity for the CRV every day. This window offers a minimum phase delay (0 hr) every fourth day or 62 orbits. At most, the delay is 33 hr. Coupled with a reentry phasing delay of 0 to 20 hr, the total mission time varies between 18.35 and 75.35 hr non-OMV, and 19.85-76.85 hr OMV. It is assumed that small out-of-plane perturbations can be corrected by the CRV's Reaction Control System (RCS).

Proximity Operations

All operations close to the Space Station are carefully monitored and avoided if possible. Surrounding the SSF is what is known as the Command Control Zone (CCZ), which extends 5 n.m. above and below the station, and 20 n.m. all around it. Any object entering this zone can endanger the safety of SSF, and is therefore required to follow many safety guidelines. For the sake of simplicity and safety, original NASA requirements stated that the CRV would not be allowed to enter the CCZ, making cargo transfers possible only using the Orbital Maneuvering Vehicle (OMV).

To transfer payloads with the OMV, the CRV would park itself behind SSF outside the CCZ. The OMV would then retrieve the cargo module from the CRV and tow it back to the station. To save orbit time, while the OMV is towing the PLOG/UPLOG, the CRV would reposition itself in front of the SSF, remaining outside the CCZ. Then, the OMV would bring the return cargo to this new position while the CRV is phasing for the deorbit burn.

Since the OMV program has been scaled back, it has become important that the CRV be able to venture safely into the CCZ and dock to SSF. This is accomplished with two short jumps inside the CCZ, that can be modeled as Hohmann transfers (see Fig. 2).

In order for the CRV to dock directly to SSF, a special docking mast was designed (see Fig. 3).

Requirements of the docking mechanisms include the ability to physically support the CRV and interface monitoring with SSF systems, and compactness. Also to be considered is the positioning of the mast such that the Space Station Remote Manipulator System (SSRMS) be able to reach the cargo bay and effectuate a transfer while the CRV is soft docked at the cupola node (see Fig. 4).

In the biconic CRV, the docking mechanism is located in front of the cargo bay. This is to allow the latter to dock to SSF vertically (Fig. 4), thereby insuring not only a good reach by the SSRMS, but also good stability characteristics. Mechanism design resulted in a short mast that rotates back into the CRV for storage when it is not docked to the Space Station (Fig. 3).

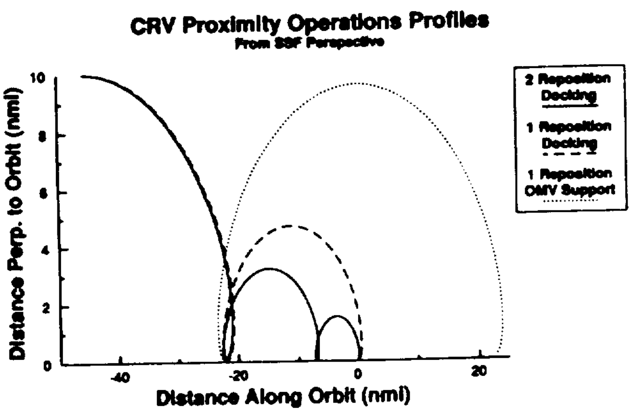

Fig. 2. CRV Position Relative to SSF During Proximity Operations

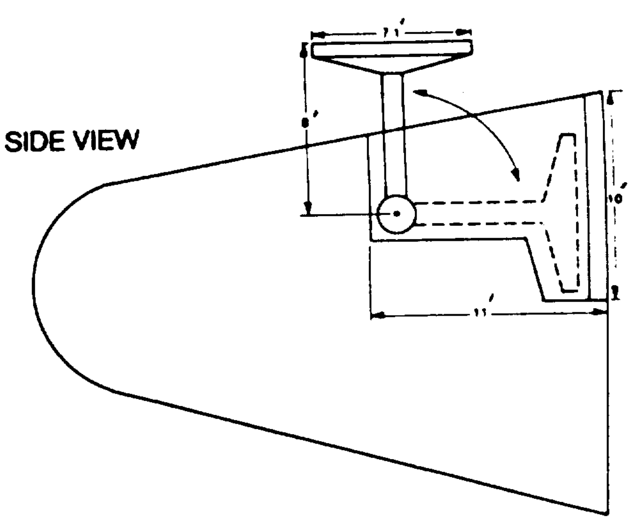

Fig. 3. The Docking Mast

Contingency Plans

Contingency plans have been developed in case any of the on-orbit maneuvers should fail to be completed on schedule. This might occur in the event of engine malfunctions or systems failure.

