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Aerospace System Design
AERO 483
The University of Michigan

Project EGRESS:
Earthbound Guaranteed ReEntry from Space Station

The Design of an Assured Crew Recovery Vehicle for the Space Station

NASA/USRA
April 1990

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ABSTRACT

Unlike previously designed space-based working environments, the Shuttle Orbiter servicing the Space Station will not remain docked the entire time the Station is occupied. While an Apollo capsule was permanently available on Skylab, plans for Space Station *Freedom* call for a Shuttle Orbiter to be docked at the Space Station for no more than two weeks four times each year. Consideration of crew safety inspired the design of an Assured Crew Recovery Vehicle (ACRV).

Keeping preliminary studies by NASA and industry in mind, including the official Request for Proposal (RFP) published by NASA Johnson Space Center, a conceptual design of an ACRV has been developed. The system allows the escape of one or more crew members from Space Station Freedom in case of emergency. The design of the vehicle addresses propulsion, orbital operations, reentry, landing and recovery, power and communication, and life support. In light of recent modifications in Space Station design, Project EGRESS pays particular attention to its impact on Space Station operations, interfaces and docking facilities, and maintenance needs.

A water-landing medium-lift vehicle was found to best satisfy project goals of simplicity and cost efficiency without sacrificing the safety and reliability requirements of the RFP. One or more seriously injured crew members could be returned to an earth-based health facility with minimal pilot involvement. Since the craft is capable of returning up to five crew members, two such permanently docked vehicles would allow a full evacuation of the Space Station. The craft could be constructed entirely with available 1990 technology, and launched aboard a Shuttle Orbiter.

FOREWORD

Aerospace Engineering 483, "Aerospace System Design", is one of a number of design courses available to students in Aerospace Engineering at The University of Michigan. In this course, each year a different topic is selected for the preliminary design study, which is carried out by the entire class as a team effort. There are no exams or quizzes in this course, but the total output of the study consists of three parts: a) a formal oral presentation at the end of the semester, b) a scale model of the design, and c) a final report. The current design is the thirty-third in the series, started in 1965 by the late Professor Wilbur C. Nelson.

The 1989-90 design topic is of a Space-Station-based vehicle to be used to evacuate one or more crew members in the event of an emergency. The subject was timely in that it coincided with the publication of a Request for Proposal (RFP) for such a design, referred to as an "Assured Crew Return Vehicle" (ACRV), by NASA Johnson Space Center. This document and the "Statement of work for Definition and Preliminary Design of the ACRV" formed the assignment to the design team. The team also had access to a series of preliminary supporting studies.

The goal thus is to design and configure a vehicle, permanently based at the Space Station, that can be boarded at fairly short notice, be separated from the Space Station and deorbited, bring the crew safely through the reentry environment, and land near one of a series of preselected landing sites. The selection of landing sites, together with a modest aerodynamic maneuvering capability during the reentry, allows for a safe return to a daytime landing near a base equipped with recovery facilities, all this within 24 hours from the decision to use the system.

The nominal mission considered for this design involves the return to earth of a critically injured Space Station crew member; during the flight he is to be accompanied by a Crew Medical Officer and the Pilot. Thus the ACRV has a nominal crew of three and virtually all landing sites are to be within reasonable distance of a Health Care Facility. Other scenarios considered are the evacuation of the entire Space Station Crew either in an emergency in case of a catastrophe on board the Space Station, or in a non-time critical manner in case of an expected long-time unavailability of a Shuttle.

Design trade-off studies were made which lead the team to the design described here.

The Project EGRESS team consists of 40 engineering senior and graduate students. In addition to Aerospace Engineering students, the Departments of Electrical and Mechanical Engineering are well represented. As is customary in this course, the students elected a Project Manager and Assistant Project Manager at the beginning of the semester and subsequently organized themselves in eight technical groups, one for each of the major subsystems of the design; the work of each group is directed by a Group Leader. The Managers direct and control the team activity and integrate the group inputs into a single, coherent design. The concept of a system approach to design was carried throughout the design process.

A Final Report Committee, with representatives from each group, was assigned the major task of integrating the team inputs into this document, to be published in May. An ad-hoc Committee was formed to create the scale model.

We gratefully acknowledge the three-year continuation Grant from the NASA/USRA University Advanced Design Program. The Grant provides funding for a graduate teaching assistant, for travel, for reproduction and distribution of the final report, for construction of the scale model, and for various other operational costs. Special recognition is due Ms. Sherri McGee, Program Technical Monitor, University Programs Branch, and Gordon Johnston, Program Manager, Space Technology University Programs, Office of Aeronautics, Exploration and Technology, both of NASA Headquarters, Washington, D.C.; Dr. John Alred, Program Manager, and Ms. Barbara Rumbaugh, Senior Project Administrator, of USRA, Houston, TX.

NASA Lewis Research Center, Cleveland, OH, gave support of key lecturers and other technical assistance; Dr. Karl Faymon and Ms. Lisa Kohout provided the usual guidance and maintained contact with the team during the year. We are thankful to them for their support and friendship.

Professor Harm Buning April, 1990

TEAM ORGANIZATION

For the 1989-1990 school year, the Aerospace Engineering 483 class concentrated on designing an ACRV (Assure Return Crew Vehicle) for Space Station *Freedom*. Forty seniors and graduate students at the University of Michigan worked on this design project which was named Project EGRESS or Earthbound Guaranteed ReEntry from the Space Station. The design team was led by Project Manager Jonathan Freidman and Assistant Project Manager Tracy Peters. The team was further divided into eight design groups, as shown in Fig 1. Each group was responsible for a certain part of the ACRV design or mission plan.

Spacecraft Configuration and Integration was responsible for consolidating the entire team's effort into a unified spacecraft package. The size, shape, framework and interior space allocation of the vehicle were determined by this group. Additionally, Spacecraft Configuration and Integration looked into berthing and docking procedures, airlocks, and possible materials for the ACRV.

Human Factors designed systems to provide a livable atmosphere for the ACRV crew during flight and to sustain an injured crew member.

The Propulsion group selected the appropriate propulsion systems for each of the four phases of Project EGRESS' mission to earth. These included: separation from the space station, attitude control in space,the deorbit burn, attitude control during atmospheric flight.

Power and Communications determined systems for the power generation, power distribution, communications, computer hardware, navigation, and avionics.

Space Operations planned the orbital operations of the mission of Project EGRESS to earth. The required orbital maneuvers were determined in order to safely land the EGRESS vehicle at a predetermined landing site.

Atmospheric Flight analyzed the flight of the EGRESS vehicle through the atmosphere. The three main areas that required attention were the following: trajectory analysis, heat transfer during reentry, and stability and control.

Landing and Recovery handled the splashdown and recovery of the crew and vehicle. Various areas were researched including: a deceleration system, an impact attenuation system, selection of appropriate landing sites, and recovery forces available at these sites.

Logistics and Support determined the following: interfaces between the ACRV and the Space Shuttle, maintenance and checkout procedures for the ACRV, the number of ACRVs produced, placement of the ACRVs on the station, and whether or not the ACRV can be reused after the mission.

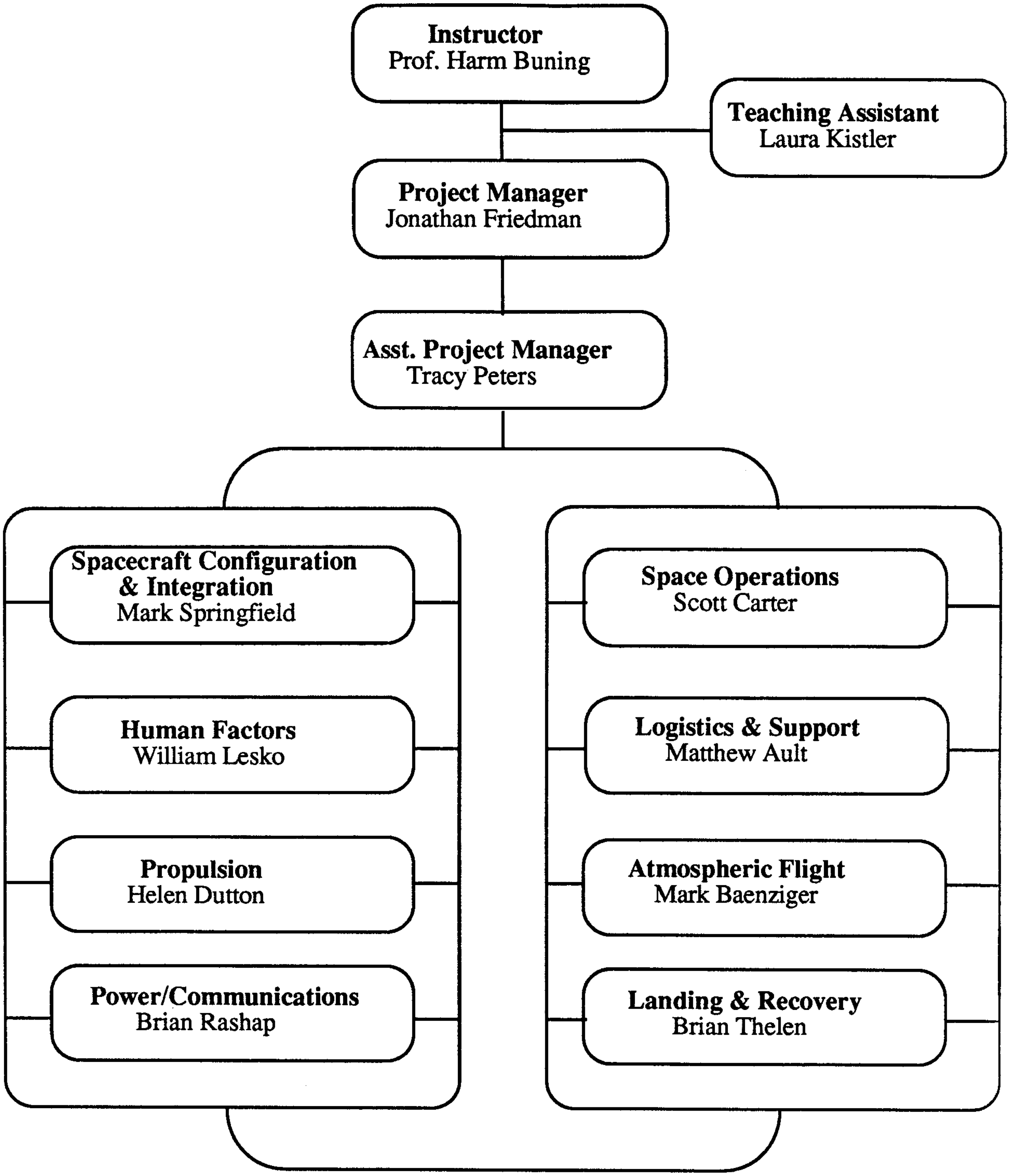


Figure 1 - Team Organization

TEAM ROSTER

Aerospace Engineering 483
Project EGRESS

Instructor: Prof. Harm Buning

Teaching Assistant: Laura Kistler

Project Manager: Jonathan Friedman

Assistant Project Manager: Tracy Peters

Propulsion
Jeremy W. Barnes
Paul M. Bombach
Gary R. Collins
Helen E. Dutton*
Lawrence B. Huston

Space Operations
Gregg M. Caggianelli
Scott C. Carter*
Michelle A. Churchill
Stephanie C. Morse

Power and Communications
Gregory M. Bartlett
Brian A. Rashap*
Ronald R. Springer

Human Factors
James E. Feiste
Jae H. Lee
William F. Lesko*
Krista A. O'Rourke
Christopher B. Pike

Atmospheric Flight
Mark M. Baenziger*
David M. Chen
Paul J. Kominsky
David E. Tew
Joseph D. Whittaker

Landing and Recovery
Diane E. Hageman
Mitch J. Leachman
Monica M. Simpson
Brian E. Thelen*

Logistics and Support
Matthew A. Ault*
Steven R. Mazure
Kristina J. Paluszny
Sue A. Prince

Configuration and Integration
Joseph W. Bielecki
Scott E. Dewicki
David H. Herman
David J. Karoski
Mark A. Springfield*
John F. Walker
Michal P. Warzecha

* denotes Group Leader

Ad Hoc Committee for the Final Report

Chairman: Paul J. Kominsky

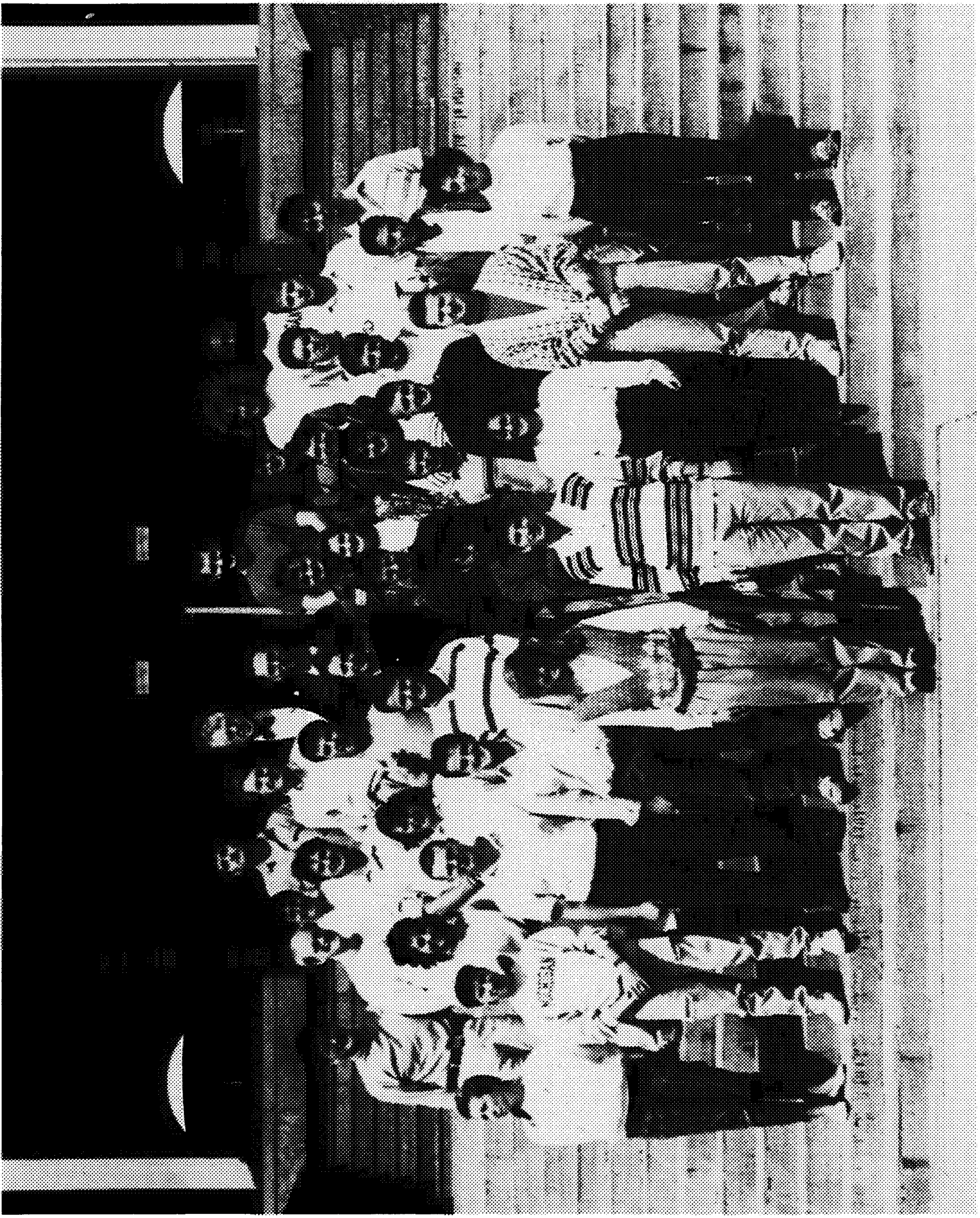
Jeremy W. Barnes
James E. Feiste
Diane E. Hageman
David E. Herman
Stephanie C. Morse
Kristina J. Paluszny
Ronald R. Springer
David E. Tew

Cover Design: Scott Dewicki

Ad Hoc Committee for the Model

Chairman: Jae H. Lee

Gregory M. Bartlett
Joseph W. Bielecki
Gregg M. Caggianelli
Michelle A. Churchill
David J. Karoski
John F. Walker



