(1)

WINGED CARGO RETURN VEHICLE CONCEPTUAL DESIGN

UNIVERSITY OF MINNESOTA

N91-18144

NASA is committed to placing a permanent space station in Earth orbit in the 1990s. Space Station *Freedom* (SSF) will be located in a circular 220 n.m. orbit at 28.5° inclination. The Winged Cargo Return Vehicle's (CRV) primary mission is to support the SSF crew by flying regular resupply missions. The Winged CRV is designed to be reusable, dry-land recoverable, and unmanned. The CRV will be launched inline on three liquid hydrogen/oxygen rocket boosters with a payload capability of 113,000 lb. The three boosters will take the CRV to an orbit of 50 × 110 n.m. From this altitude the orbital maneuvering engine will place the vehicle in synchronous orbit with the Space Station. The Winged CRV will deliver cargo modules to the Space Station by direct docking or by remaining outside the SSF command zone and using the orbital maneuvering vehicle to transfer cargo. The CRV will be piloted by SSF crew while in the command zone. After unloading/loading, the CRV will deorbit and fly back to Kennedy Space Center. The Winged CRV has a wing span of 57.8 ft, a length of 76.0 ft, and a dry weight of 61.5 klb. The cargo capacity of the vehicle is 44.4 klb. The vehicle has lift/drag ratio of 1.28 (hypersonic) and 6.00 (subsonic) resulting in a 1351-n.m. cross-range. The overall mission length ranges between 18.8 and 80.5 hr. The operational period will be the years 2000-2020.

NOMENCLATURE

AFSRI	Advanced Flexible Reusable Surface Insulation
CCZ	Command Control Zone
CRV	Cargo Return Vehicle
FRCI	Fibrous Refractory Composite Insulation
GLOW	Gross Lift Off Weight
GPS	Global Positioning System
HABP	Hypersonic Arbitrary Body Program
IMU	Inertial Measuring Unit
L/D	Lift-to-Drag Ratio
LEO	Low Earth Orbit
LM	Logistics Module
LRB	Liquid Rocket Booster
MSBLS	Microwave Scan Beam Landing System
OMS	Orbital Maneuvering System
OMV	Orbital Maneuvering Vehicle
RCC	Reinforced Carbon Carbon
RCS	Reaction Control System
SPDS	Stabilize Payload Deployment System
SSF	Space Station *Freedom*
SSRMS	Space Station Remote Manipulator System
TPS	Thermal Protection System

INTRODUCTION

The Cargo Return Vehicle Design project was performed by students in the senior design class at the University of Minnesota. The project is intended to help supply Space Station *Freedom* (SSF) with its logistics needs. With development of the SSF, NASA has calculated that there will be logistic problems in supplying the station with enough to support a permanent manned contingent. It is with this shortfall in mind that a new vehicle was proposed. Currently NASA predicts that the SSF will need 8 flights per year and 250,709 lb of payload to support it. Currently the space shuttle can only be committed to 5 flights per year and 178,285 lb of cargo. This leaves the Space Station with a shortfall of three flights and 71,929 lb of payload per year. It is with this basic requirement that the project was undertaken. The project was conducted in three parts: Trade Study, Conceptual Design, and Testing and Analysis. The first phase, the trade study, considered a lifting body, a biconic, and a winged configuration based on performance, reliability, and availability of technology. The trade studies were also used to determine major vehicle systems, and preliminary mission profile. The configurations chosen were the winged and biconic configurations.