Only one maneuver requires significant correction: the 110-210-n.m. transfer, which is timed to bring the CRV behind the Space Station. The ΔVs required to reposition in such an event are shown in Fig. 5. Any other errors can be resolved by either waiting for the phase difference to correct itself, or by small perturbations methods.

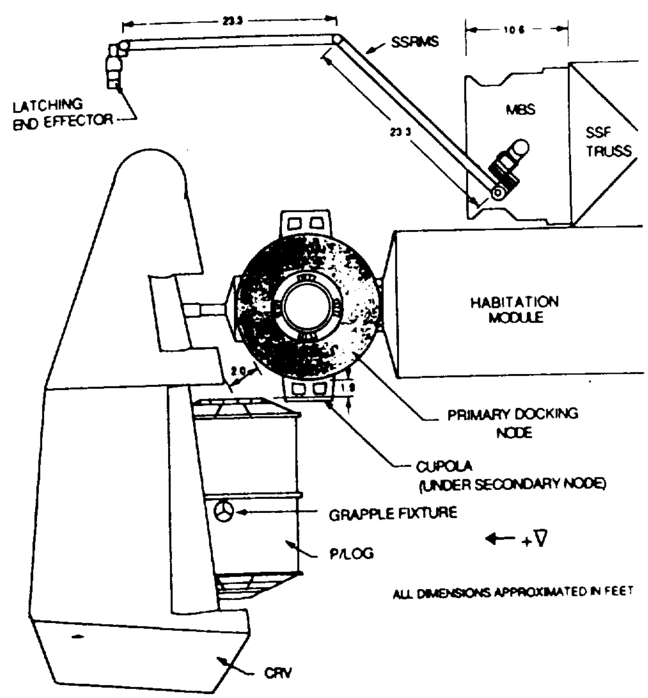

Fig. 4. Vertical Docking of the CRV at SSF

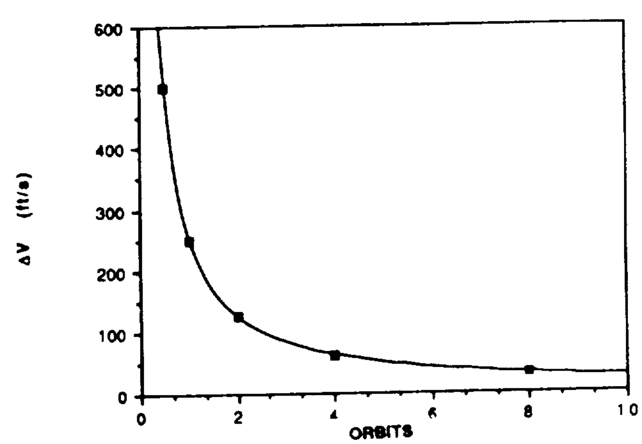

Fig. 5. Phase Correction Burn

Reentry

The initial deorbit burns require a 0-20-hr phase delay. After this initial burn, the dynamics of the CRV are governed by the atmosphere during an unpowered reentry. More detail on this phase is offered in the aerodynamics section of this report.

Ground Operations

While on the ground, the CRV has been designed to be compatible with all space shuttle processing facilities except the launch pad vertical payload integration bay.

The primary landing site is Edwards Air Force Base, while the launch site is Kennedy Space Center. This raises the problem of transporting the CRV back to KSC after landing. One of the objectives of design dealt with this problem. The CRV was designed to be as small as possible, and as a result it is possible to fit the CRV inside the Boeing Superguppy's cargo bay.

The processing scenario of the CRV has been modeled to follow that of most unmanned spacecraft, with a few minor changes. The predicted maintenance operations for the CRV are estimated to require 23 days, with a processing turnaround time of 66 days and a 7-day layover for transportation back to KSC, making the landing-to-takeoff turnaround 73 days.

PROPULSION

Propulsion is a part of almost all the CRV's phases of operation. It starts with the launch, continues with on-orbit transfers and proximity operations, and ends with the deorbit burn; after which the reentry is supported by aerodynamic lift only.