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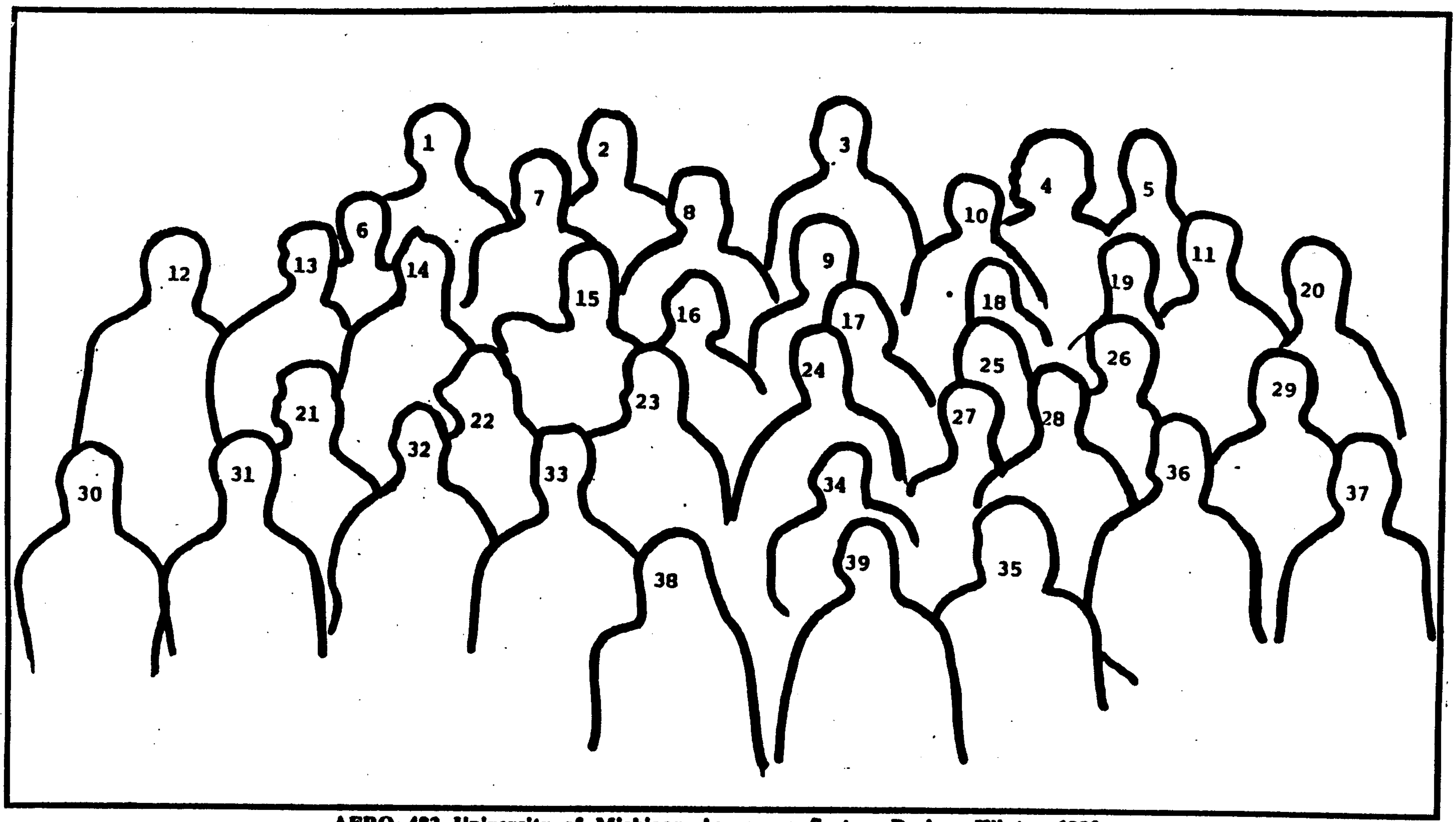

AERO 483 University of Michigan Aerospace System Design, Winter 1990

1. Joseph W. Bielecki
2. Prof. Harm Buning
3. David H. Herman
4. Laura Kistler
5. Mark A. Springfield
6. Brian A. Rashap
7. Gregory M. Bartlett
8. Ronald R. Springer
9. Michal P. Warzecha
10. David J. Karoski
11. John F. Walker
12. Jae H. Lee
13. James E. Feiste
14. William F. Lesko
15. Christopher B. Pike
16. Krista A. O'Rourke
17. Monica M. Simpson
18. Scott E. Dewicki
19. Brian E. Thelen
20. Mitch J. Leachman
21. Michelle A. Churchill
22. Stephanie C. Morse
23. Scott C. Carter
24. David E. Tew
25. Diane E. Hageman
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33. Lawrence B. Huston
34. Matthew A. Ault
35. Kristina J. Paluszny
36. Stephen R. Mazure
37. Sue A. Prince
38. Tracy Peters
39. Jonathan Friedman

Chapter 1

Introduction

1.0 Background

1.1 Project EGRESS

1.0 Background

Humanity has always looked to the sky in wonder and awe, and longed to conquer the unknown world above. The desire to go beyond the confines of earth has produced an active manned space program, which the United States entered on May 5, 1961, with the launch of Alan Shepard aboard Freedom 7. America has continued to lead the way in the exploration of space with the Apollo program, which brought man to the surface of the moon, and the National Space Transportation System (the Space Shuttle), which provides America with a reusable means to transport man and materials into Low Earth Orbit (LEO). The next step for the United States in the exploration of space is the construction of the permanently manned Space Station *Freedom*, which will reside in LEO.

Space Station *Freedom* will be an international effort spearheaded by the United States. In addition to the American habitation and experimental modules, the station will include modules from the European Space Agency and the Japanese Space Agency. As with all of America's previous ventures into space, the National Aeronautics and Space Administration (NASA) will need to assure the safe return of *Freedom's* crew from space.

NASA has a long standing dedication to the concept of Assured Crew Return Capability (ACRC). The first trajectories of the Mercury and Gemini programs assured the return of the capsule into the atmosphere. The dedication to ACRC continued during the Apollo missions which flew in a "free return" trajectory. This trajectory allowed the capsule to circle the Moon and return to earth automatically in the event of an emergency. Furthermore, the Lunar Module had the capacity to serve as an emergency vehicle. On November 13, 1970, the explosion of an oxygen tank on board the Apollo 13 service module mortally damaged the tanks and systems inside the vehicle, and forced the crew to use the lunar module for the return to earth.

NASA continued to assure the return of any space-based crew during the Skylab missions. Crew return was assured by the Apollo Capsule, which transported the crew to Skylab and remained docked at the orbiting lab throughout the mission. In addition, NASA configured an Apollo capsule to carry five crew members (the normal capacity of an Apollo Capsule was three crew members) so that two crew members could travel to Skylab and return to earth with the Skylab crew.

However, unlike the Apollo capsule on Skylab, the crew transportation vehicle for Space Station *Freedom* (the Space Shuttle) will not remain docked at the station during the crew work cycle (approximately 90 days). NASA originally planned for the Space Shuttle to assure the return of *Freedom's* crew. However, the tragic explosion of the Space Shuttle *Challenger* over the Atlantic Ocean on January 28, 1986, forced NASA to re-evaluate the means of assuring the return of any or all of *Freedom's* crew. In order to assure the safe return to earth of the Space Station crew, NASA proposed and issued an Request For Proposal (RFP) for an Assured Crew Return Vehicle (ACRV).

The Assured Crew Return Vehicle will serve as an alternative return vehicle from the Space Station in the event the Shuttle is not available or rapid return is required. The ACRV will be permanently docked at Space Station *Freedom* and will serve *Freedom* in three primary reference missions:

1. The return of the entire Space Station crew (eight crew members) in the event that the National Space Transportation System (NSTS) is unavailable.

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2. The return of the entire Space Station crew in the event rapid evacuation from Space Station *Freedom* is required.

3. The return of an injured or ill crew member in the event that rapid return is required.

1.1 Project EGRESS

Project EGRESS (Earthbound Guaranteed ReEntry from the Space Station) is a preliminary conceptual design of an Assured Crew Return Vehicle completed by the University of Michigan Aerospace System Design team. EGRESS, which is defined as "the act of going out," will guarantee the safe departure for any or all of the crew of Space Station *Freedom.*

The EGRESS design team used the Request For Proposal and the NASA Phase A Studies as well as the resources available through both industry and the University of Michigan to complete the design of the EGRESS vehicle, which is presented in this report. The goal of the team was to design a vehicle which would be simple, reliable, and would minimize impact on existing programs. Simplicity and reliability are always goals in the design of a space vehicle, but even more so for an emergency vehicle. In order to reduce impact on existing programs the design of the vehicle would need to minimize both crew training and maintenance requirements and maximize its independence for the Space Station.

Keeping in mind the old adage "what goes up must come down," the EGRESS design team needed to determine how the vehicle would return to earth. The primary concerns were the lift to drag ratio (L/D) and the vehicle's landing mode. Initially, a high lift to drag, such as the Shuttle or an aeroplane, was researched by the team. A high lift to drag vehicle encounters low forces during reentry, and is very maneuverable. However, this configuration would require wings to generate lift. The Request For Proposal requires that the ACRV fit into the Space Shuttle cargo bay, which has a diameter of 15 ft. This stipulation would require a winged ACRV to have retractable wings, which are both mechanically and structurally complicated. In addition, such a vehicle configuration would require complicated control surfaces to control yaw, pitch, and roll maneuvers. Finally, a high L/D would require extensive initial training and continuous refresher training for the pilots of the vehicle.

On the other hand, a low L/D vehicle is simpler to operate than a high L/D vehicle, and requires less training time. Furthermore, a low L/D vehicle uses flight proven hardware, since the Mercury, Gemini, and Apollo vehicles were all low L/D vehicles. However, low L/D vehicles encounter high reentry forces and have limited, if any, maneuverability. Thus, the design team chose a medium L/D for the EGRESS vehicle. This configuration will encounter mild reentry forces and have modest maneuverability, while still being simple to operate.

After the decision to design a medium L/D vehicle was made, the team needed to determine the landing mode of the EGRESS vehicle. There are two possible places for a vehicle to land; on the land or in the water. A land landing vehicle would allow for landing site selection in close proximity to a Health Care Facility for rapid transportation of an injured or ill crew member to the facility. In addition, a land landing vehicle would be reusable since it would not suffer the corrosive effects of salt water. However, since the vehicle was to have a medium L/D it would not be capable of gliding to a landing site as the Space Shuttle does. Instead the vehicle would need to deploy parachutes to slow its decent, and then use an impact system (such as retro rockets or airbags) to minimize its impact with the ground. This configuration would still encounter large impact loads at touchdown. Since the EGRESS vehicle must have the capability to return an injured or ill crew member, it is desirable to minimize the impact loads experienced by the occupants of the vehicle. Furthermore, a land landing vehicle would require extensive training in order to complete the precise maneuvers required for an accurate land landing.

The impact loads encountered during a water landing are less than those of a land landing, which makes the configuration more desirable for the return of an injured or ill crew member. Furthermore, a water landing does not require the accuracy of a land landing, and will not require the extensive training for landing procedures. Thus the EGRESS team chose to design a medium lift to drag vehicle which will land in the water.

Chapter 2

Spacecraft Configuration and Integration

2.0 Summary

2.1 Vehicle Analysis

2.2 Airlocks

2.3 Antenna Placement

2.4 Shuttle Bay Interface

2.5 Rejected Ideas

2.0 Summary

The Spacecraft Configuration and Integration group was responsible for consolidating the activities of the entire Project EGRESS team into a unified spacecraft package. This group compiled a set of minimum mission requirements from the other groups and produced a primary design of the vehicle. In collaboration with the other groups, the vehicle's size, shape and functions were finalized. Using this information, the vehicle's dynamic characteristics were found. Materials selection and framework design were completed, as well as investigations into vehicle berthing on the Space Station, airlocks, impact diminishment techniques, vehicle placement in the Space Shuttle payload bay, and antenna placement.

The final configuration developed from an amalgamation of existing and experimental reentry vehicles. The final configuration of the EGRESS vehicle is squat with a rounded, triangular body that is 13.5 feet long, 6 feet high and 9 feet wide, that weighs 8018.83 lbs, and that has an exterior volume of 355 cubic feet and an interior volume of 250 cubic feet. It has an airlock and a deorbit propulsion package which are both detachable.

The airlock is a short cylinder with length 6.25 feet and diameter 8.00 feet, an inner volume of 332 cubic feet, a total mass of 3282 lb, and the ability to contain and to sustain two spacesuited astronauts. Meteoroid impact causes habitable airlock lifetime to diminish; therefore, the airlock is double-hulled.

The propulsion package consists of three rocket engines and a box framework. The framework houses two sets of fuel and two sets of oxidizer in four spherical tanks, two sets of helium propellant-feed tanks, also in spherical tanks, and four reaction control system thruster clusters. The box framework is 7.8 feet tall, 7.4 feet wide, 3.4 feet thick, and weighs 108 lbs. The total weight of the propulsion package is 2275 lbs.

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2.1 Vehicle Analysis

The primary considerations that influenced the design of EGRESS were: 1) that it be possible for ground crews to recover the vehicle within one hour of splashdown; 2) that it be possible to get the crew out of the vehicle and to a health care facility within two hours of splashdown; and 3) that this be possible without a ground crew on standby and without dependence upon ships or aircraft dedicated to recovering the vehicle. In addition, the vehicle must be cost effective, reliable and easy to operate.

2.1.1 Performance

The basic operational performance capabilities of EGRESS are as follows:

CREW SIZE CAPABILITY	3-5 persons
VEHICLE POWER CAPABILITY	3.4 Kilowatts(maximum) 3.0 Kilowatts(average)
COMM TRANSMISSION POWER	350 Watts
STATION DEBARKING	3 ft/sec
ATTITUDE CONTROL RATES TIMES TO ACHIEVE MAXIMUM ANGULAR RATE OF 5 REV/SEC	9.99 seconds in roll 10.85 seconds in yaw 8.39 seconds in pitch-up 7.90 seconds in pitch-down
VEHICLE REENTRY ΔV	330 ft/sec
PROPULSION UNIT REORBIT	800 ft/sec
TILE HEAT DISSIPATION	55 BTU/(ft^2sec)
LIFT/DRAG	0.8
CROSSRANGE	500 N.Mi.
SPLASHDOWN SPEED	13 MPH

2.1.2 Shape, Area and Volume

Due to the rescue nature of the EGRESS project, a design objective was initiated, under the considerations of cost effectiveness, reliability and simplicity. To adhere to this objective, a vehicle based closely upon the Apollo reentry capsule was envisioned. Its primary landing site would be in the ocean, with a secondary landing contingency on land. However, this concept jeopardized basic minimum mission requirements. Therefore, a wider vision was necessary: consideration was given to high lift-to-drag vehicles. Such a vehicle would be able to reduce reentry accelerations, decrease vehicle heating, increase the availability of landing sites by being able to deviate from its ground track, and by doing so increase the response, rescue and care times for the vehicle crew.

Although the advantages of such a vehicle are great, this concept conflicted with the basis guidelines. This vehicle configuration would be very cost intensive, would be very complex and thus more likely to have a catastrophic component failure. Furthermore, it would require extensive crew training for piloting the vehicle. Such a vehicle would require wings with an aspect ratio and area that would not allow fully assembled placement within the Space Shuttle payload bay.