The second phase of the project was a conceptual design of the vehicle. To conduct this the class was divided into two design teams, one for each configuration considered. The remainder of this summary will focus primarily on the design and testing of the winged configuration. The winged configuration design team was further broken down into eleven discipline groups: System Integration, which oversaw the design process of the vehicle as well as the overall management of the design team; System Layout, which was responsible for the placement of systems, vehicle drawings, and the mass properties of the vehicle; Mission Operations, which was responsible for the orbital mechanics, mission profile, space station operations and ground operations; Reentry Dynamics, which was responsible for the flight profile from reentry to ground; Aerodynamics, which was responsible for the analysis of the vehicle aerodynamically, including the various control devices considered such as winglets, canards, and the vertical tail; Stability and Control, which calculated the stability derivatives as well as examining the control requirements on orbit and in the atmosphere; Thermal Protection and Control, which was responsible for thermal analysis of the vehicle and the placement of thermal protection; Avionics and Power, which was responsible for the choice of avionics and power systems needed by the vehicle; Propulsion, which selected the number of engines, engine type, and the launch system; Structures, which determined the overall layout of structural members; and Cost and Optimization, which examined optimization of some of the systems on the vehicle. The disciplines each met individually twice each week; the team as a whole met once a week. There was also a weekly meeting of the configuration control board whose responsibility it was to define the vehicle design and to settle all disputes between discipline groups over the final design of the vehicle. The overall vehicle designed by the group had physical characteristics as given in Table 1.

Table 1. Vehicle Physical Characteristics

Overall Dimensions	
Length	76.0 feet
Span	57.8 feet
Height	19.8 feet
Cargo Bay Dimensions	
Length	30.0 feet
Width	19.8 feet
Height	19.8 feet
Vehicle Weights	
Weight (dry)	61,596 lb
Weight (launch)	113,000 lb
Consumables	5,568 lb
Weight (landing)	106,012 lb
Max. Payload	44,416 lb

Major systems on the vehicle are given in Table 2.

Table 2. Major Systems

	Propulsion
Launch system	Liquid Rocket Booster system
Main Orbital	1 OMS Engine
RCS (normal)	28 NTO/MMH thrusters
RCS (special)	24 Cold Gas Thrusters (for use around SSF)
	Avionics Systems
Guidance and Navigation	Global Positioning System (GPS), Star Tracker, IMU
Communications and Tracking	Tracking and Data Relay Satellite System (TDRSS)
Autoland	Microwave Beam Scan Landing System
Control	Electro-Servo Actuators
	Power Systems
Avionics	Fuel Cells
Controls	Ni Cad Batteries

The vehicle contains many other subsystems that will be explained later in the summary. The final vehicle configuration can be seen in Fig. 1. The configuration features a delta-wing planform with a strake and winglets for lateral stability and control. The cargo bay is similar in design and length to the space shuttle so as to be compatible with all the same cargo handling systems. There is a docking ring bay located ahead of the cargo bay to facilitate docking of the vehicle to SSF without affecting payload capability or placement in the cargo bay. The vehicle will glide in to land on cyclical landing gear (not shown).

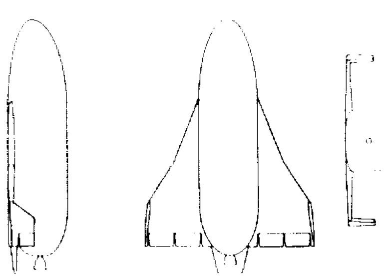

Fig. 1. Three View Drawing of Vehicle

The third stage of the Project was the Testing and Analysis Stage. The class was again broken into eleven discipline groups: System Integration, Integration Staff, Modeling, Wind Tunnel Testing, Wind Tunnel Data Analysis, Water Tunnel Testing, Structural Analysis, Cost and Optimization, and Marketing and Promotion. The main function at this stage was to analyze more completely the design of the vehicle. The System Integration group acted as the project managers while the Integration Staff primarily worked on editing the contractor reports. The Wind Tunnel groups worked on analyzing the vehicles' lift-to-drag ratio and some of the stability derivatives to determine if they coincided with the calculated ones found during the design phase. The Water Tunnel group examined qualitatively the flow around the vehicle examining the effects of the strakes and winglets. The Modeling group worked with both testing groups building the test models as well as building a display mock-up for the Marketing group. The Structural Analysis group worked on analyzing the structure of the vehicle using the program NASTRAN in order to finalize the size of the structural members. The Marketing group was responsible for the promotion, public relations, and the displays of the vehicle for the ADP Summer Conference as well as at the university. Cost and Optimization examined the feasibility of the overall concept as well as performing a justification study. The testing and analysis confirmed much of the work done earlier.