The CRV has been designed to launch vertically integrated with single-core expendable LRBs (see Fig. 6). As has already been specified, designing a launch vehicle was beyond the scope of this project. Instead, a choice was made from already existing systems. Design considerations include a 4.0-g maximum acceleration due to PLOG constraints.

The LRBs used for the launch are being designed by NASA and, while not yet in existence, are planned for service well ahead of time of the CRV's operational period. These rockets have a booster-out capability in excess of 85 klb. Since the CRV has a maximum takeoff weight of 74 klb, its safety is assured.

The boosters will insert the CRV at a 50×100-n.m. orbit and then reenter the atmosphere.

The CRV also has three Orbital Maneuvering System (OMS) engines, which are capable of producing the large ΔVs needed to move the CRV from the low Earth orbit up to its $220 \times 220 \times 28.5°$ final orbit. The OMS engines are fueled by a liquid hydrogen/oxygen mixture, and weigh only 86.65 lb each, with a specific impulse (vac) of 414.4 sec.

The amount of fuel needed to support the burns was a very important factor in choosing the OMS. The propulsion system is designed with a 20% fuel reserve.

REENTRY AERODYNAMICS AND CONTROL

Reentry of a biconic CRV cannot be aided by a fixed rigid wing, so an Advanced Recovery System (ARS) is needed. Trade studies conducted early in the development of this biconic's conceptual design showed that a ram-air parafoil would make a very efficient ARS in terms of size and weight. The ram-air parafoil also showed good control characteristics and soft landing capabilities. Its low range, however, made a two-stage reentry a must.

Stage 1—Atmospheric Reentry

During the first stage of reentry, the CRV enters the atmosphere. It is in this stage that the CRV is expected to cover most of its range. To help the CRV meet its crossrange

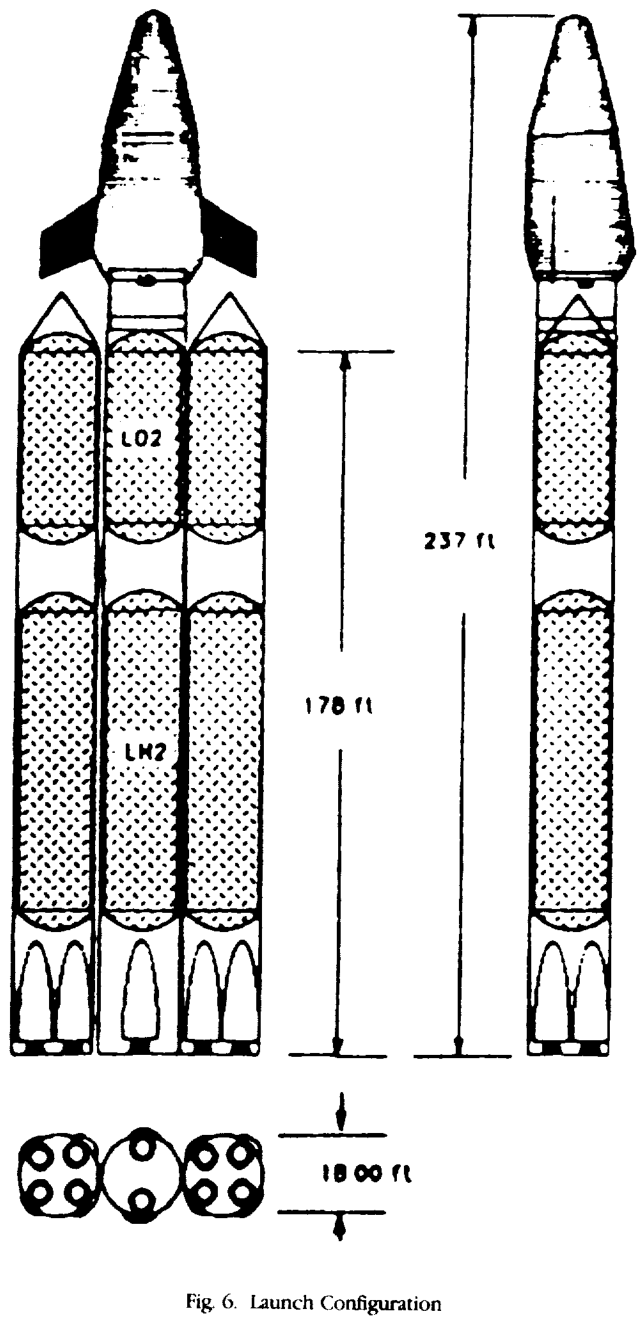

Fig. 6. Launch Configuration

requirements, it was designed with an axis bent with respect to the fore and aft cones. The result of the bend is aerodynamic lift.