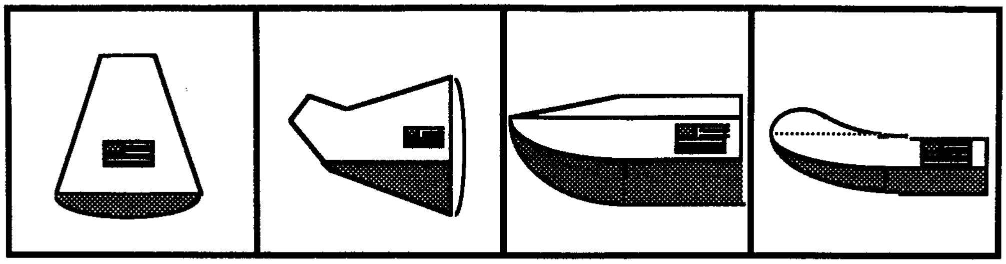

APOLLO BICONIC BOAT SLED

Figure 2.1 - The progression of EGRESS's shape

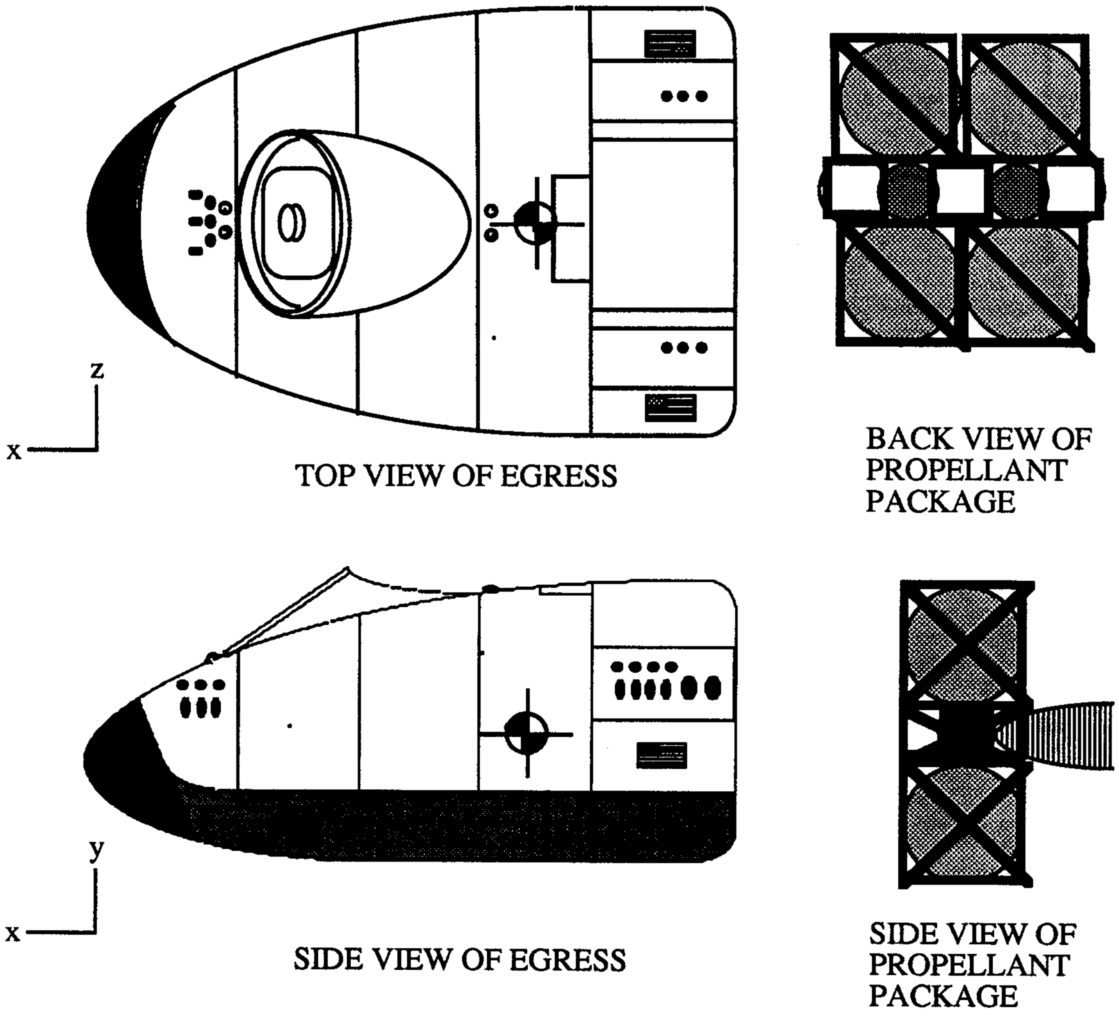


Figure 2.2 - The EGRESS vehicle with propulsion package

A compromise between the two vehicles was needed. The vehicle needed to feature medium-lift capabilities with a simple and reliable design. This compromise was found with use of a bent-nose biconic reentry vehicle. The Apollo module was a conic vehicle. A biconic would be formed if the nose cone of the Apollo were stretched into a longer cone, with the rest of the vehicle unchanged, and then bent at an angle to the rest of the vehicle. EGRESS was designed to be a medium-lift vehicle thus capable of a cross-range travel much greater than that of an Apollo vehicle, which was a low lift-to-drag vehicle. In addition, EGRESS will possess better thermal emissivity characteristics and lower reentry accelerations than Apollo.

To achieve the desired aerodynamic characteristics, the vehicle required certain shape constraints and a minimum wetted surface area. One of the shape constraints imposed by atmospheric reentry was that the vehicle's hatch be protected from reentry burn-up by placing it behind the vehicle's nose from an angle of impingement of 60 degrees. The shape of the vehicle was designed under all of these requirements, as well as to fulfill the mission guidelines. EGRESS was first transformed into a flattened bent biconic and then slowly transformed into what was referred to as a "raft" shaped vehicle. The progression of the EGRESS vehicle is seen in Fig. 2.1, with the final shape displayed in Figs. 2.2 and 2.3.

After the minimum wetted area was determined, the volume of the vehicle was found from the desired shape. The wetted area of the vehicle was calculated by defining the ship shape as a parabola and then integrating to obtain an area of 85 sq.ft. The volume of the vehicle was derived by describing the ship as a series of rings and of boxes, and summing to obtain a value of 355 cu.ft.

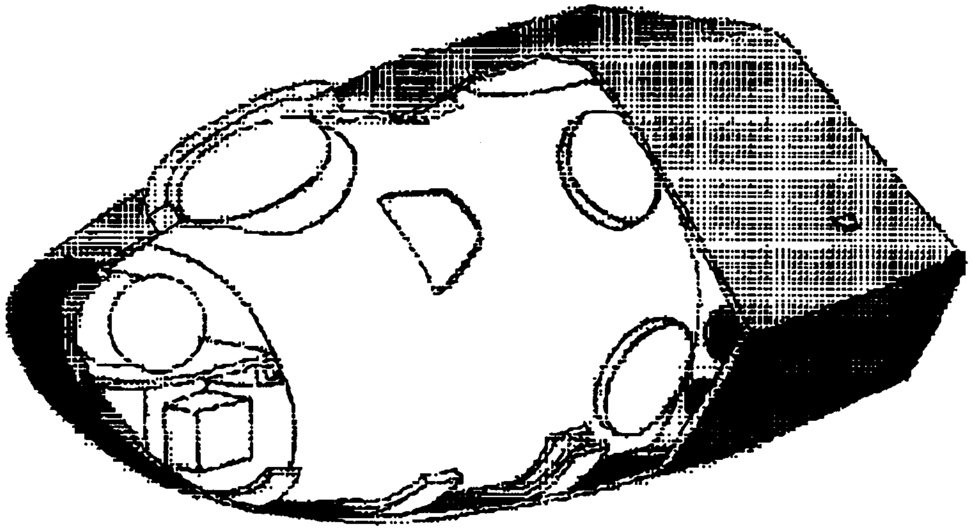


Figure 2.3 - The final shape of the EGRESS vehicle with cut-away view

2.1.3 Weight and Balance

The equipment and supplies were located within the vehicle so that the stability and the center of mass of the vehicle met the stability requirements at all phases of the mission. For the first phase of the mission, the vehicle acted as an orbiter and the center of mass was located along the centerline of the body at a position 9.45 feet from the nose and 2.10 feet from the bottom. During the second phase of the mission, the vehicle was an aerodynamic reentry craft with the center of mass 8.10 feet from the nose and 2.70 feet from the bottom. At phase three, the craft became a parachutist with the center of mass 6.75 feet from the nose and 2.35 feet from the bottom. For the final phase, the vehicle became a lifeboat with the center of mass 6.75 feet from the nose and 2.35 feet from the bottom, as in phase three.

2.1.4 Mass Itemization

This is a vehicle component mass list with all units in pounds mass, Lb_m.

TOTAL MASS OF VEHICLE		10293.83
SPACECRAFT STRUCTURE		2988.00
Lower outer skin	248.00	
upper outer skin	145.00	
Internal pressure cell	712.00	
Frames and stringers	883.00	
Hatch assembly	200.00	
Heat shield	1000.00	
PROPULSION SYSTEM		3815.00
Deorbit engines (3)	75.00	
Deorbit fuel	1100.00	
Tanks and Structure	1100.00	
Attitude control engines (42)	50.40	
Attitude control fuel	200.00	
Attitude control tanks	100.00	
Space Station Separation Equipment	100.00	
MEDICAL SYSTEM		980.73
Medical equipment	91.60	
Life support equipment	484.13	
General supplies	405.00	
POWER/COMMUNICATION		1712.00
Batteries (4)	713.00	
Computers (3)	265.00	
Navigation	114.00	
Communications	120.00	
Airlock batteries	500.00	
LANDING AND RECOVERY		798.10
Parachutes	735.10	
Mortars	33.00	
Gauges and sensors	30.00	

2.1.5 Moments of Inertia

Using a reference frame where the x-axis lies along the length of the vehicle, the y-axis lies along the height of the vehicle and the z-axis lies along the width of the vehicle, with the origins of the axes centered on the center of mass for the vehicle, the moments of inertia for EGRESS are as follows:

$I_x = 75{,}000\ lb_m ft^2$ $\qquad I_y = 150{,}000\ lb_m ft^2$ $\qquad I_z = 100{,}000\ lb_m ft^2$

2.1.6 Materials and Framework

EGRESS contains two hulls: one internal for the crew compartment and one external for reentry and atmospheric loading. The design came from the research of proven structures used in recent spacecraft and in conventional aircraft. Skins of both hulls are reinforced by stringers, bulkheads and a frame using conventional aluminum alloys that are cost effective, reliable and easily attainable. Two basic structural approaches were reviewed for designing the structure: trusses and skins. The truss concept was terminated because of the bulkiness, the need to support a skin-like pressurized vessel, and the atmospheric reentry forces challenging structural integrity. A reinforced skin-like structure has proven to be reliable through aircraft design and to be space worthy by the Space Shuttle. The Space Shuttle utilizes this concept of aircraft design and similar elements of the configuration were incorporated into Apollo's structure. The skin thickness was estimated through calculations using spherical and cylindrical pressure vessel formulae, taking into account pressure and other forces on the shell due to humans and equipment. The vehicle's framework will be constructed from aluminum 2024, 2124 and 2219. The external hull will consist of a shell with five annular I-beam supporting spars as seen in Fig 2.4. The I-beams were positioned so that they would support the vehicle itself, plus the forces due to the astronauts in their seats. Also as shown in Fig. 2.4, the seats are bolted through the floor of the crew compartment and into the support spar.

Aluminum 2024-T81 was chosen for the external hull skin. Aluminum 2124 was chosen for the spars and the stringers for the external hull and they will weigh a total of about 300 lbs. The stringers are hat shaped and are positioned in increments of three inches along the external hull, much like the Space Shuttle. The structure consisting of a thin shell supported by I-beams was chosen because it provides the necessary structural support while maintaining a low total weight of 883 lb.

The internal hull (ie. the crew compartment) will be made of aluminum 2219-T851 at a thickness of .15 inch. Aluminum at this thickness withstands the requirement of a crew compartment pressure of 14.7 psi and provides extra protection from the low-Earth orbit environment. The structure of the crew compartment weighs 805 lb. The hatch will be made out of aluminum 2219 at a thickness of 1.25 inches so that the integrity of the crew compartment will not be compromised by hatch structural failure. The hatch weighs 127 lb. The structure that will contain the jettisonable propulsion package will be a framework made from aluminum 2124 tubing with an outer diameter of 1 inch and an inner diameter of .8 inch so that it can withstand the mission's maximum acceleration load of 3 g's which will occur at lift-off.

2.2 Airlocks

As decided by the Project EGRESS design team, two EGRESS's will be deployed to Space Station *Freedom.* As stipulated in the Request For Proposal, if multiple vehicles are deployed, all vehicles must depart along the same flight path. An additional constraint is the Space Station *Freedom* berthing ring size. All Space Station nodes berthing rings are 7 feet in diameter. The EGRESS has been designed with a 3 foot hatch and 4 foot diameter berthing ring, (the maximum possible for the EGRESS vehicle size). Hence, a berthing adapter must be used to dock the EGRESS to the Space Station. An airlock was used as the berthing adapter to solve this problem and to facilitate other needs.

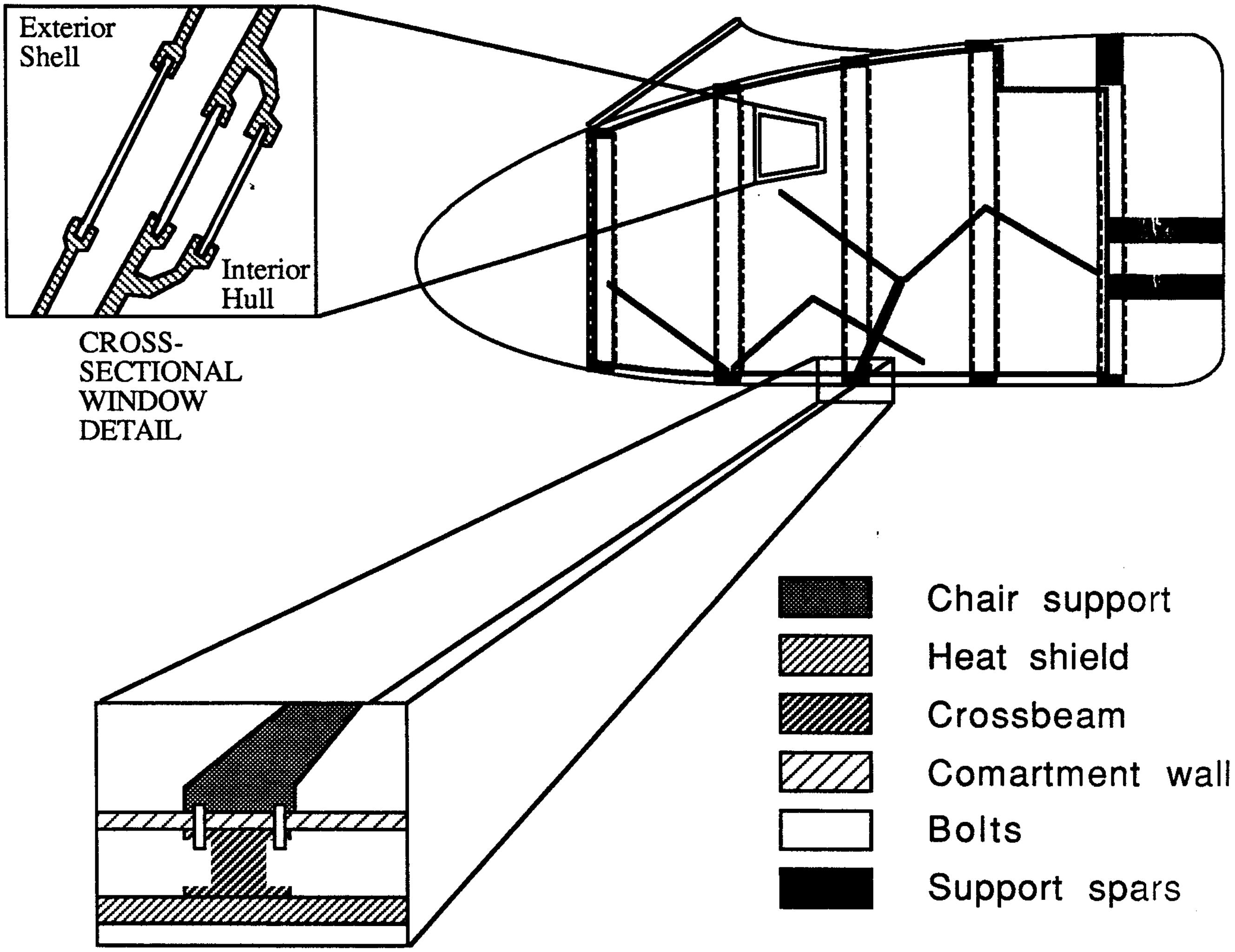


Figure 2.4 - A view of the astronaut seats with detailed window and floor attachment

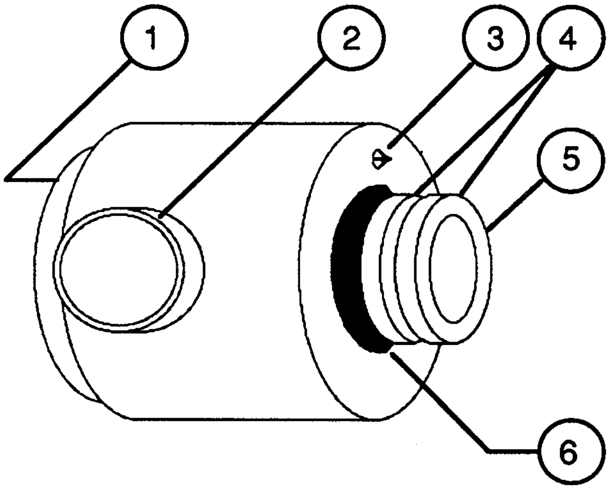
2.2.1 Airlock Necessity

During normal Space Station operations, astronauts will be conducting regular Extra Vehicular Activity (EVA) missions in pairs. The EVA astronauts can only enter the Space Station through designated EVA airlocks at only a few nodes. If a Space Station catastrophic failure terminates either the Space Station power system or any nodes between the astronauts' entrance airlock and the EGRESS, the EVA astronauts will not be able to enter the EGRESS. In order to insure that EVA astronauts can enter the EGRESS during a station integrity failure, an EGRESS must have its own airlock.