SYSTEMS LAYOUT

The systems layout discipline's major responsibilities were to keep track of the placement of the various systems through vehicle drawings, and to calculate the mass properties of the vehicle. The vehicle final weight statement can be seen in Table 3.

Table 3. CRV Finalized Weight Statement

Body	11,693 lb
Wings	8,809 lb
Thermal Control System	250 lb
Propulsion System	1,353 lb
Avionics and Power	12,000 lb
Landing Gear	3,200 lb
Docking Module	250 lb
Growth	5,000 lb
Dry Weight	61,596 lb
Payload	44,416 lb
RCS Propellent	241 lb
OMS Propellent	4,627 lb
Cold Gas Propellent	700 lb
Adapter	1,420 lb
Total Launch Weight	113,000 lb
Less Consumables	5,568 lb
Less Adapter	1,420 lb
Total Landing Weight	106,012 lb

MISSIONS OPERATIONS

The total mass in orbit will increase approximately 833% from 1998 to 2006. The SSF must receive approximately 115,000 lb of cargo per year. Of this cargo, 76% would be returnable and the other 24% would be trash. The SSF will need fluids for continued growth and for use in experiments to be conducted on the station. For growth to occur there is a need for 12 flights per year by the year 2004. The U.S. will be responsible for carrying 42% of the cargo to the SSF. The CRV must have the ability to meet SSF cargo requirements. The station will have of 275 KW of power, 24 crewmembers, and 5 or more modules. Cargo transfers must be of the order of 200 metric tons per year, which can be provided by 9 enhanced CRV flights per year.

The CRV will be capable of performing the required mission utilizing one of two possible mission plans—denoted nominal (primary) and alternate (secondary).

In the nominal mission, the CRV would leave a 110-n.m. injection orbit, en route to a stabilized "parking orbit" at the rear edge of the Space Station *Freedom* Command and Control Zone (CCZ). An Orbital Maneuvering Vehicle (OMV) would be dispatched from the SSF and perform two round-trips in the process of transferring and exchanging the Logistics Modules (LM). LM pickup and dropoff at the CRV would take approximately 30 min each and would be simplified by the inclusion of a Stabilized Payload Deployment System (SPDS). LM exchange at the SSF would nominally be performed solely by the OMV (~1 hr exchange time) and contingently by the OMV with the aid of the SSRMS (~2-3 hr exchange time). The overall nominal mission would be completed in 18.8 hr.

In the alternate mission plan, the CRV would leave the injection orbit and proceed directly to the SSF and dock with the help of the SSRMS. The SSRMS would berth and deberth the CRV and perform all LM exchange maneuvers. The CRV would be required to stay docked to the SSF for at least 6 hr, until a launch window opens. As a result, the alternate mission plan would take considerably longer to perform.

In either mission plan, the flight would be directed by several ground control centers and the SSF crew. Any vehicle inside the CCZ would be controlled by the SSF crew and any vehicle outside the CCZ would be controlled by ground crews.

REENTRY GUIDANCE AND DYNAMICS

The main purpose of the discipline was to define the CRV's flight profile, determine the *g*-loading, maximum dynamic pressure on the vehicle, and cross range requirements. They were also responsible for defining the minimum lift-to-drag ratio for the vehicle to reach the primary landing sites and determining the cross range. The cross range was calculated using standard empirical approximation. The cross range was determined to be 1351 n.m. The maximum *g*-loading was found to be 2.25 *g* and occurs during S-turn maneuvers used to decelerate the vehicle. The flight profile is shown in Table 4.