At first, the bent biconic body was modeled after a previously designed biconic interplanetary vehicle (see Fig. 7), because a large amount of wind tunnel data was available for that configuration, allowing the design team to validate several analytical aeroprediction codes.

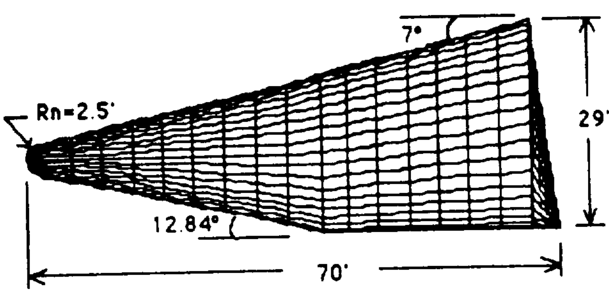

Fig. 7. HABP Model of the Baseline Configuration

The Supersonic/Hypersonic Arbitrary Body Program (HABP) was the main tool used in determining the aerodynamic characteristics of the body and understanding how each change affected the vehicle performance. The HABP accepts several methods to determine the pressure distributions around the vehicle. Using the baseline configuration as a reference, it was found that the Modified Newtonian and the Van Dike methods yielded the best results, compared to wind tunnel data. The former method was chosen as the standard for calculations, and was applied to the initial model to reshape the biconic in order to make it an efficient CRV.

Aerodynamics played the greatest role in shaping the CRV. Other considerations included providing good interior volume efficiency and acceptable heat load distributions. For example, during the design, the nose radius was increased from 2.5 ft to 4 ft. During reentry, heating is greatest around sharp edges. Therefore, increasing the nose radius lowered the heating levels in the nose making the use of lighter heating tiles in that area possible. Another advantage of the increased nose radius is that it allowed placement of onboard systems a lot closer to the front of the vehicle (see Fig. 8), not only improving the volumetric efficiency of the vehicle, but allowing a forward shift of the vehicle's center of gravity, a needed element in vehicle control.

CONTROL

During this stage of reentry, early versions of the vehicle displayed unacceptable instabilities (see Fig. 9). The lack of control surfaces made the Reaction Control System (RCS) the only means of controlling maneuvers. This was not only a costly proposition in terms of weight, but also did not yield good control characteristics. One of the biggest instabilities of the early versions was in the yaw direction, while its longitudinal axis symmetry makes it completely roll stable.

To render the CRV more stable, control fins were added. These consist of two tail-mounted horizontal fins, which have zero camber and can deflect ±30° to provide the needed longitudinal control. Further, the outer third of the fins can fold upwards 90° to function as winglets. Yaw control is achieved by staggering the deflection of the left and right fin, making either the left or right "rudder" more effective, thus creating the appropriate yaw moment (see Fig. 10).

CRV stability was tested longitudinally in both the Phugoid and Short period modes. Laterally, it was tested in the rolling, spiral, and Dutch roll modes. The biconic CRV is satisfactorily stable in all these modes.

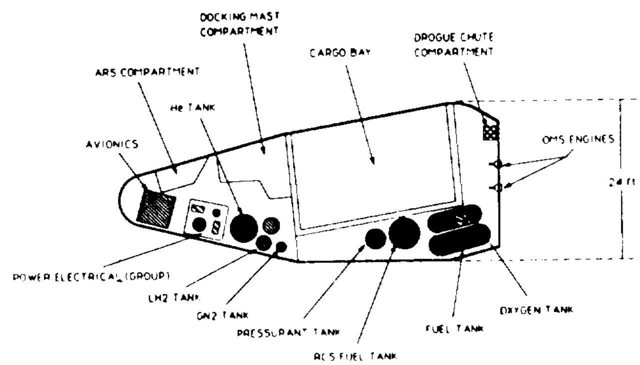

Fig. 8. System Placement (side view)