2.2.2 EVA Rescue Options

Under current NASA Space Station operation procedures, provisions have been made so that EVA rescue can be safely conducted without flying the entire EGRESS and airlock to the EVA astronaut, even under catastrophic failure of all Space Station systems. If a catastrophic failure occurs on the Space Station requiring immediate use of the EGRESS, the crew members conducting an EVA will be able to immediately return to the EGRESS. Since all astronauts will be tethered to the Space Station at all times during EVA, it is therefore highly unlikely that an astronaut will become separated from the Space Station.

NASA will install a Crew-Equipment Translation Aid (CETA) across the Space Station truss system. The CETA is a very simple and reliable transportation cart that travels along a rail built into the Space Station main truss, and is designed for normal EVA work and for rapid return of an EVA astronauts in the event of astronaut or Space Station emergency. The entire CETA system is powered by the EVA astronauts and works independently of the Space Station power system. The CETA system is much safer to use than flying the entire EGRESS and EGRESS airlock to the EVA astronauts. An accidental impact of the EGRESS with the Space Station could severely damage the EGRESS, jeopardizing the entire EGRESS crew. Also, to maneuver close to the EVA astronauts, the EGRESS would require usage of its RCS thrusters, which use corrosive Hydrazine as a fuel, posing a hazard for the EVA astronauts.



① Space Station Berthing Ring
② EVA Entrance
③ ACRV Redocking Target
④ Retractable Sleeve
⑤ ACRV Berthing Ring
⑥ Kevlar Skirt

Figure 2.5 - Exterior view of EGRESS's airlock

Since that the airlock is only used when the EGRESS is docked to the airlock, having the airlock built directly into the EGRESS causes a needless increase in vehicle mass and cost. Leaving the airlock attached to the Space Station solves many problems: the EGRESS departs at a considerably smaller mass, a replacement vehicle can be docked to the airlock, reducing NSTS launch costs, and EVA rescue can be safely and effectively conducted without risking the entire EGRESS crew. Also, considering that a berthing adapter ring is required for the EGRESS to dock with the Space Station, designing the berthing ring to be an airlock requires little additional cost when compared to total vehicle design costs.

2.2.3 Final Airlock Configuration and EGRESS Departure

The final EGRESS airlock meets all of the criteria discussed earlier and is shown in Fig. 2.5. The system consists of a cylindrical airlock with a retractable docking sleeve. The retracting sleeve allows both EGRESS vehicles to depart along the same flight path and avoids the problem of having a different geometry for each nodal airlock. All Space Station nodes, except for the Earth facing nodes, can use the same basic airlock design with the retracting sleeve configuration and preserve all outlined criteria.

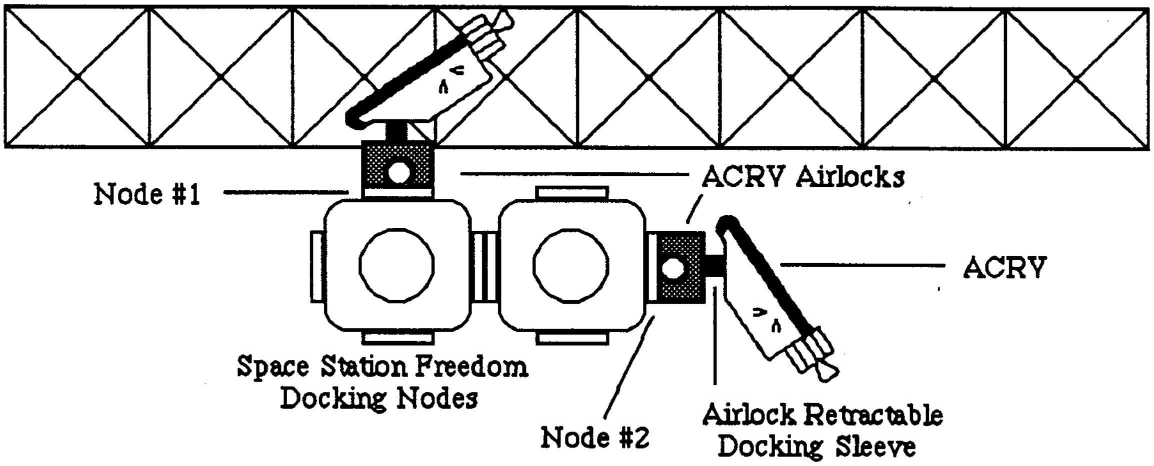


Figure 2.6 - EGRESS configuration using retractable sleeve airlock for node #1 and node #2

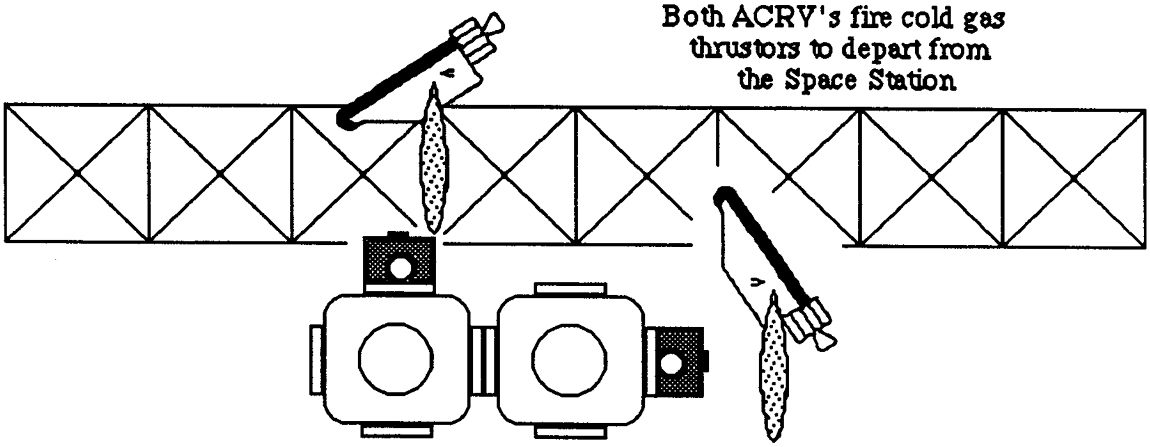


Figure 2.7 - The sleeves retract and the EGRESS departs

The EGRESS departure concept is simple, and the departure procedure is virtually identical for all involved nodes as seen in Fig. 2.6 and 2.7. First, the sleeve retracts, imparting no forces or moments onto the EGRESS. The EGRESS vehicle is simply floating with the Space Station and has zero velocity with respect to the Space Station. Then, depending on which node the EGRESS is docked, the vehicle fires, opposite to the direction of departure, one of two sets of cold gas thrusters.

One important difference between departures from node #1 and node #2 is that perpendicular sets of cold gas thrusters are used on the EGRESS for each respective node. This is required because the vehicle is oriented in a different attitude for node #1 and node #2.

A very important aspect of this design is failure modes. Sleeve failure is designed to be passive. If retractions fails to occur, the EGRESS is not placed in a dynamically dangerous position. Contingency planning calls for using the EGRESS RCS jets to depart from the Space Station. Though this would cause plume impingement and possible Space Station environment contamination, it must be weighed against the safety of the EGRESS crew.

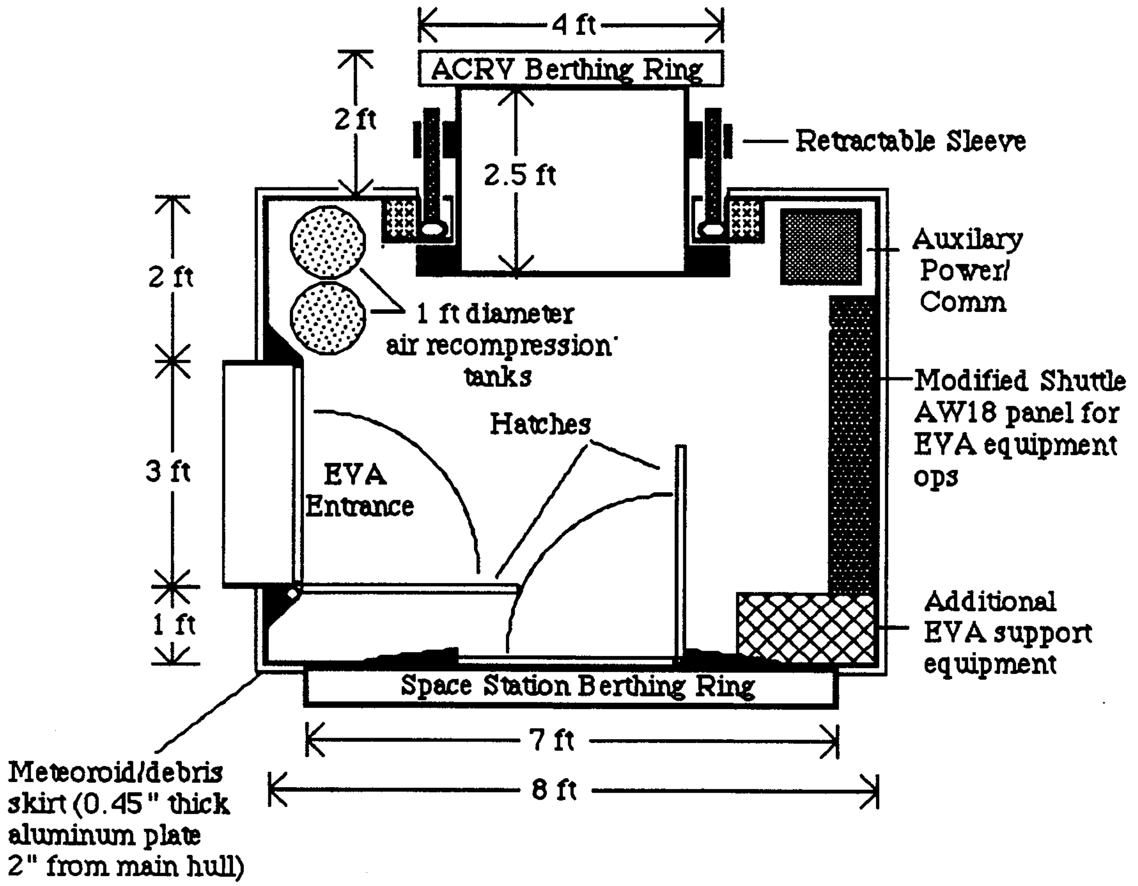


Figure 2.8 - Airlock side internal view

2.2.4 Other Configuration Considerations

As outlined previously, in order to give the vehicle an impulse away from the Space Station, two sets of cold gas thrusters are built into the EGRESS. Springs were proposed to push the EGRESS away from the Space Station but were later dropped due to the fact that the spring force could not be designed to pass through the EGRESS center of mass. Airlock geometry was considered as a possible solution to the flight path departure requirement. This would require that node #1 and node #2 have different airlock designs. This meant that the same airlock design could not be used on nodes lying in different planes, which was undesirable due to complexity and excessive cost.

2.2.5 Configuration

The internal configuration, as seen in Fig. 2.8 and 2.9, is limited by several important design factors; the ability of the airlock to hold the pressure load (including the cyclic recompression and decompression of entering EVA astronauts), to allow for EGRESS redock incase of EGRESS return to Space Station, and to prevent micrometeoroids and space debris from piercing the airlock walls. The minimal hull thickness required for debris shielding is 0.3 in. This thickness is well above the minimal wall thickness to safely maintain the airlock pressure load (0.07 in.); however, the design can not rely solely on the hull for maintaining the pressure load. To maintain a pressure load, two complete structures will be used: one will be the inner pressure vessel and the second will be the network of support frames. To increase the protection against debris damage, the design will use a bumper outside of the pressurized hull with a thickness of .45 inches and a 2 inch spacing between the bumper and the pressurized hull.

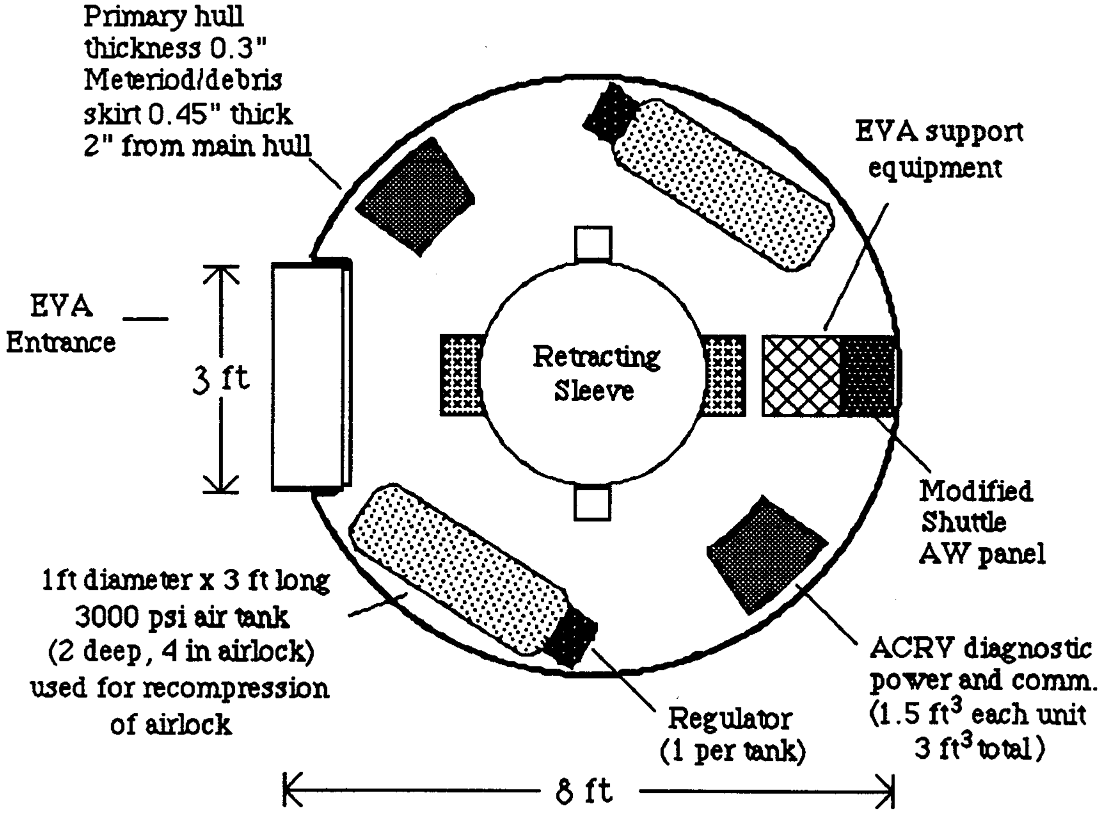


Figure 2.9 - Airlock top internal view

Components included in the airlock are: rechargeable diagnostic batteries, pressurized volume repression air tank for entering EVA astronauts, berthing mechanisms, and sleeve retraction machinery. For the entering EVA astronauts a complete EVA support system is included. A modified Space Shuttle AW 18 panel and breathing air tank is also installed for the entering EVA astronaut. This is required because the standard soft shuttle spacesuits used on the Space Station can not supply the astronaut with breathing air if the spacesuit is not in a vacuum. Therefore, a modified shuttle EVA breathing system is installed. The airlock has the capacity to hold two EVA astronauts, to provide life support, and to recompress the airlock to allow the astronauts to enter the EGRESS. Upon entering the airlock, the EVA astronauts would connect themselves to the AW 18 panel for breathing air and recompress the airlock with one of the airlocks air tanks. Each tank is capable of recompressing the airlock to a 14.7 psi atmosphere and contains its own regulator. Four tanks are installed in the airlock with three designated for airlock recompression. The forth tank is reserved for EVA astronaut breathing while the airlock is recompressing and the astronaut is connected to the AW 18 panel. The AW 18 panel and support equipment power is drawn from the airlock power system.