Table 4. Flight Profile

Event	Time to Touch-down	Altitude (ft.)	Velocity (ft/sec)
De-orbit Burn	1 hr	220 n.m.	Mach 26
Blackout	30 min	300,000	23,900
Maximum Heating	20 min	230,000	19,350
Exit Blackout	12 min	180,000	13,500
Begin Energy Management Systems	5 min	80,000	1,900
Initiate Autoland System	1.5 min	14,000	650
Initiate Preflare	30 sec	2,000	580
Complete Flare	15 sec	135	450
Landing Gear Down	10 sec	100	400
Touchdown	0 sec	0	320

AERODYNAMICS

The aerodynamics discipline group was in charge of defining the wing shape, camber, and essential body surface designs. The group used a Hypersonic Arbitrary Body Program (HABP) to evaluate the winged CRV's aerodynamic characteristics in the hypersonic and supersonic regions (Table 5). The HABP program is capable of calculating aerodynamic characteristics of arbitrary 3-D shapes in both the hypersonic and supersonic regions. For the subsonic aerodynamics the Boeing computer program AIREZ was used to estimate characteristics of all flight regimes, from subsonic to supersonic. Another program, developed at the University of Minnesota, ULTIMATE, was employed to reveal flight qualities that AIREZ was not capable of performing. Also studied was the possibility of employing canard surfaces for longitudinal control.

Table 5. Maximum L/D Characteristics

Mach	AIREZ	HABP Fins and Tail	HABP w/Strake
1.2	1.83	N.A.	N.A.
1.5	1.66	N.A.	N.A.
2.0	1.58	1.36	1.66
5.5	1.39	1.29	1.58
10.5	1.50	1.28	N.A.
20.5	1.52	1.28	1.28

Sweep = 47°	Nose Length = 27 ft
Wing Taper = 0.28c	Nose Dia. = 19.9 ft
S = 1888 ft^2	Effect Dia. = 21.6 ft
Fin Taper = 0.34c	Nose Droop = -2 ft
Fin S = 170 ft.2	Nose Radius = 1.8t
Strake = 70.76°	Thick Ratio = 1.1

Throughout the trade study and conceptual design phases the CRV body was continually changed and redefined. The CRV began with vertical tail, deployable canards, and variable winglets. Based on the determination that a subsonic L/D of 6 would be adequate for approach and landing, a variable winglet option was eliminated. The performance of the winglet-only and vertical-tail-only configurations in the hypersonic and supersonic regions were found to be comparable. Therefore, use of both wing fins and a vertical tail was redundant, and the vertical tail was dropped from the body design. Theoretically the use of fins should increase the L/D favorably in the subsonic region due to a reduction in induced drag. Fins also are less susceptible to blanketing during reentry. Finally, the use of fins allows flexibility in docking with the Space Station. As a result of these benefits the winglet-only configuration was chosen to be the final form for the CRV.

STABILITY AND CONTROL

The stability analysis of the vehicle was performed using two main computer programs, the MINNEMAC program for computation of root loci for different stability modes and the Stability Analysis Program, which computed the aerodynamic derivatives. The analysis was performed in hypersonic/supersonic and subsonic flight regimes. The neutral and maneuver points for the different flight regimes are listed in Table 6.

Table 6. Neutral and Maneuver Points*

Regime	Neutral Point (ft)	Maneuver Point (ft)
Subsonic	45.05	46.08
Hyper/Supersonic	53.40	54.43

*All points measured from the nose of the vehicle.

From the calculation of the neutral points and the center-of-gravity envelopes from the system layout discipline it was determined that the vehicle would be stable throughout the hypersonic and supersonic ranges but would be unstable in the subsonic regime. This was decided to be acceptable since current fly-by-wire technology exists to control unstable flight.

The other function of the group was to examine control systems and size the control surfaces. The overall control of the vehicle would be accomplished by the RCS engines while on orbit and during reentry until the dynamic pressure on the CRV reached 10 psf. At this point the aerodynamic control surfaces would begin to be used and the RCS would be phased out. The vehicle would rely totally on aerodynamic surfaces by the time the dynamic pressure reached 170 psf. The control surfaces were sized using both a scaled-down space shuttle approximation, and deflection and moment constraints for refinements.