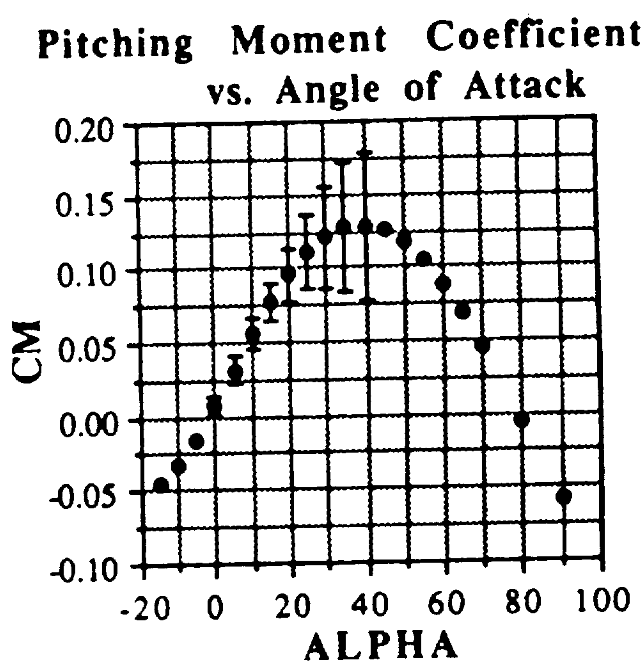

Fig. 9. Early Versions of the CRV Showed Instabilities

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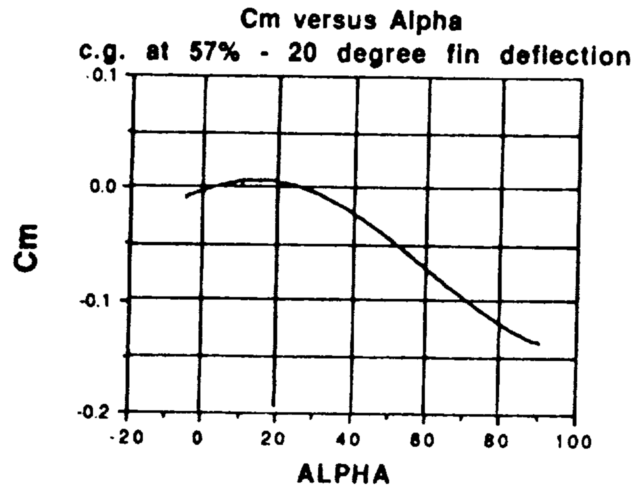

Fig. 10. Stability Characteristics

Stage 2—Advanced Recovery System

During this stage, the Advanced Recovery System (ARS) is deployed. Just prior to its deployment, a drogue shoot is deployed to bring the dynamic pressure down to less than 100 lb/ft^2. This allows the ARS to be deployed safely.

The ARS is a ram-air parafoil with a planform area of 22,250 sq ft, with a wingspan of 250 ft and a chord length of 89 ft. A modified Clarke-Y-17 airfoil section was chosen for the parafoil, as this type of section is most widely used on ram-air parafoils. The Clarke-Y-17 is shown in Fig. 11.

The ARS is made entirely of fabric with no rigid structures and is packed in a manner similar to a conventional parachute. It is deployed at an altitude of 10,000 ft. The parafoil is designed to be deployed and disreefed with 75% flap retraction. The flaps are actually the trailing edge of the parafoil and can be retracted to provide additional lift and directional control. The retractions occur by reeling in the lines attached to the trailing edge.

The parafoil is made up of 51 cells. The midspan reefing technique is used and is accomplished by folding and stowing a number of cells two places for each reefing stage. After deployment, the parafoil is disreefed in three stages, as shown in Fig. 12. During the first stage, the 11 center cells are opened. The five outer cells on each side are then opened during the second stage. The remaining 30 cells are disreefed in the final stage.

Wind tunnel tests of similar airfoils lead to the following aerodynamic characteristics:

Trim Angle of Attack	7°
Lift Coefficient	0.84
Drag Coefficient	0.22
Moment Curve Slope	-0.005
Lift-to-Drag Ratio	3.8

The flare maneuver just prior to landing is performed by cutting the lines connecting the parafoil to the rear of the CRV. The weight of the CRV is shifted forward until a "lazyleg," or piece of cable that lengthens each line connected to the rear of the CRV, is tightened. The CRV touches down immediately after this maneuver.