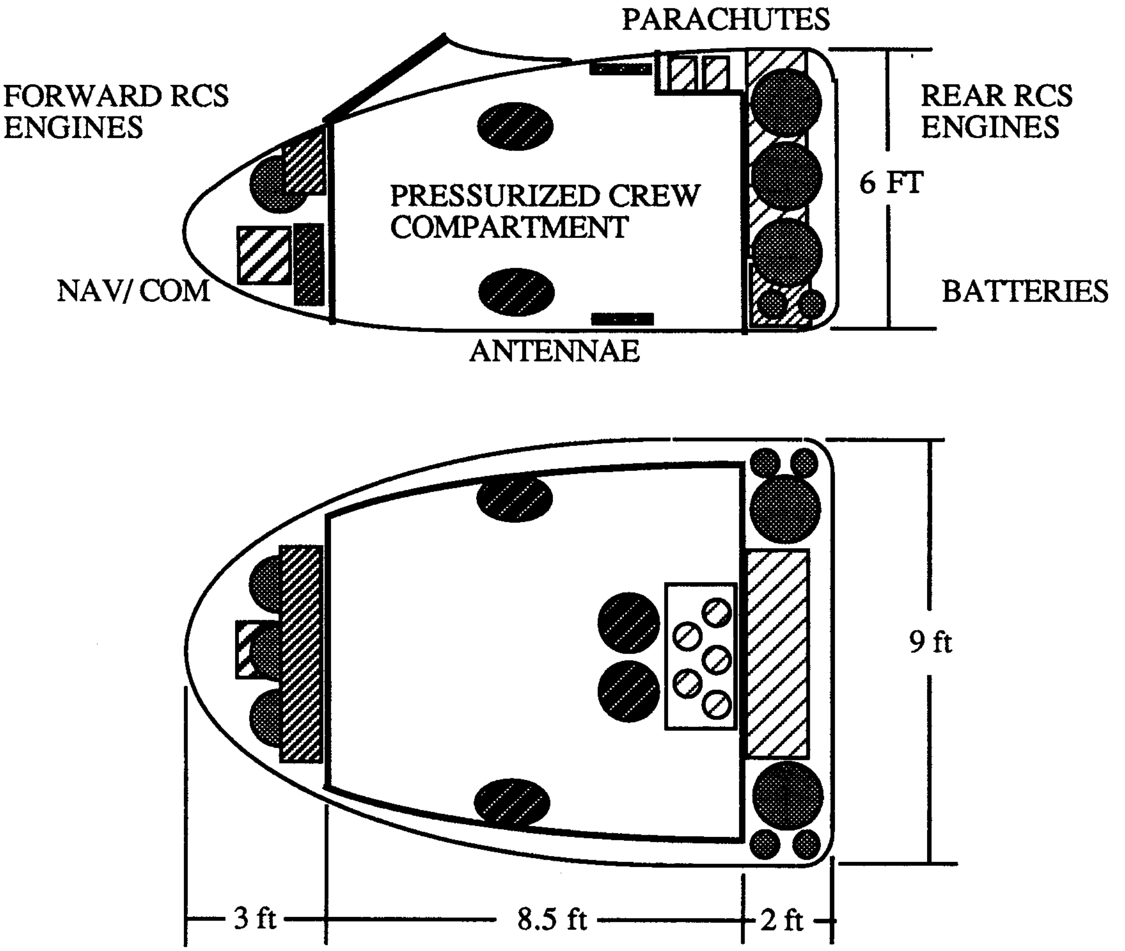


Figure 2.10 - Component placement in EGRESS including antennae

2.2.6 Reberthing of EGRESS

In considering contingency situation of EGRESS operations, the possibility of redocking with the Space Station must be considered. An inflight failure of a critical EGRESS subsystem, such as the deorbit burn engines, requires that the EGRESS immediately return to the Space Station. The airlock berthing system has been designed to insure that the EGRESS is capable of redocking under virtually every situation.

Under normal operations, the airlock berthing sleeve is commanded to extract outward. However, if the sleeve is stuck in the retracted position, the EGRESS is still capable of full reberthing capability. There is sufficient clearance between the vehicle and the airlock if the sleeve is retracted to insure safe redocking. Furthermore, the berthing mechanism between the EGRESS and the sleeve will passively capture the EGRESS vehicle. For guidance during reberthing, the EGRESS pilot uses a passive birthing target guide that aligns itself with a display on the EGRESS exterior window. This is a concept similar to the Apollo design for docking Command Module with the Lunar Module.

2.3 Antenna Placement

There will be three different types of antennas mounted on the exterior of the EGRESS. These include four S-band, two L-band and two VHF antennas. The S-band antennas will be used to provide contact with the Tracking and Data Relay Satellite System (TDRSS) and to provide a direct link to the ground. The L-band antennas will be used to maintain contact with the Global Positioning System (GPS) and for navigational purposes. The VHF antennas will be used to establish contact with ground forces during atmospheric flight and after splashdown.

The placement of these antennas was determined by their performance requirements and the availability of space on the spacecraft. For maximum performance, the antennas must be placed on the spacecraft to be able to receive and transmit information in all directions. Due to this performance requirement, the placement of the antennas was limited mainly by the space taken by the forward hatch and the parachute storage area. Thus, the placement of the L-band and VHF antennas on the top and bottom of the spacecraft and the S-band antennas around the circumference of the spacecraft at 90 degree intervals was decided upon as seen in Fig. 2.10. These antennas are approximately one foot in diameter and weigh a total of 50 lbs.

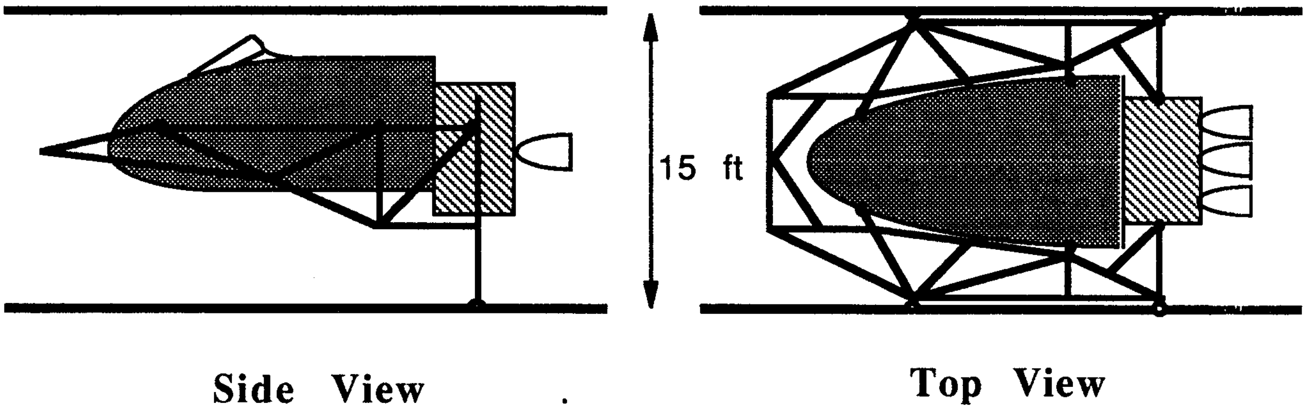


Figure 2.11 - The placement of the EGRESS in the shuttle payload bay

2.4 Shuttle Bay Interface

The spacecraft will be securely attached in the Space Shuttle payload bay by means of a frame, as seen in Fig. 2.11. This frame will attach to the payload bay by means of a longeron and keel attachments using a seven-point attachment scheme due to the weight of EGRESS.

The attachment points will be connected to hard points on EGRESS's frame that will be indented handholds, as seen in Fig. 2.12, so that EGRESS may be freely removed from the bay with the Space Shuttle's or with the Space Station's Remote Manipulator System (RMS). The frame thus serves the purpose of transferring the loads on EGRESS directly to the frame of the Space Shuttle. The means of attachment of the spacecraft will consist of two inch diameter handles located in the supporting frame. In order for the frame not to interfere with the shell of the vehicle, 3.5 inch diameter holes will be made in the shell to provide access to EGRESS's frame. Members of the frame between the vehicle and the shuttle bay will be attached to these handles by means of 1.25 inch diameter clasps. They will be retracted when the vehicle needs to be removed from the shuttle's bay. A three inch diameter by four inch long bolt will be placed on the vehicle as in seen in the attachments figure.

A frame was chosen over using an existing palette to maintain simplicity. A palette would still have required designing a frame to hold EGRESS in the palette and it would have required further research into available palettes. In either case, the space occupied by the frame or palette could not be used for other cargo on the Space Shuttle once EGRESS is removed. The frame will be made from aluminum (4.4% copper, 2014-T6) with a diameter of approximately 2 inches. The keel and longeron trunions will be made from chrome-plated steel with diameters of 3 and 3.25 inches, respectively. The total frame weight is 1050 lb_m. The airlock for EGRESS cannot be mounted to the vehicle while the vehicle is in the shuttle bay; therefore, it too will be mounted within the shuttle bay in a separate framework assembly. Like EGRESS, the airlock will be mounted by means of a seven-point attachment scheme using longerons and keels as seen in Fig. 2.13.

The means of attachment of the frame to the airlock will consist of two inch diameter holes located in the airlock's supporting frame. In order for the frame not to interfere with the shell of the airlock, 2.5 inch diameter holes will be made in the shell to provide access to the airlock's frame. Members of the frame between the airlock and the bay will be inserted in these holes to support the airlock. They will be retracted when the airlock needs to be removed from the shuttle bay. A three inch diameter by four inch long bolt will be placed on the airlock as seen in the attachments figure. This bolt will enable either the Space Shuttle's or the Space Station's RMS to remove the airlock from the bay once the frame has retracted. This framework will be of the same materials and dimensions as for the EGRESS, but will weight only 460 lb_m.

2.5 Rejected Ideas

During the course of designing this vehicle, several variations were examined until a final configuration materialized. This section discusses a some of the more prominent variations, from where they were derived and why they were eventually discarded.

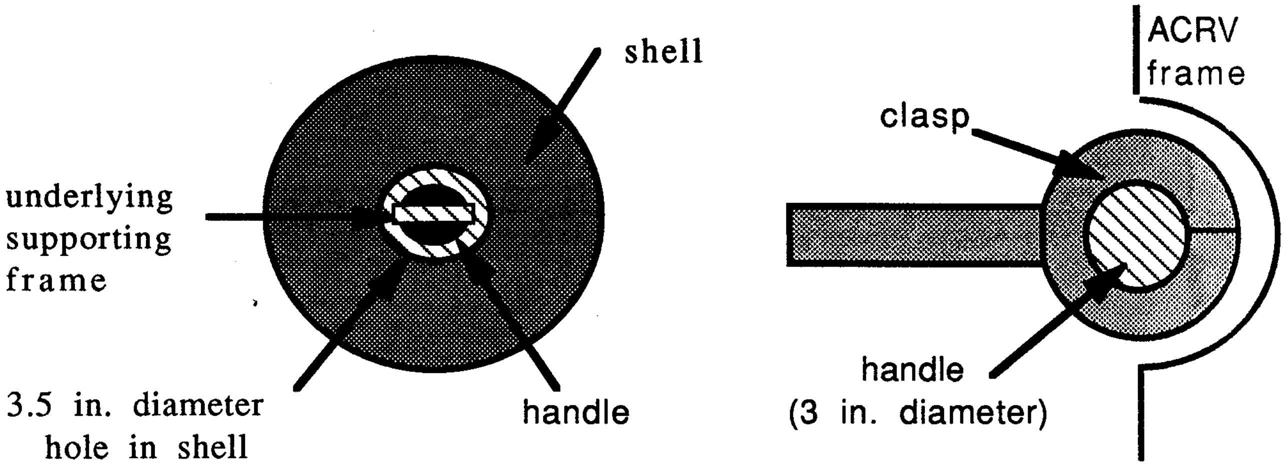


Figure 2.12 - An attachment point handle and a payload bay frame clasp

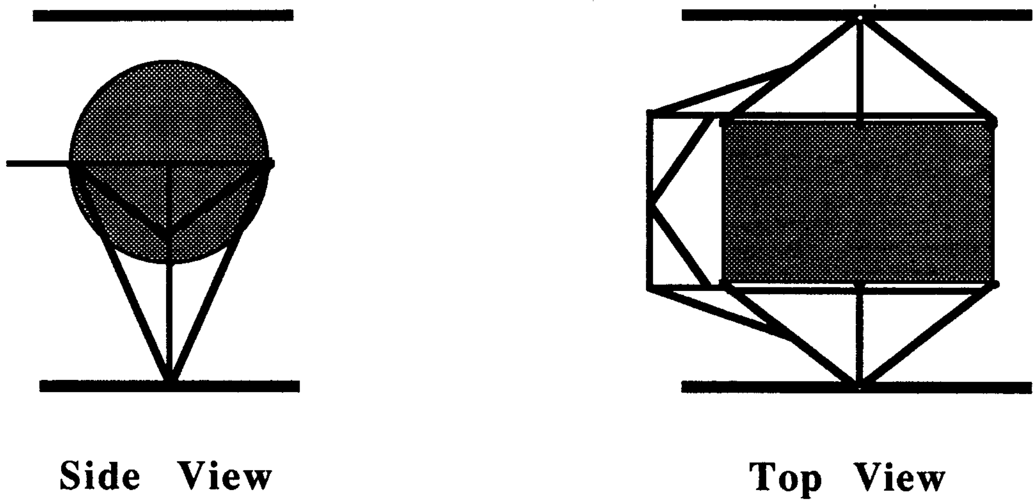


Figure 2.13 - The placement of the airlock in the shuttle payload bay

2.5.1 The Final Configuration

The final configuration of the assembled vehicle (i.e., propulsion package and airlock attached to the reentry vehicle) went through several modifications during the design process. One objective was to determine a configuration that would allow the healthily deconditioned crew member to be taken into and out of the vehicle with the least discomfort. To accomplish this, the original design of an airlock that docked perpendicularly to the length and through the top of the vehicle was modified so that the airlock was attached parallel to the length and at the tail-end of the vehicle. With this objective satisfied, a new objective materialized: if the airlock is positioned at the tail-end of the vehicle, then where is the propulsion package to be placed?

Several options for propulsion package placement were evaluated. Place it around the airlock; no, the airlock is too large to allow the propulsion package to be placed around it and still be attached directly to the main vehicle structure. Place it on the nose; no, the supporting structure would have been too complex and potentially unsafe. Place it on the bottom; no, the Thermal Protection System tiles are too delicate and too essential to the mission to be threatened by propulsion package placement. Place it on the top: yes, the airlock can be placed on the tail-end and the propulsion package can be placed on the top of the vehicle. With these objectives accomplished the configuration was complete.

Then it was discovered that the mandate of having the center of mass set near the tail-end of the vehicle meant that the vehicle would be tail heavy in the water after splashdown and thus the airlock would be submerged. New objective: place the airlock so that it has easy traversability and so that it is not submerged after splashdown. Place the propulsion package directly on the tail-end and place the airlock so that it is attached to the top at the tail-end angling back above the propulsion package; no, fitting both units in that confined space was not possible and the airlock could not be moved up any further without violating the entry objective. A few more variations on the aforementioned placements were attempted but were unsuccessful. The best compromise to all of the objectives-the final configuration-placed the airlock on top of the vehicle, near the nose and angled forward, with the propulsion package placed at the tail-end of the vehicle.

2.5.2 Extraneous Rejections

Other, less relevant, ideas focussed upon atmospheric operations and soft-landing methods. The use of a spacecraft/ramjet to reduce reentry acceleration and to increase cross-range after reentry to be able to fly to an airport was examined. This was too complex of a vehicle to be used as a fail-safe return device and the fuels that it would require would not be storable in the environment of outer space.

Consideration was given to the idea of using counter-rotating blades as a means of reducing airspeed, but this was too complex, its mass was prohibitively large for its function, and it would not have been easily shroudable or deployable.