POWER AND AVIONICS SUBSYSTEMS

Power Supply

The power system on the CRV must satisfy several requirements. The most crucial aspect of any power supply for the Winged CRV is reliability. Power supply must be flexible regarding length of operation and must be cost effective. Of the power systems available, fuel cells satisfied the requirements.

Avionics have a peak usage of approximately 2.0 kW during thrusting maneuvers. If a pressurized logistics module is on board then an additional 1.5 kW would be required. This produces a peak power need of about 6 kW depending on the type and number of other components in use. Current fuel cells produce 7 kW continuous and 12 kW peak. One fuel cell could supply all the power required for the vehicle, but the design incorporates three fuel cells for system redundancy. The fuel cells are self-cooling units with their own oxidizer and fuel supply. They are located in the bottom of the vehicle along with their fuel and oxidizer tanks. (A separate fuel supply is required because fuel cells need a much higher grade of fuel than that used for propulsion.) The hydrogen/oxygen fuel exits the cells as water at about 140°F. This water could be used for heating or cooling other components.

Servo Actuator Power Supply

The servo power supply comes from a separate battery system because these servos require too high a peak load to be powered by the fuel cells. The type chosen were NiCad batteries because of their weight, volume, and performance characteristics.

Guidance and Navigation

The major components of this subsystem are the Global Positioning System (GPS) receiver, Inertial Measuring Units (IMU), and a star tracker. The GPS system determines the position of the vehicle relative to the Earth and SSF. The GPS works in either an arbitrary three-axis system or with latitude, longitude, and altitude. By giving a continuous update of the position, the GPS also provides a constantly updated velocity vector. The IMUs are the primary sensor for the guidance and navigation system. They sense both lateral and longitudinal rotational acceleration and detect rotational velocity. The CRV would incorporate 2-4 IMUs. The star tracker mounts directly on the hull of the CRV and would have a small view port. Each component feeds into a digital integration unit and then is sent to the main data handling computers.

Automatic Landing System

The main components of the auto landing system are the Microwave Scan Beam Landing System (MSBLS), a radar altimeter, the landing gear, steering and braking systems, and television cameras for remote control. The main functions of this subsystem are to capture and track lateral guidance path, capture and track the vertical guidance path, provide sideslip maneuvers prior to landing, drop landing gear automatically, and steer and brake while on the ground. The MSBLS is the primary navigation device. It is activated at 10,000 to 14,000 ft when the vehicle is parallel to the runway and provides azimuth angle, elevation angle, and distance during final approach and landing. The on-board radar altimeter provides height above the ground up to 5480 ft.

THERMAL PROTECTION SYSTEMS

The following materials were selected: Reinforced Carbon-carbon (RCC), Fibrous Refractory Composite Insulation (FRCI), and Advanced Flexible Reusable Surface Insulation (AFSRI). Approximate thermal calculations were made to justify the TPS placement on the vehicle.

The TPS for the Winged CRV is based primarily on the effective protection of the substructure while considering weight penalties. The aeroheating effects were defined from a computer program, MINIVER, approximate calculations, and space shuttle data. The protection materials chosen were RCC, carbon-carbon tiles, Fibrous Refractory Composite Insulation-8, and Tailorable Advanced Blanket Insulation (for the shuttle-type heat sink and hot structure system). The placement of the materials can be seen in Fig. 2. The total weight is 11,609 lb. Future use of an active cooling system appeared promising for use in connection with improved hot structures.

Aeroheating Analysis

To effectively apply thermal protection to the CRV accurate analysis of the temperature and heating rate along a trajectory is required. To fulfill this requirement, the program MINIVER was used. Using the trajectory established by the Reentry Dynamics group, and models for the various body sections, the thermal environment encountered by the CRV was estimated. The CRV was split into five sections for modeling purposes. These sections consisted of the nose, body, wing tips, wing section one (sweep = 68°), and wing section two (sweep = 54°). The models for each of these sections were input into MINIVER and analyzed twice; once, at laminar flow, and once, at turbulent flow. From the Reynolds number data in the MINIVER output, it was found that the air flow would remain laminar for this trajectory. This was based on transition beginning at $Re = 3 \times 10^5$, and fully turbulent flow at 4×10^8. From this methodology the TPS was chosen and placed in each of the five regions. From Fig. 2 and Table 7 an accurate idea of the vehicle protection regions can be analyzed.