THERMAL ANALYSIS

The Thermal Protection System (TPS) is designed to protect the CRV from the excessive heat loads during reentry. It is necessary to protect not only the structure itself, but also the avionics, the cargo bay area, and the control surfaces.

The avionics are cooled by placing them on a freon-cooled cold plate inside a pressurized (air) container. The freon is pumped through a radiator with approximately 117 sq ft of area placed on the inside of the cargo bay doors. In tandem with the radiator system, an evaporative system provides direct cooling to the freon system. In the lower atmosphere, where evaporative and radiative cooling cannot take place, freon and water are circulated through a heat exchanger. The water absorbs some of the heat.

The cargo carrying PLOG and UPLOG were designed to withstand a heating load of approximately 440 Btu/hr/sq ft. This is the value chosen to be a maximum constraint on the heating of the cargo bay. The insulation chosen is a low-weight Q-fiber insulation lining the cargo bay in a layer 0.375 in thick.

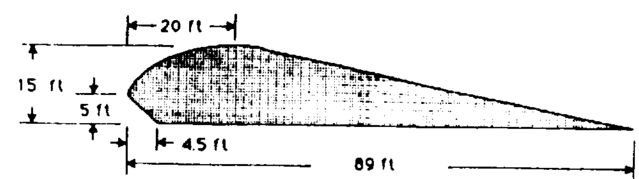

Fig. 11. Clarke-Y-17 Airfoil

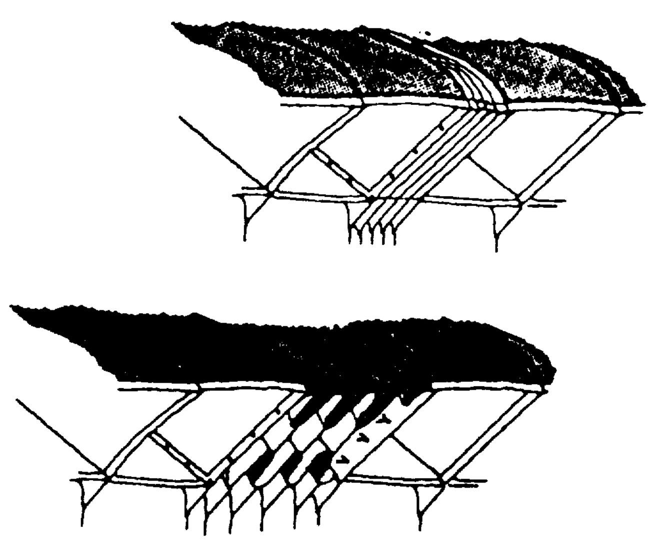

Fig. 12. Disreefing of the Parafoil

The program MINIVER was used to determine the external heating loads along the surface of the vehicle and on the control surfaces. Using this program, the maximum temperature was found to be 2775°F in the nose of the vehicle and along the leading edges of the control surfaces. These areas are covered by LI-2200 in 6-in by 6-in tiles at an angle of 18° to the airflow. The tiles were put at an angle to prevent them from being ripped off the way they are on the space shuttle. The tiles vary in thickness from 2.5 in near the flow stagnation area to 2 in toward the rear of the vehicle.

The underside of the vehicle experiences the next highest heating loads. Fibrous Refractory Composite Insulation (FRCI) will cover this area as well as the remainder of the control surfaces. These tiles are also 6 in by 6 in at an angle of 18° to the flow. The thickness decreases from approximately 2 in to 1.5 in moving towards the rear of the CRV.

The rest of the vehicle is covered by Tailorable Advanced Blanket Insulation (TABI). These tiles are approximately 2 ft by 2 ft and decrease in thickness from 1.5 in to 0.75 in moving toward the rear. The different insulations are shown on the CRV in Fig. 13.

The tiles are attached to the CRV by two different methods. All tiles are directly or indirectly connected to the outer skin of the structure by the cost-effective adhesive, RTV-560. However, due to the frequent replacement of tiles, a "hook-and-loop" method is used to attach the TABI tiles. Fig. 14 shows the three types of insulation and their attachments.