Consideration was given to the idea of using an airbag and retro-rockets to ease the shock impact, but found that airbag storage within the heatshield to be too risky, in terms of heat shield integrity and of assured deployability, and that retro-rockets are only required for landing on land. When the impact accelerations were computed, the need for impact reduction devices beyond parachutes was insubstantial.

Chapter 3

Human Factors

3.0 Summary

3.1 Criteria for Use

3.2 Life Support Systems

3.3 Medical Systems and Provisions

3.4 Interior Systems and Configurations

3.0 Summary

A successful EGRESS mission involves returning healthy and/or ill or injured crew members from the Space Station *Freedom* to the earth. In order to accomplish this, the EGRESS spacecraft will contain all of the provisions and equipment necessary to maintain the safety and comfort of an EGRESS crew, while also providing for their normal physiological and psychological needs. The design of systems and procedures to meet these requirements was the primary function of the Project EGRESS Human Factors Group.

The Human Factors Group approached design of the crew cabin and related systems from the astronaut's perspective. Crew members on Space Station *Freedom* will need to know when and how to use the EGRESS vehicle. Once these have been accomplished, the EGRESS crew will require adequate life support, medical, and flight provisions and systems to perform an EGRESS mission. Therefore, development of the crew systems and procedures involved two phases: development of criteria for use of the EGRESS vehicle and design of the crew systems.

Because space travel and reentry into the atmosphere inherently involve risks to human life, criteria for use were developed to ensure that the EGRESS vehicle will only be used when remaining on the space station would pose greater risks than would returning to earth. These criteria were also used as a basis for defining the necessary crew systems and provisions according to the use of the vehicle.

The EGRESS vehicle's crew systems include life support, medical, and interior systems. The life support system will meet all the physiological requirements of up to five crew members for 24 hours. Medical systems will allow advanced life support for one ill or injured crew member on board the EGRESS for up to 48 hours. The interior systems, including the seats, control panels, windows, general provisions, were all designed and placed within the EGRESS crew cabin according to the basic physiological, ergonomic, and psychological requirements of five crew members.

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3.1 Criteria For Use

An essential part of design of the EGRESS vehicle was the definition of absolute criteria for use of the vehicle in order to ensure both proper provisioning and reasonable use of the spacecraft. Use of the EGRESS is presently restricted to three general categories: crew evacuation if depletion of essential provisions is imminent, crew evacuation in the event of a space station catastrophe, and return of a critically ill or injured crew member who cannot be adequately cared for on the space station.

Separate criteria were described for each of these "Design Reference Missions" (Chapter 1), specified by the NASA ACRV Request For Proposal, because of the different time-line and provisional requirements for each mission. The criteria presented here will be used to determine if, in fact, use of the EGRESS spacecraft is warranted for a given emergency.

3.1.1 Depletion of Space Station Provisions

The first general criteria for use of the EGRESS vehicle involves the imminent depletion of critical space station life support provisions, including oxygen, nitrogen, water, and food, before either a shuttle or an expendable launch vehicle can be dispatched. In most cases, the space station crew will know in advance of an impending supply depletion, allowing adequate time to prepare the EGRESS for a return to earth.

NASA currently plans for a space shuttle to return to the space station every 90 days to replace the crew, exchange experiments, and replace the Logistics Module, which contains enough atmosphere, water, and food for the 90 day period between flights. In addition to this 90 day supply, NASA currently plans to provide "safe-havens" in each module which contain up to 45 days of food and other expendable provisions in the event that supplies on the logistics module are depleted or unreachable. Thus, in the event of a delay in the space shuttle beyond the planned 90 day return period and assuming that the station has enough oxygen, a standard station crew of 8 could survive for 45 additional days.

With these guidelines in mind, the following criteria were established to determine if use of the EGRESS is required in light of dwindling supplies:

1. Use of the EGRESS will be required if advanced planning indicates that provisions which are critical to life support, including oxygen, nitrogen, clean water, food, essential waste management supplies, and essential medical supplies will run out before a space shuttle or expendable launch vehicle can be sent to the station with replacements.

2. The EGRESS system will be activated - that is, planning for and using the EGRESS vehicles - no sooner that one week before an essential provision is expected to be depleted. Allowing the crew members to continue to work on the station beyond the normal resupplying time while provisions are still available will allow for maximum usage of the space station for scientific and technological work. Furthermore, activating the EGRESS system one week before the expected depletion of an essential provision will give the crew a sufficient margin of safety in the event of any problems related to use of the EGRESS vehicle.

3. All space station crew members will continue a normal daily routine, as far as possible, until one week before an essential provision is expected to

be depleted. One crew member will be appointed to keep special track of all essential provisions during the time before activation of the EGRESS system.

4. All crew members must be evacuated from the station on the two EGRESS vehicles attached to the space station. Assuming a space station crew of eight, three crew members will ride in one vehicle and five in the other. The EGRESS spacecraft carrying three crew members will be used to transport critical experiments and equipment back to earth, if necessary.

5. The station will be shut down by the Space Station Commander such that the space station is left in a dormant state.

3.1.2 Space Station Catastrophe

In contrast to the first, the second general criteria for use of the EGRESS involves a sudden catastrophe on Space Station *Freedom*, requiring an immediate evacuation of the station. In general, the EGRESS will be used during this case if essential space station life support systems cannot function adequately to meet the needs of the crew members.

While advanced planning and special design considerations will help make major disasters and failures on the space station improbable, the nature of the environment of outer space and the types of experiments that are planned make the dangers of such occurrences quite real. Fires started from flammable experiments or faulty equipment have the potential to spread quickly in the closed environment of the space station. Explosions, resulting from these fires or other malfunctions, could severely endanger the lives of the crew. These and other severe catastrophes, including meteorite punctures through the hull of the station, the release of poison gases into the atmosphere of the station, and severe equipment failures, could cause a sudden shut down of essential power or life support systems.

These scenarios falls into two categories:

1. A major failure occurs on the station, but the safe-havens in one or more modules are available such that life can be sustained until a space shuttle can be dispatched to rescue a stranded crew. Under this category, EGRESS will not be used.

2. A major failure occurs on the station and the safe-havens are not available for safe maintenance of the crews' lives, requiring immediate evacuation of the station onto the EGRESS spacecraft.

The first category includes emergencies in which fires, meteorite impacts, or other related emergencies necessitate the shut down of one or more modules, restricting access to any number of essential provisions. As long as provisions exist to maintain life support until a space shuttle can be dispatched on a rescue mission, the EGRESS will not be used. If essential supplies run short, the crew should follow the guidelines in Section 3.1.1.

The second category includes emergencies in which the damage done to the station permanently disables important life support functions, such as the atmosphere supplies or the power systems. The impossible recovery from such a contingency requires immediate evacuation of the space station, according to the following criteria:

1. Immediately after the contingency occurs, the EGRESS system will be activated by the designated EGRESS pilot. If the pilots are unavailable due to the nature of the emergency, then crew members near the EGRESS airlock should enter and activate the EGRESS vehicle.
2. As in the first criteria, three crew members should enter one EGRESS and five should enter the other; however, exact deployment of the crew to the vehicles will likely be determined by location of the disaster. If four crew members must ride in each craft, the center "stretcher-seat" (Section 3.4.2) should remain vacant in order to maintain flight stability.
3. If the safety of the crew is in grave danger due to the accident, both EGRESS vehicles will release from the station as soon as all crew members are accounted for. Reentry and splashdown locations will be determined when a safe distance between the EGRESS and the station has been achieved.
4. If immediate departure is not required, the station should be shut down as described in Section 3.1.1.

3.1.3 Medical Emergencies

The third type of emergency does not involve evacuation of the entire crew, but rather the return of one or more severely ill or injured crew members to the earth. The EGRESS vehicle is designed to transport one critically injured crew member from the space station to the earth while maintaining a high standard of intensive care for up to 48 hours during flight and recovery. Although the life support systems and medical provisions can support as many as three non-critical patients, volume and weight constraints allow critical care capabilities for only one. Therefore, in the event that two crew members are critically ill or injured, two EGRESS vehicles will be required to return both patients to earth.

3.1.3.1 Classes of Illness on Space Station *Freedom*

The criteria for using the EGRESS in a medical emergency is dependent upon what types of injuries the space station is equipped to handle. According to present space station planning for the Health Maintenance Facility (HMF), NASA engineers and flight surgeons have defined three general "Classes of Illness" that may be encountered on the space station [3-1]. These general classes are as follows:

CLASS I	Mildly to moderately ill. Examples of this class include colds, viral gastroenteritis (stomach flu), other common viruses, space sickness, cavities, sprains or minor breaks, small lacerations, or other minor illnesses. All Class I illnesses can be handled easily on the HMF with minimal impact on normal space station operations.
CLASS II	Moderately to severely ill. Examples of this class include decompression sickness, kidney stones, severe toothaches (requiring root canals or removal of tooth), small area partial thickness burns, ulcers, or other related illness. These illness can either be treated on the HMF or the crew member can be maintained until a space shuttle returns to the station.

CLASS III Severely ill. Examples include severe third or fourth degree burns, compound fractures, acute appendicitis, severe eye injuries, hemorrhaging, severe internal injuries, myocardial infarction, uncontrollable arrhythmias, sepsis, or ARDS (Adult Respiratory Distress Syndrome). While crew members with these illnesses can be stabilized on the HMF, crew training and/or the HMF medical equipment would be inadequate for long term care.

3.1.3.2 Medical Criteria For Use

From considerations of these three Classes of Illnesses, a list of medical criteria for use of the EGRESS vehicle was developed. The following medical criteria must be met before the EGRESS system is activated:

1. The crew member has a Class III or a severe Class II illness or injury such that:
    a. Long term care on the space station HMF until the next space shuttle arrival would severely decrease the crew member's chances of survival, or
    b. The equipment required to treat the crew member is not present on the HMF, or
    c. The ill crew member requires surgery under a general anesthetic.
2. The crew member's condition is stable enough to survive a return to Earth aboard the EGRESS.
3. The crew member is not dead - that is, the EGRESS will not be used to return deceased crew members to earth.
4. Mission control flight surgeons have approved the transport of the injured crew member on the EGRESS based on the crew member's condition and these criteria.

Fig. 3.1 summarizes these medical criteria based upon the Space Station *Freedom's* Classes of Illnesses and the stability of the patient.

Transportation of an injured crew member who meets the above criteria will require a crew of three: one injured person, one pilot, and one crew medical officer. The remaining five crew members continue their normal duties on the space station until a replacement crew is sent. In the event that another crew member must be returned to the earth in a medical emergency, the remaining four crew members must be evacuated; for a normal medical crew in both vehicles would leave two crew members stranded at the station. As described in Section 3.1.1, the space station will be shut down in the event of a total evacuation.

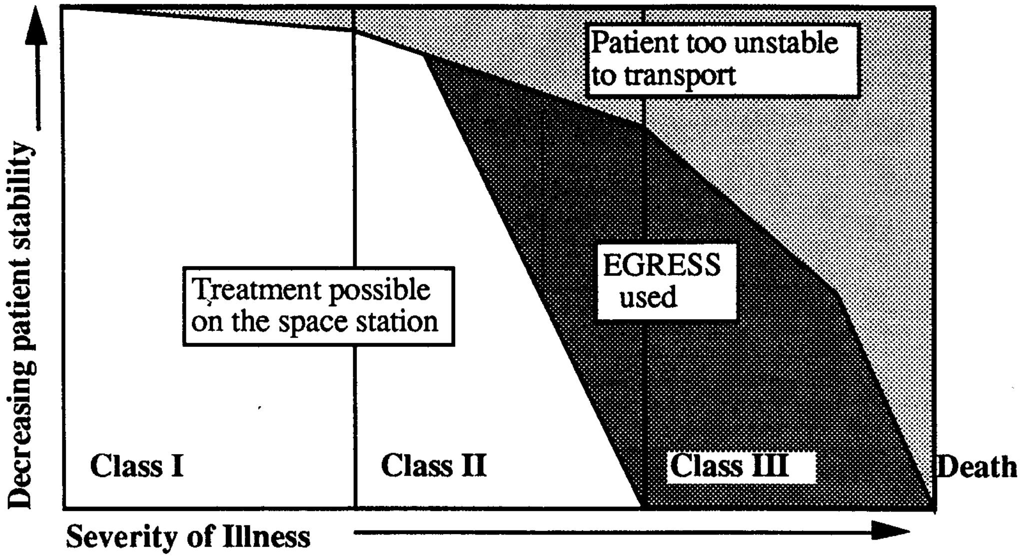

Figure 3.1 - Medical criteria for use of the EGRESS

3.2 Life Support Systems

Absolutely essential to the successful utilization of the EGRESS spacecraft is the presence of a simple but efficient Environmental Control and Life Support System (ECLSS) on the vehicle. The EGRESS ECLSS is composed of three basic subsystems: an environmental control subsystem, a crew water and food provisioning subsystem, and a waste management subsystem. The environmental control subsystem, shown in Fig. 3.2, includes the Atmospheric Supply and Pressurization System (ASPS), the Main Environmental Control System (MECS), the Patient Environmental Control System (PECS), the Emergency Environmental Control System (EECS), In order to provide a simple, yet representative quantitative description of each of the ECLSS subsystems, calculations were made using ideal assumptions (for example, the ideal gas law, perfect insulation, and perfect heat exchange) whenever applicable. This section details the design and use of the EGRESS ECLSS.

3.2.1 Basic Crew Requirements

In order to maintain an acceptable level of comfort and performance for the EGRESS crew, the ECLSS is designed according to the physiological requirements of up to five healthy crew members or four healthy crew members and one critically ill patient. The system is designed to maintain a shirt-sleeve environment in the EGRESS cabin while allowing for light to moderate work loads by the crew.

Fig. 3.3 lists the physiological requirements for which the EGRESS vehicle's ECLSS is designed. These figures were determined from physiology data from both American [3-2] and Soviet [3-3] space flights, studies of intensive care patients on earth, and the present atmosphere conditions planned for the space station.

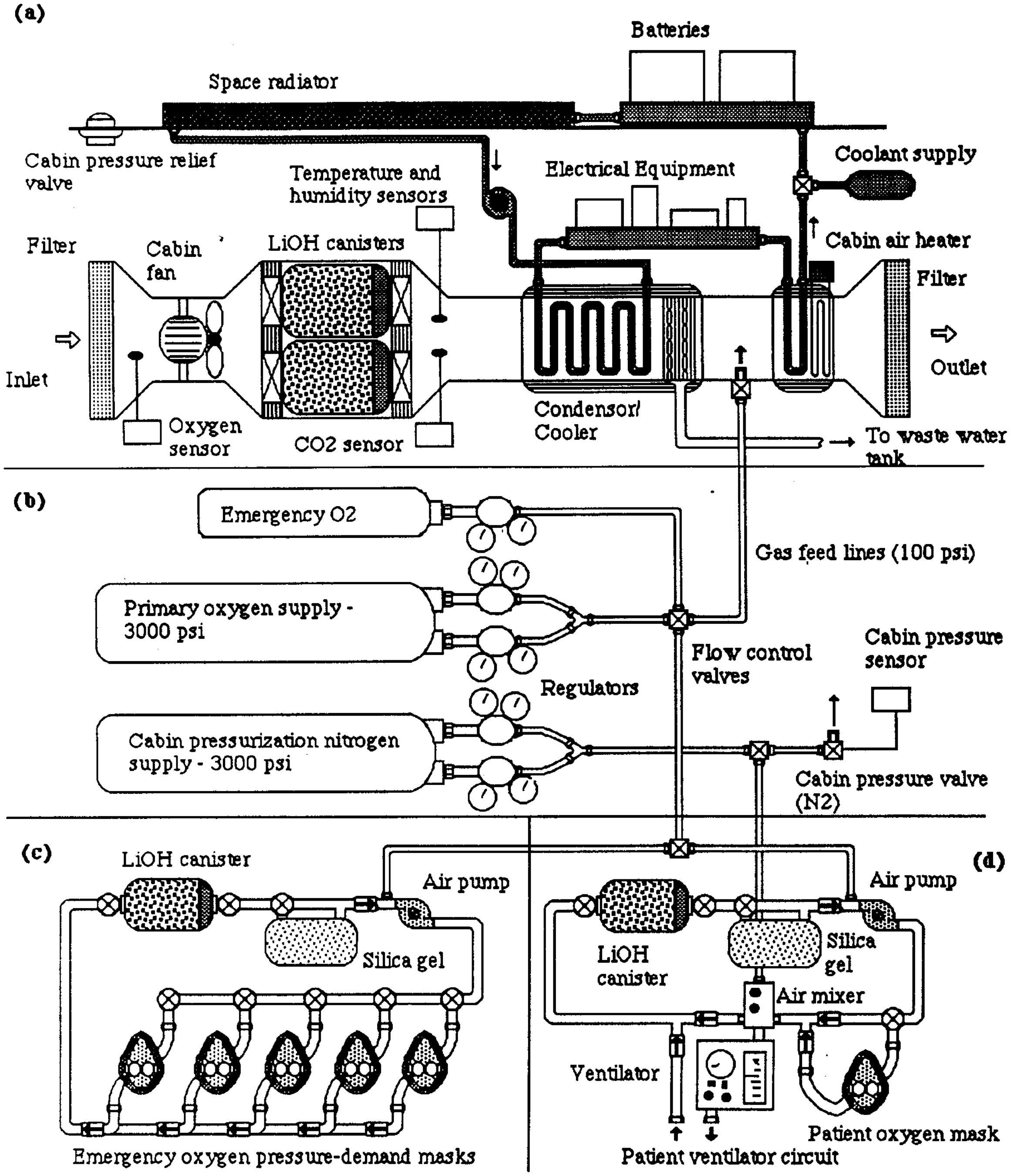

Figure 3.2 - <u>The EGRESS environmental control subsystems</u>:
(a) the Main Environmental Control System (MECS)
(b) the Atmospheric Supply and Pressurization System (ASPS)
(c) the Emergency Environmental Control System (EECS)
(d) the Patient Environmental Control Systems (PECS)