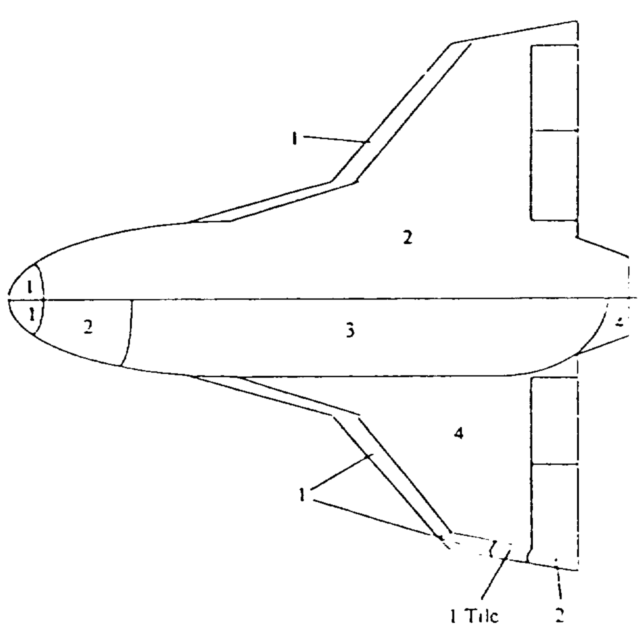

Fig. 2. TPS Placement

Table 7. Material Key

Region	Temperature	Material
1	2000-3000°F	RCC
1-Tile	2000-2700°F	Carbon-Carbon Tile
2	1500-2300°F	FRCI-8
3	800-1500°F	TABI
4	<800°F	TABI

PROPULSION

The objective of the propulsion discipline was to design a propulsion system for the CRV to meet all the mission requirements. The primary design inputs were thrust level, ΔV requirements, and total dry weight of the CRV. The two possible propulsion configurations for the CRV include a system with SSF control zone capabilities, and one without.

Orbital Maneuver System Engine Selection

The Orbital Maneuvering System (OMS) of the CRV serves two main purposes. First the system must produce the necessary thrust to propel the CRV from a 100-n.m. to a 210-n.m. orbit after booster shutdown. Second, the system must produce sufficient ΔV for de-orbit.

Based on a theoretical engine, it was concluded that the current space shuttle OMS would satisfy all the requirements. The Aerojet AJ10-190 was chosen for the use in the CRV. The dimensions of the engine are given in the following sections.

Reaction Control System

The Reaction Control System (RCS) for the Winged CRV is responsible for fine orbital and attitude adjustments in space and will not be used in the lower atmosphere. The system consists of 52 thrusters positioned as shown in Fig. 3.

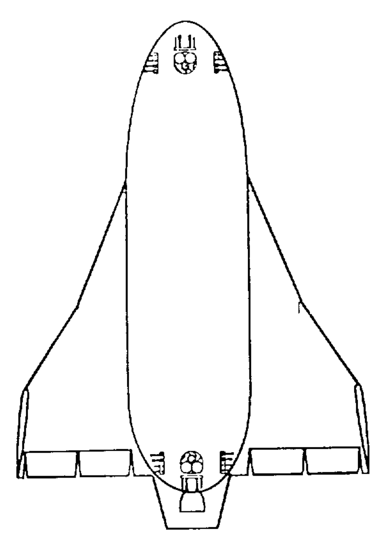

Fig. 3. RCS Placement

RCS Auxiliary

SSF regulations prohibit all but the use of cold gas propellents within the SSF control zone. To meet this requirement an auxiliary RCS system was designed to be used within the SSF control zone. The system was designed with the possibility of hard-docking to SSF.