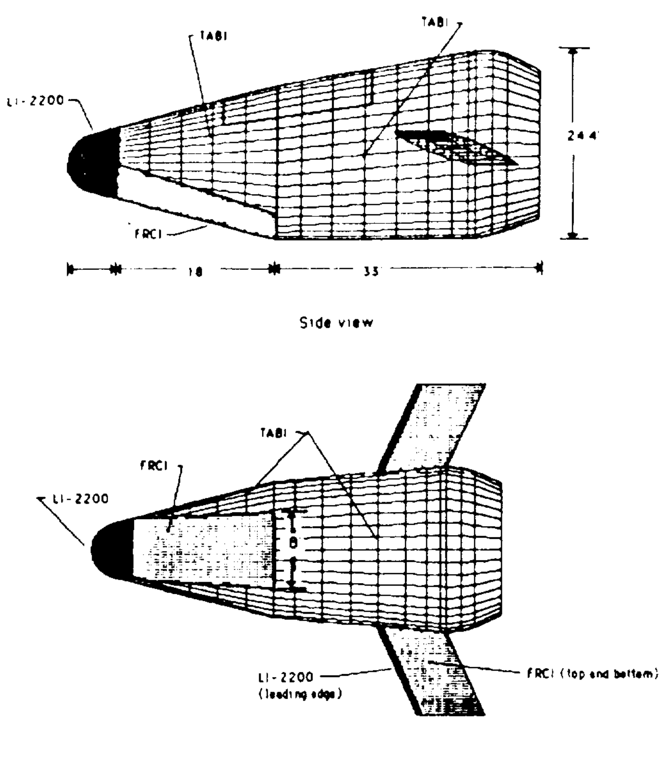

Fig. 13. CRV Insulated Tiles

STRUCTURAL DESIGN

The fuselage substructure, the cargo bay support structure, the outer skin, and the ARS Docking Mechanism and Drogue Chute compartments were some of the substructures designed by the structural design team. This was a very critical part in the design of the CRV. All substructures must be designed to withstand any applied load.

The fuselage support structure consists of a system of ring frames and stringers. There are 32 box-shaped ring frames spaced 22 in apart from the nose to the rear. There are 74 Z-shaped stringers surrounding and supporting every ring frame, except for the first 6 rings, which only require 37 stringers. The stringers are spaced approximately 12 in apart at the largest diameter of the CRV and converge slowly as the diameter decreases.

The cargo bay support structure designed to support the PLOG or UPLOG is a series of half rings just over 15 ft in diameter. There are 14 of these half rings coplanar with outside rings numbers 15-28 from the front, also spaced 22 in apart. The inside rings are all box shaped and are arranged as shown in Fig. 15.

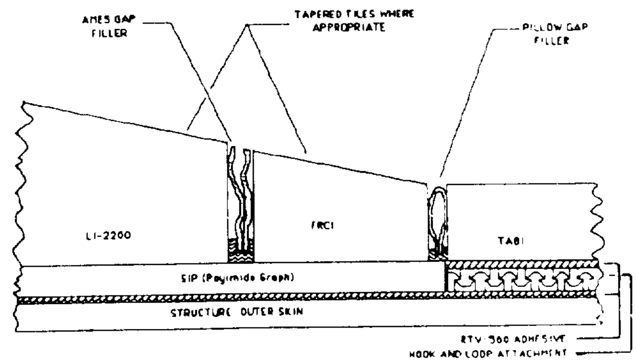

Fig. 14. TPS Materials and Attachment Methods

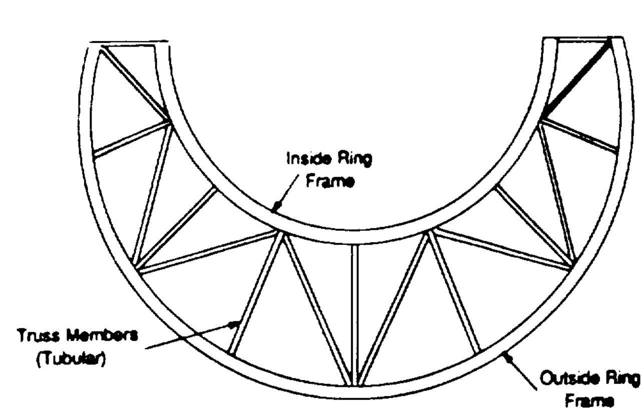

Fig. 15. Payload Bay Support Structure

The outer skin is made of HRH-327 honeycomb with aluminum 2219 facing material on each side. The reason for using the honeycomb structure is that it is the most efficient way to get the maximum strength out of the lightest material. The honeycomb panel consists of five layers of material, as shown in Fig. 16. The layers consist of an aluminum face sheet on the inner and outer surfaces attached to the HRH-327 honeycomb by an adhesive, as shown in Fig. 16. Each aluminum face sheet is 0.02 in thick and the honeycomb is 0.05 in thick.