Requirement	Per Crew Member
Oxygen consumption	0.5 liters per minute
Carbon dioxide production	0.4 liters per minute
Atmospheric water produced	1.2 kg per day
Energy expenditure	3600 kcal per day
Recommended water intake	2 kg per day
Recommended caloric intake	2000 to 3000 kcal per day
Optimum air circulation speed	0.203 meters per second

Figure 3.3 - Physiologic requirements for each crew member

3.2.2 Atmospheric Supply and Pressurization System (ASPS)

The EGRESS Atmospheric Supply and Pressurization System (ASPS) will provide a cabin pressure of 14.7 psi and a 21% oxygen, 79% nitrogen atmosphere in order to provide a safe, comfortable environment for the crew during a normal flight of the EGRESS vehicle. In addition, the ASPS contains redundancy and emergency features to allow life support in emergency situations. Constant monitoring of the total cabin pressure and oxygen partial pressure will be done by the Main Environmental Control System (MECS) described in Section 3.2.3.

A schematic of the ASPS is shown in Figure 3.2 (b). This section details the design and functions of the EGRESS ASPS.

3.2.2.1 Cabin pressurization

The ASPS is designed to maintain a cabin pressure of 14.7 psi - equal to sea-level atmospheric pressure on earth and cabin pressure on the space station. Lower pressures, such as that of the 5.0 psi, 100% oxygen Apollo cabin environment [3-4], were considered because they would allow for a reduction in the weight of the cabin pressure hull. However, low pressures would require extensive pre-breathing of pure oxygen as well as a slow, gradual pressure decrease in order to prevent decompression sickness. These activities would clearly not allow immediate entry into the EGRESS and take off from the space station as might be required in the event of a space station catastrophe. Thus, a cabin pressure of 14.7 allows maximum safety and ready access to the EGRESS vehicle for the crew members.

Cabin pressurization is primarily a function of the on-board nitrogen supply. Under normal physiologic conditions, humans do not consume atmospheric nitrogen. Therefore, because enough nitrogen will be in EGRESS cabin during dormancy to maintain a 14.7 psi cabin pressure, an additional supply would seem unnecessary. However,due to the high probability of leakage while sealing the hatch and the possibility of leakage during emergency situations such as a meteorite strike or a faulty hatch seal, the EGRESS vehicle will carry enough nitrogen to allow for one complete repressurization of the cabin from a vacuum. This will allow for the maintenance of normal pressures during EGRESS flights and during possible emergencies. As the EGRESS vehicle has a total cabin volume of 7.1

m^3 (250 ft^3), repressurizing the EGRESS cabin from a vacuum to 14.7 psi will require 7100 liters of nitrogen.

Several redundant and emergency features have also been designed into the ASPS. The EGRESS cabin includes a pressure relief valve to be used in the event of an accidental cabin overpressurization due to an equipment failure. A cabin vent will allow pressure equalization during decent into the atmosphere. In the event of a sudden pressure loss due to a punctured hull or another anomaly, the ASPS can lower and maintain a pressure of 10 psi in order to decrease structural stresses.

3.2.2.2 Oxygen Supplies

In order to maintain the health of the crew members and to be compatible with earth and the space station, the EGRESS crew cabin will contain a 21% oxygen, 79% nitrogen atmosphere. Human beings require an atmospheric oxygen partial pressure between 2.5 and 3.5 psi to remain alert and productive. Below 2.0 psi, crew members can experience a loss of coordination, clear vision, and consciousness due to hypoxia. Conversely, prolonged exposure to partial pressures of oxygen greater that 4.0 psi can cause severe lung damage from hyperoxia and oxygen toxicity. The earth and the space station both meet the oxygen partial pressure requirement of 3.1 psi by maintaining a 21% oxygen atmosphere at a total cabin pressure of 14.7 psi. Nitrogen accounts for the remaining 79% of the atmosphere, with a partial pressure of 11.6 psi.

Because normal EGRESS missions will range in length from six to twenty four hours, enough oxygen will be provided to 5 crew members for a maximum period of twenty four hours (1440 minutes). In the event that recovery is delayed beyond twenty four hours, an additional twenty four hours of oxygen is also provided to support an ill or injured crew member on higher oxygen concentrations.

Based on an oxygen consumption of 0.5 liters per minute per crew member (Fig. 3.3), the total oxygen requirement for five crew members and one patient was determined from the following equation:

$$\text{Oxygen requirement} = (\text{Oxygen consumption})\,(\text{crew size})\,(\text{time for use}). \qquad (3\text{-}1)$$

Thus, for five crew members:

$$(\ 0.5 \text{ liters per minute}\ )\ (\ 5 \text{ crew members}\ )\ (\ 1440 \text{ minutes}\ ) = 3600 \text{ liters per day,}$$

and for patient support beyond a twenty four hour mission:

$$(\ 0.5 \text{ liters per minute}\ )\ (\ 1 \text{ patient}\ )\ (\ 1440 \text{ minutes}\ ) = 720 \text{ liters per day,}$$

which gives a total oxygen volume requirement of 4320 liters of oxygen. To compensate for the possibility of cabin leaks while sealing the hatch, the total volume of the primary oxygen system will be 4500 liters at cabin pressure.

In the event of a failure of the primary oxygen supply due to a severe tank leak, regulator damage, or other contingencies, a secondary oxygen tank can provide six hours (360 minutes) of oxygen to 5 crew members. From Eqn. 3-1, the total required volume at normal cabin pressures is:

(0.5 liters per minute) (5 crew members) (360 minutes) = 900 liters.

In the event of a pressure loss or atmospheric contamination, the primary and the secondary oxygen supplies will be routed from the main ECLSS system to an emergency system which provides the required oxygen to each crew member through pressure-demand masks (Section 3.2.5).

3.2.2.3 Atmosphere tank design

The EGRESS ECLSS will utilize pressurized gas tanks to contain the atmospheric nitrogen and oxygen required for all EGRESS missions. Cryogenic storage tanks were initially considered due to their compact size and smaller tank weights. However, for the EGRESS tanks, which will carry only twenty-four hours of gas supplies, cryogenic tanks have no weight or volume advantages over pressurized tanks. Furthermore, pressured tanks are much simpler to design and maintain, require no direct power input, and can maintain virtually constant pressure with very little leakage during long dormancy periods on the space station [3-2].

The pressurized tanks were sized according to both SAE Aerospace pressurized oxygen and nitrogen tank specifications [3-2] and the Ideal Gas Law. For a tank made of SAE 4340 Steel [3-2], a tank pressure of 3000 psi minimizes the total tank weight to gas weight ratio at 3 [3-2]. Therefore, a tank pressure of 3000 psi was chosen.

Assuming constant cabin temperature, the Ideal Gas Law states:

$$P_{cabin}\, V_{cabin} = P_{tank}\, V_{tank}, \tag{3-2}$$

where P_{cabin} is the cabin pressure, V_{cabin} is the cabin volume, P_{tank} is the tank pressure, and V_{tank} is the tank volume. The tank volume can be determined by rearranging Eqn. 3-2 as follows:

$$V_{tank} = (P_{cabin}\, V_{cabin}) / P_{tank}, \tag{3-3}$$

Thus, for the EGRESS nitrogen and oxygen volume requirements (Sections 3.2.2.1 and 3.2.2.2), Eqn. 3-3 was used to determine the tank volumes which are listed in Fig. 3.4.

In order to best fit the tanks on the floor of the cabin, cylindrical tanks with a length (H) to diameter (D) ratio of 5 were chosen over spherical tanks. Because of thicker tank requirements, cylindrical tanks with a length to diameter ratio of 5 weigh 30% more than a spherical tank with an equal volume [3-2]. The volume of a cylindrical tank is given by:

$$V_{tank} = \pi R^2 H, \tag{3-4}$$

where V_{tank} is the cylindrical tank volume, R is the tank radius (R = 0.5 D), and H is the tank length. For an H:D ratio of 5, Eqn. 3-4 becomes:

$$D = 2[\, V_{tank} / (10\, \pi)\,]^{1/3}, \tag{3-5}$$

from which the pressurized nitrogen and oxygen tanks were sized. Fig. 3.4 gives the volumes and measurements of all of the EGRESS ECLSS tanks. The location of the tanks on the floor of the EGRESS crew cabin is shown in Fig. 3.22.

Tank	Gas volume at cabin pressure	Gas volume at tank pressure	Tank length	Tank diameter
Nitrogen	7100 liters	34.79 liters	103.46 cm	20.69 cm
Primary oxygen	4500 liters	22.05 liters	88.87 cm	17.77 cm
Emergency oxygen	900 liters	4.41 liters	51.97 cm	10.39 cm

Fig. 3.4 - Volumes and measurements for the EGRESS ECLSS tanks

3.2.3 Main Environmental Control System (MECS)

The Main Environmental Control System (MECS) is the heart of the EGRESS ECLSS. The primary function of the MECS is to remove carbon dioxide and excess water from the air while maintaining cabin temperature and humidity levels suitable for a "shirt-sleeve environment." The MECS also removes heat from the cabin, the instruments, and the EGRESS batteries during all phases of an EGRESS mission. Finally, the MECS also continuously monitors cabin atmospheric conditions including pressure, oxygen content, carbon dioxide content, temperature, and humidity.

The MECS is designed to maintain cabin atmospheric conditions based upon normal human physiologic requirements (Fig. 3.3). As with the cabin pressures (Sections 3.2.2.1 and 3.2.2.2), the temperature, humidity, and air speeds are similar to those experienced on the earth and on the space station, thereby maximizing the comfort of the crew and ease of entry and exit. Fig. 3.5 lists the conditions that the MECS will maintain during a normal flight of the EGRESS vehicle.

Atmospheric Condition	EGRESS Cabin Levels
Cabin pressure	14.7 ± 1.0 psi
Oxygen partial pressure	3.1 ± .5 psi
Cabin temperature	22.5 ± 2.5°C
Cabin humidity	50 to 70%
Air circulation speed	0.203 meters per second

Figure 3.5 - Cabin atmospheric levels maintained by the MECS.

The MECS consists of a fan, two lithium hydroxide (LiOH) canisters, a heat exchanger, and several atmospheric sensors and controls. The individual systems will be located in a single unit that spans the rear of the cabin to allow air to circulate easily around the interior of the cabin. Fig. 3.2 (a) shows a schematic diagram of the MECS and Fig. 3.22 shows the location of the MECS at the rear of the cabin, below the parachute housing.

The MECS functions as follows. Cabin air, having been heated and humidified by the astronauts and cabin electronic systems, is drawn into the inlet vent by the cabin fan. The fan moves the air at a continuous mass flow rate of 0.1042 kg per second (this gives an optimal cabin velocity of 0.203 meters per second) to allow for maximum heat exchange in the cabin (Section 3.2.3.2). The air is then circulated through two LiOH canisters which remove carbon dioxide. Finally, the air passes through a heat exchanger where heat is removed, bringing the temperature and humidity back to the limits shown in Fig. 3.5. Thus, the treated air is returned to the cabin through the outlet duct, whereupon the cycle repeats. Meanwhile, the MECS continually monitors the total pressure and oxygen content of the air and activates oxygen or nitrogen valves to correct any discrepancies.

3.2.3.1 Carbon Dioxide Removal

Carbon dioxide removal is a critical function of the MECS. Under normal conditions, a human produces between 0.2 and 0.4 liters of carbon dioxide (CO2) every minute through normal expiration. In a closed system, such as the EGRESS cabin, this causes an increase in the partial pressure of atmospheric carbon dioxide. On earth, where oxygen and nitrogen are by far the most prevalent gases, the partial pressure of carbon dioxide is only 0.005 psi, well below the limit of human tolerance. Both the space shuttle and Space Station *Freedom* allow a carbon dioxide partial pressure of 0.15 psi, which is still below the limit of human tolerance [3-4]. However, at concentrations above 0.30 psi, crew members would experience an increase in respiratory rate, heart rate, and minute ventilation - their bodies' attempt to "blow off" excess carbon dioxide in the blood. If left unchecked, these physiological responses can lead to "acidosis," a dangerous and potentially disabling condition. Clearly, carbon dioxide removal in the EGRESS cabin is essential to the maintenance of the crew members' lives.

On the EGRESS vehicle, Lithium hydroxide (LiOH) will be used to remove carbon dioxide from the cabin during an EGRESS mission. LiOH canisters were used in Mercury, Gemini, and Apollo missions and are presently being used in the Space Shuttle due to their simplicity and reliability for short missions [3-2]. LiOH reacts with atmospheric carbon dioxide in the air circulated through the canisters to produce LiCO3, water, and heat.

The amount of LiOH required for the twenty-four hour EGRESS mission is a function of the weight of carbon dioxide produced by a maximum crew of five per day. The weight of carbon dioxide produced by the crew was determined from the equation:

$$\text{Weight of CO2} = (\text{CO2 production})(\text{time})(\text{crew size})(\text{density of CO2}). \qquad (3\text{-}6)$$

From Eqn. 3-6, the amount of LiOH required was determined by the equation:

$$\text{Weight of LiOH} = (\text{weight of CO2})(\text{consumption of LiOH}). \qquad (3\text{-}7)$$

Thus, for the specified maximum rate of carbon dioxide production of 0.4 liters per minute (Fig. 3-3) and a density of carbon dioxide of 0.00196 kg/liter, the amount of carbon dioxide produced is:

$$(0.4\ \text{liters/minute})(1440\ \text{minutes})(5\ \text{crew members})(0.00196\ \text{kg/liter}) = 5.64\ \text{kg}.$$

LiOH is consumed at a rate of 1.059 kg-LiOH / kg-CO2 [3-2]. Therefore, the amount of LiOH required for a twenty-four hour EGRESS mission is:

$$(5.64\ \text{kg CO2})(1.059\ \text{kg LiOH/kg CO2}) = 6\ \text{kg LiOH}.$$

The use of LiOH on previous space missions has shown that two canisters in the environmental control circuit remove carbon dioxide more efficiently than one. Therefore, the EGRESS MECS will use two LiOH canisters, each containing 3 kg of LiOH (Fig. 3.7(a)).

Because exposure to humidity and atmospheric carbon dioxide can shorten the life of the canisters, the canisters will be sealed in plastic and stored in the cool and dry EGRESS vehicle during dormancy. Just prior to separation from the space station, the EGRESS crew will remove the plastic and insert the canisters into the MECS duct. A color dye suspended in the LiOH will indicate water and carbon dioxide saturation levels, thereby informing crew members of the remaining life of the canisters.

3.2.3.2 Heat and Humidity Control

Without the proper control, cabin heat and humidity, the by-products of normal human metabolism and some cabin equipment, can reach levels that will damage equipment and endanger the lives of the EGRESS crew. Based on a maximum oxygen consumption of 0.5 liters per minute (Fig. 3.3) and a metabolic efficiency of 40% [3-5], the human body releases 2160 kilocalories (105 Watts) of heat per day of the 3600 kilocalories it produces. In addition, the human body releases 1.2 kg of water per day through normal respiration and perspiration. The heat and humidity from these and other sources, listed in Fig. 3.6, are controlled by a single condensation/heat exchange loop in the EGRESS MECS.