Number of RCS Thrusters and Placement

For effective six-axis control, 24 cold gas and 28 NTO/MMH thrusters were placed as shown in Fig. 3 . Each main thruster will produce 400 lb of thrust. All thrusters will be fired individually except in emergencies. This number of thrusters allows for at least one degree of redundancy for each axis of motion. The thrusters will also be located to allow for paired-thruster operation if needed.

Launch System

The launch system must deliver the loaded CRV to a 100 n.m. insertion orbit. The launch system was chosen on the basis of payload to low Earth orbit, the mounting procedure of the CRV and the fuel type. The final decision was a delivery system consisting of two liquid rocket boosters (LRB) mounted on each side of one core unit, each with its own engines and fuel (Fig. 4). The core would also carry all of the avionics and controls. The fuel used for this system is liquid hydrogen (LH_2) and liquid oxygen (LOX). The engines for this application would be space shuttle main engines (SSME).

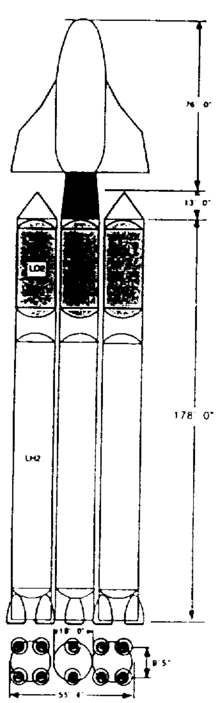

Fig. 4. Launch System

Table 8. Launch System Data*

Height (w/o CRV)	178′
Payload to LEO	125,000 lb
GLOW	2,600,000 lb
Engines	10-SSME

*For further description see System Mass Comparison.

STRUCTURAL DESIGN AND ANALYSIS

The structural design was completed during the design phase of the project. The vehicle was intentionally over-designed so that the elements would not fail. The main structural materials chosen for the vehicle were aluminum TA2219 for the construction of the frames, aluminum TA2024 honeycomb for the skin of the vehicle, and a Graphite/Epoxy composite was chosen for the cargo bay doors, since they do not contribute to the overall strength of the airframe. The design was divided into four sections, front, middle and aft fuselage, and the wing. The fuselage sections were connected by means of two main structural bulkheads fore and aft of the mid fuselage section (see Fig. 5).

The front fuselage was based on a semi-monocoque design similar to conventional aircraft. This design utilized TA2219 for the majority of the structure. The front fuselage houses the front landing gear, the avionics bays,and the docking module bay.

The wing is a conventional wing design consisting of spars, webs, and honeycomb skin. The wing is constructed from aluminum TA2219 except for the skin, which is TA2024. The aft landing gear base was placed within the wing structure.

The mid fuselage consists of a 30-ft-long primary load-carrying structure housing the payload bay. The mid fuselage is a truss frame construction of aluminum TA2219 that includes a wing carry-through structure and the payload bay doors. The payload bay doors are constructed entirely out of a graphite epoxy composite.

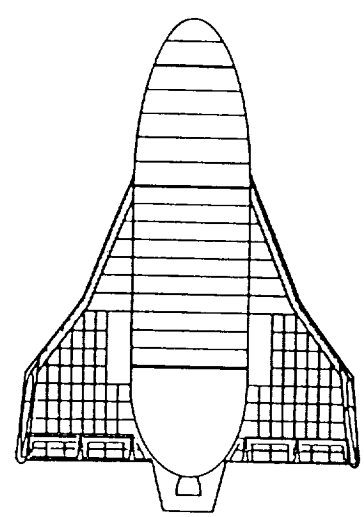

Fig. 5. Structural Layout

The aft fuselage consists of an external shell structure and an internal thrust structure. Both are constructed primarily out of aluminum TA2219 along with boron epoxy laminates and titanium reinforcements. The section houses the OMS engine and was designed to transfer the thrust and launch loads to the mid fuselage.