With the given ARS design, a 69.05-cu-ft compartment would be necessary to pack the chute. A 25% margin of error and an additional 10 cu ft for the deployment chute were also added, making the necessary volume of the ARS storage compartment 96.3 cu ft. Due to the location and size of the cargo bay, it was necessary to place the compartment in the fore cone of the vehicle. The compartment is 3.2 ft deep, 4.5 ft wide, and has a maximum length of 8.3 ft on the surface, tapering off towards the center of the CRV to 5.1 ft. The taper is at a 45° angle.

The drogue chute compartment is placed near the rear of the CRV on the top surface just behind the cargo bay. Its volume is 15 cu ft, including a 50% margin of error. The compartment is 3.42 ft wide with a depth and length of 2.17 ft.

The docking mechanism compartment was uniquely designed to fit the shape of the mechanism. It is also placed in the fore cone of the CRV between the ARS compartment and the cargo bay. The compartment is 8 ft wide, 11 ft long, and has a maximum depth of 10 ft, as shown in Fig. 3.

CONCLUSION

Worthy of mention is the absence of a backup recovery system to the ARS. A design for such a system was actually carried out, but it was decided not to include it as part of the design for several reasons. First, the extra weight would necessitate downscaling the maximum payload. This is undesirable. Second, volume constraints in the backup system bay are such that the size of the secondary chute would have to be limited; given these limits, the touchdown velocity of the CRV, in case of main system failure, would have to be greater than desired, causing some systems to be damaged on impact. Third, the high reliability of the ram-air ARS does not warrant the penalty weight of a back-up system.

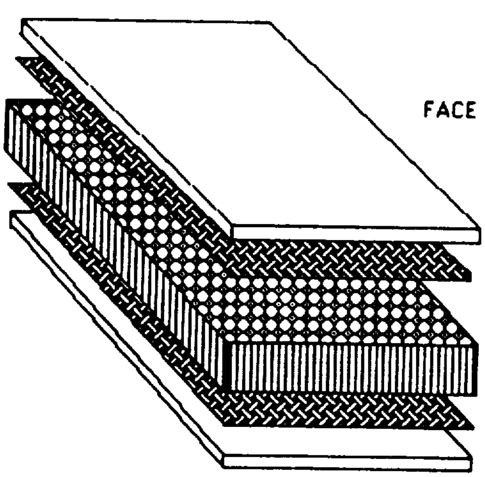

Fig. 16. Honeycomb Structure

INFORMATION SUMMARY

Bent-axis biconic with a ram-air inflated parafoil ARS
- $(L/D)_{Hyper} = 1.5$
- $(L/D)_{Subsonic} = 3.8$ -ARS
- Weight Unloaded = 34.06 klb
- Cargo Capacity = 40 klb
- Crossrange ≈ 700 n.m.

The advanced recovery system
- Planform Area = 22,250 ft^2 (250 ft × 89 ft)
- Deployed at 10,000 ft altitude
- Midspan reefing in three stages

Vehicle dimensions
- Length = 59 ft
- Diameter nose = 7.7 ft
- Diameter max = 24.4 ft

Supersonic reentry control is via tail-mounted adjustable deflection fins, with folding winglets.

The CRV will be capable of docking directly to SSF as well as being OMV compatible.

- Mission time with OMV = 19.85-76.85 hr
- Mission time non-OMV = 18.35-75.35 hr

Propulsion
- Top-mounted launch on dual-booster/single-core LRBs
- Orbit insertion at 50 n.m. × 100 n.m. at 28.5°
- Three OMS engines
  - LH_2/LO_2 propellant and oxidizer
  - Weight = 86.65 lb (each)
  - $I_{sp, vac} = 414.4$ sec
  - $Thrust_{vac} = 1600$ lbf
- The RCS system uses LH_2/LO_2 outside the CCZ and GN2 inside, as specified by SSF requirements.

Transportation of the CRV back to KSC will be via the Boeing Superguppy. CRV turnaround time is 66 days.