The analysis phase involved using the NASTRAN program to examine the design from the previous quarter. The program used finite element methods to determine forces and stresses on the different elements in the vehicle. To perform the analysis the vehicle was divided into two main sections, the fuselage and the wing. Dynamic pressure data from HABP runs were used as input for the program. The stresses were then used to determine which of the elements failed and which were overdesigned so that the crosssections and shapes of the materials could be refined.

DESIGN OPTIMIZATION AND COST ANALYSIS

During the second phase of the project the optimization group worked on the optimization of two systems on the CRV, the CRV/Booster interface and the propulsion system.

The optimization of the interface focused on defining the material used on the structure, the crosssection of the members in the structure, and the number of vertical members in the structure. The most important parameter to optimize was weight. The propulsion system optimization, sizing of fuel tanks and feedlines, was done by determining the ideal sizes and then looking for existing hardware.

During the second phase of the project, optimization focused on the overall justification of the CRV project as well as deciding which vehicle to go ahead with. Optimization groups from both the Winged and Biconic teams worked together, and examined reusable and expendable launch vehicles. The primary vehicles examined were Atlas Centaur, Shuttle C, both the Winged and Biconic CRVs, and increasing the shuttle's commitment to the Space Station. Criteria were cost per pound to orbit, reusability, reliability, and availability. Conclusions were that the CRV and, more specifically, the winged version, was the most viable option.

MODELING

The primary responsibility of the Modeling Group was to build models for physical testing of the vehicle. The testing group entered surface location coordinates into a CAD/CAM system and models were milled on a numerically controlled milling machine.

Two models were made for the testing of the vehicle. A wooden model was constructed for wind tunnel testing, and an aluminum model was used for water tunnel testing. The group also worked on constructing a display model for the ADP Summer Conference.

WIND TUNNEL TESTING

The Wind Tunnel Testing Group was responsible for developing and implementing the test plan. The group constructed and instrumented the setting and conducted the testing.

The primary purpose of the testing was to find the lift/drag ratio of the vehicle as well as various aerodynamic derivatives. Testing was conducted in the University of Minnesota's Aerospace Engineering Department subsonic, continuous flow tunnel. The test plan included running the model in the tunnel at two different velocities and at six different angles of attack (between 0° and 25°). The vehicle was also tested at three different sideslip angles.

WIND TUNNEL DATA ANALYSIS

The objective of the Wind Tunnel testing group was to calculate stability derivatives from data obtained from the wind tunnel testing group. The stability derivatives calculated included the lift-to-drag ratio, L/D; lift curve slope, $C_{l\alpha}$; $C_{m\alpha}$; and weathercock stability, $C_{n\beta}$.

The results were compared with computed values from aerodynamics and stability studies performed during the design phase of the project. Table 9 gives a comparison between the tested values and computed values.

Table 9. Test Results

	Testing	Computed
L/D	5.846	5.96
$C_{l\alpha}$	0.1055	1.929
$C_{m\alpha}$	-0.1158	-0.3968
$C_{n\beta}$	0.09071	0.07106

The two sets of values compare fairly well, particularly, the lift-to-drag ratio. The lack of correlation in the other values probably results from the very low speeds at which the tests were conducted.

WATER TUNNEL TESTING

The Water Tunnel Group was responsible for a qualitative analysis of the flow around the vehicle. Tests were conducted at the St. Anthony Falls Hydraulics Lab at the University of Minnesota. The tests were made at several different angles of attack, Reynolds numbers, and sideslip angles. The vehicle was pulled through a stationary water tank. The flow was examined to determine the effect of the winglets, strake, and the rest of the vehicle. From the tests no unusual effects were found. The flow behaved as expected; the angle of attack at stall was approximately 25°. This closely matches what was predicted by the Aerodynamics Group.

CONCLUSIONS

The Winged CRV met all the specifications and requirements that were set out for it. The conclusions of the design project were that the Winged CRV could easily provide the necessary cargo to supply Space Station *Freedom* with its logistics needs. The CRV also appears to be the most cost effective option available to accomplish this task.