Source	Heat Produced	Water produced
5 crew members	0.523 kW	6.0 kg / day
LiOH	0.133 kW	2.3 kg / day
Electronic instruments	0.500 kW	none
EGRESS batteries	0.525 kW	none
TOTAL	**1.681 kW**	**8.3 kg / day**

Figure 3.6 - Heat and water sources on the EGRESS vehicle considered for the MECS

The design of the MECS is based on the heat and humidity generated by the crew. The second law of thermodynamics relates heat flux to temperature by the relation [3-6]:

$$Q' = m' \, C_p \, \Delta T, \qquad (3\text{-}8)$$

where Q' is the heat given flux in kilowatts (kW), m' is the mass flow rate in kg per second (kg/s), C_p is the specific heat of the fluid (kJ/kg°K), and ΔT is the temperature change in degrees centigrade (°C). In order to maintain an average cabin temperature of 22.5°C, air leaving the outlet vent of the MECS at 20°C can increase to 25°C ($\Delta T = 5$°C) without sacrificing crew comfort. For a total heat flux of 0.523 kW and a specific heat of air of 1.0035 kJ/kg°K, the mass flow rate requirement for air in the cabin was determined by rearranging Eqn. 3-8 such that:

$$m' = Q' / (C_p \, \Delta T), \qquad (3\text{-}9)$$

or $m_{air}' = .1042$ kg/s. This mass flow rate of air through the MECS ducts and around the cabin will allow for the proper exchange of heat from the crew members to the air to be processed by the MECS.

Air processing begins as cabin air is drawn into the MECS inlet vent at 25°C by the cabin fan. The air first passes through the LiOH containers which remove carbon dioxide while adding 0.133 kW and a small amount of water to the air. This process raises the air temperature to 26.7°C (Eqn. 3-8) and the relative humidity beyond acceptable cabin limits inside the MECS duct. Therefore, before returning to the cabin, the air must pass through a heat exchanger and water removal system.

Initially, separate systems for heat and water removal were considered. One method considered involved collecting excess humidity with silica gel while cooling the cabin with a separate heat exchanger. However, a twenty-four hour EGRESS mission would require approximately 40 kg of silica gel and 10 kg of hardware, not including the mass of the additional heat removal system. In addition to these excessive weight requirements, the silica gel system is not regenerable, and could not be used during periodic EGRESS system checks while also maintaining mission readiness. For these reasons, the EGRESS MECS combines both heat exchange and water removal in one condensor/cooler sub-system.

The condensor/cooler is a heat exchanger which combines heat and temperature control with humidity control. In order to maintain a comfortable cabin relative humidity of 60% at the average cabin temperature of 22.5°C, the condensor/cooler lowers the air temperature from 26.7°C to the dew point for cabin conditions, or 14.44°C [3-7], and releases 1.237 kW (Eqn. 3-8). Water in excess of 60% relative humidity at 22.5°C condenses out of the air, and is collected on special wicks [3-2] which deposit the condensate into a waste water tank (Section 3.2.7). The cold air then passes over heating coils which add 0.581 kW to the air and raise the temperature to 20°C (Eqn. 3-8). Finally, the air passes through the MECS outlet vent and back into the cabin.

The net effect of the condensor/cooler sub-system is the removal of 0.656 kW from the cabin air. This heat, along with the additional 0.500 kW from the cabin electrical instruments and 0.525 kW from the batteries, is carried out of the cabin by a water-coolant loop and radiated into space.

The coolant loop begins as water at 12°C is pumped into the condensor/cooler. To minimize the power requirements of the coolant pump, the coolant mass flow rate was reduced by allowing the water to increase to a maximum possible temperature of 26°C (approximately the maximum air temperature). Therefore, for a 14°C temperature increase, a specific heat for water of 4.184 kJ/kg°K, and a 1.237 kW heat addition, Eqn. 3-9 gives a mass flow rate of:

$$m_{water}' = Q' / (C_p\, \Delta T) = (1.237) / [(4.184)(26 - 12)] = .0211 \text{ kg/s.}$$

From the condensor/cooler, the heated water picks up an additional 0.500 kW as it circulates through an instrument heat exchanger, mounted near the top of the EGRESS crew cabin, above the instrument panels. This heat transfer raises the water temperature to 31.7°C (Eqn. 3-8).

This warm water is then cooled slightly as it circulates back through the end of the condensor/cooler in order to warm the cabin air from 14.44°C to 20°C. In this process, the water releases 0.581 kW to the air and decreases to a temperature of 25.08°C.

Next the water flows out of the cabin and through a battery heat exchanger, where it picks up 0.525 kW for a final temperature of 31.03°C. The water then passes through a space radiator which dissipates a total of 1.681 kW, returning the water to a temperature of 12°C. Finally, the coolant pump draws the cool water back into the cabin and the cycle continues. A schematic of the overall heat and humidity control system is shown in Fig. 3.7.

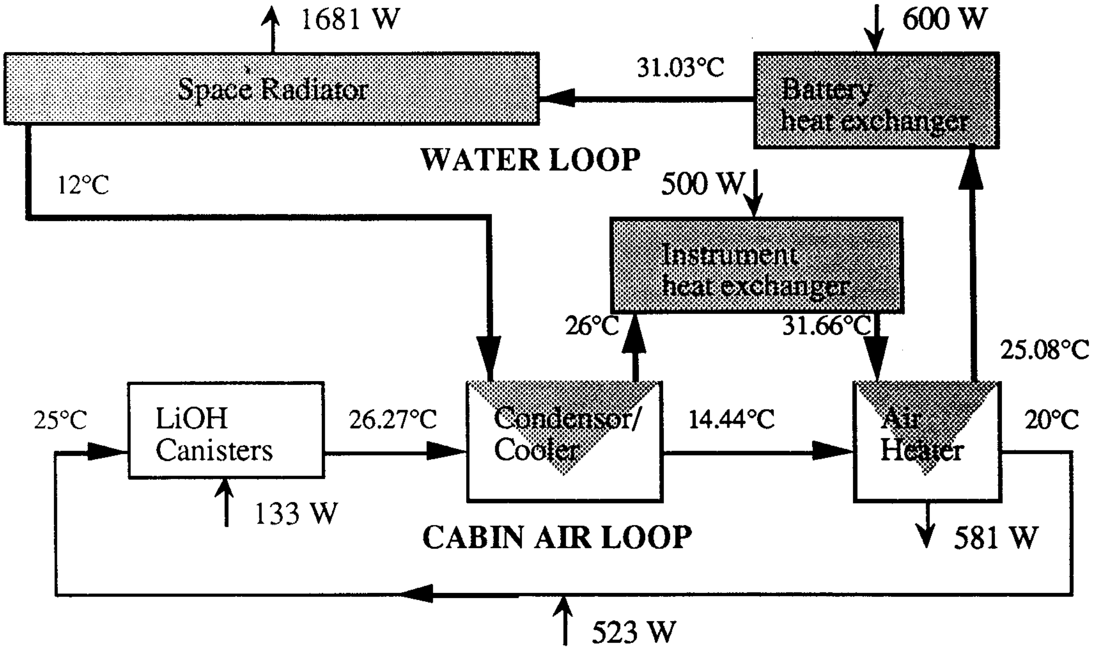

Figure 3.7 - Heat and Humidity Control Schematic

The space radiator consists of large radiating panels on the upper exterior surface of the EGRESS vehicle. The radiator panels were designed according to the Stephan-Boltzman Law:

$$Q = e\,k\,A\,T^4, \tag{3-10}$$

where Q is the heat radiated, e is the emissivity of the radiator surface, k ("Stephan's Constant") is equal to 5.6703×10^{-8} W/m^{2}K^4, A is the area of the radiator in square meters, and T is the average temperature of the radiating surface in degrees Kelvin. The required radiator area was determined by rearranging Eqn. 3-10 such that:

$$A = Q\,/\,(e\,k\,T^4). \tag{3-11}$$

In order to keep the radiator area small to minimize the weight and space required for the radiator panels, a surface of white TiO2 paint was chosen for its high emissivity (e = 0.94) and low solar absorbance (a = 0.19). Applying Eqn. 3-11 to the EGRESS conditions: e = 0.94, T = 294°K, and Q = 1.681 kW, the total required area of the radiator was determined to be 4.19 m^2. The precise dimensions and locations of the panels are discussed in Chapter 2.

3.2.4 Patient Environmental Control System

Together, the EGRESS MECS (Section 3.2.3) and ASPS (Section 3.2.2) provide a 21% oxygen atmosphere to five healthy crew members for twenty-four hours. However, to maintain the stability of an ill or injured crew member, higher oxygen concentrations ranging from 21% (normal cabin oxygen) to 100% may be required. In order to prevent the toxic effects that these higher oxygen concentrations can have on the healthy crew members (Section 3.2.2.1), a patient requiring oxygen support will breath through the EGRESS Patient Environmental Control System (PECS).

The PECS is a separate environmental loop which provides oxygen and processes exhaled air for up to 48 hours. The PECS first draws exhaled air from the patient through a narrow duct to a LiOH canister where carbon dioxide is removed. Air is then circulated through a silica gel canister to decrease the humidity. Finally, oxygen is added to maintain the required concentration and the air returns to the patient through a pressure-demand mask or through a ventilator. A schematic diagram of the PECS is shown in Fig. 3.2 (d).

3.2.4.1 PECS Carbon Dioxide Removal

The LiOH canister used in the PECS is the same size as each of the canisters used in the MECS (Section 3.2.3.1). A separate LiOH canister for the PECS is required because of the smaller ducts and higher pressures in the PECS than the MECS.

This size was determined based upon a normal carbon dioxide production of 0.4 liters per minute during a maximum period of 48 hours (2880 minutes). From Eqn. 3-6:

$$(0.4 \text{ liters/minute})(2880 \text{ minutes})(1 \text{ patient})(0.00196 \text{ kg/liter}) = 2.26 \text{ kg},$$

which, from Eqn. 3-7, requires:

$$(2.26 \text{ kg } CO2) (1.059 \text{ kg LiOH/kg } CO2) = 2.4 \text{ kg LiOH}.$$

One canister in the MECS contains 3 kg LiOH - enough to meet the requirements of the PECS. Furthermore, by using the same size canisters for both systems, the PECS canister can serve as a backup MECS canister in an emergency, provided that the PECS canister is not already being used. As with the MECS LiOH canisters, the PECS canister will be sealed in plastic during EGRESS dormancy.

3.2.4.2 PECS Water Removal

Water removal in the PECS is accomplished by a silica gel canister. Although this system was rejected from the MECS because of its weight penalty and short life-span (Section 3.2.3.2), the PECS requires a substantially smaller quantity of silica gel and will only be used during EGRESS mission phases. Furthermore, the silica gel canisters are simple and reliable, have no power requirements, and generate no additional heat. Based on a total of 3.33 kg water generated in the PECS in 48 hours (2.4 kg from the patient and 0.93 kg from the LiOH canister), the PECS canisters carry 13.3 kg of silica gel to maintain a 60% relative humidity [3-2].

3.2.4.3 PECS Patient Delivery Equipment

Processed air can be delivered to a patient on the PECS either through a pressure-demand mask or through a ventilator. Valves in the PECS connect the air processing equipment with the patient delivery equipment.

In conditions where the patient can breath normally but requires higher oxygen concentrations, the PECS delivers a condition-specified mixture of nitrogen and oxygen to the patient through a pressure-demand mask. The mask fits over the patient's mouth and nose and is held in place by two wide elastic bands that stretch around the back of the patient's head. A rubbery plastic material where the mask contacts the patient's face forms a tight seal to prevent air leakage from the PECS into the cabin. Two ports in the front of the mask allow air exchange between the PECS and the patient. An inlet port delivers processed air through a pressure-demand valve which opens only during inspiration. The exhalation port directs air back into the PECS for processing as the pressure-demand valve closes and a one-way exhalation valve opens.

For a patient who cannot cannot breath independently , a ventilator can provide adequate oxygenation and pressure support (Section 3.3.1). Like the pressure-demand mask, the ventilator draws processed air from the PECS directs exhaled air from the patient back through the PECS for processing. Manually controlled valves allow the PECS air flow to be directed either to the mask or to the ventilator.

3.2.5 Emergency Environmental Control System

In the event of a sudden pressure loss, fire, or atmospheric contamination in the EGRESS crew cabin, the EGRESS ECLSS can provide a five member crew with oxygen for twelve hours through the Emergency Environmental Control System (EECS). The EECS is a closed-circuit system which provides carbon dioxide removal, humidity control, and oxygen delivery to the crew the same way that the PECS provided these functions to a patient (Section 3.2.4). In an emergency, the EGRESS computer system will automatically activate the EECS, directing oxygen flow from the MECS control valve to the EECS. A schematic diagram of the EECS is shown in Fig. 3.2 (c).

3.2.5.1 EECS Carbon Dioxide Removal

The maximum EECS usage time of twelve hours comes from the maximum lifetime of a single MECS size LiOH canister. As with the PECS, one MECS sized LiOH canister will be used in the EECS for simplicity and redundancy (Section 3.2.4.1). Since two MECS canisters can remove the carbon dioxide produced by a crew of five for twenty-four hours (Section 3.2.3.1), one canister will remove the same amount for twelve hours. As with the MECS and PECS LiOH canisters, the EECS canister will also be sealed in plastic during EGRESS dormancy.

3.2.5.2 EECS Water Removal

As the the PECS, water removal in the EECS is also done with a one-use silica gel canister. In twelve hours, a five man crew will produce half of the 24 hour total listed in Fig. 3.6 (4.16 kg) requiring the EECS canisters to carry 16.6 kg of silica gel to maintain a 60% relative humidity [3-2].

3.2.5.3 EECS Patient Delivery Equipment

Air is delivered to the crew members in the closed-circuit EECS through the same pressure-demand masks used in the PECS (Section 3.2.4.4). These masks are stowed above the upper control panels near the center of the EGRESS crew cabin, and can be unstowed and ready for use immediately.

3.2.6 Potable Water and Food Supplies and Systems

An essential part of providing an adequate life support system involves maintaining the proper fluid balance and meeting the nutritional requirements of the EGRESS crew members. This Section describes the potable water and food supplies and systems provided in the EGRESS ECLSS.

3.2.6.1 Potable Water Supplies and Systems

A healthy human being requires approximately 2.0 kg of water per day [3-4] in order to prevent dehydration. As well, previous space flights have shown that astronauts experience relative dehydration due to the effects of weightlessness and require an additional 1.0 to 2.0 kg of water immediately before returning to earth [3-1]. Although normal EGRESS missions are not expected to exceed 24 hours in length, additional water provisions will be required in the event of a delayed landing or recovery to meet these basic requirements. Therefore, the EGRESS ECLSS will provide water to five crew members for up to 48 hours, for a total of 20 kg of water.

The EGRESS ECLSS will provide water to the crew with a simple “fill and draw” system, similar to ones used on the Mercury and Gemini spacecraft in the 1960's [3-4]. Fuel cells, used for water and electricity production during Apollo, Skylab, and space shuttle missions [3-8,3-9,3-10], will not be used on the EGRESS vehicle due to their complexity and heavy weight. The EGRESS "fill and draw" system provides a water storage and delivery system with no power requirements or safety hazards.

The EGRESS ECLSS potable water storage tank consists of a 6061 aluminum outer shell and a flexible polyisoprene interior bladder, which contains the water supply [3-4]. A hand operated air pump provides air pressure between the tank and the bladder, forcing water from the tank, through a 70 inch long hose, and to a nozzle in 1/2 oz increments. An analog counter on the nozzle records the amount of water used. To determine the volume of interior bladder, the following formula was used:

$$\text{Volume} = (\text{mass}) / (\text{density}). \qquad (3\text{-}12)$$

For a water density of 1000 kg/m^3, Eqn. 3-12 gives an interior bladder volume of:

$$(20\ \text{kg}) / (1000\ \text{kg/m}^3) = 0.0200\ \text{m}^3\ (0.71\ \text{ft}^3).$$

The aluminum exterior will occupy a total volume of 1.0 ft^3 to allow the hand pump to operate effectively. The choices for materials used for the EGRESS potable water system, diagrammed in Fig. 3.8, are based on the materials used in the early Mercury and Gemini water systems [3-4].

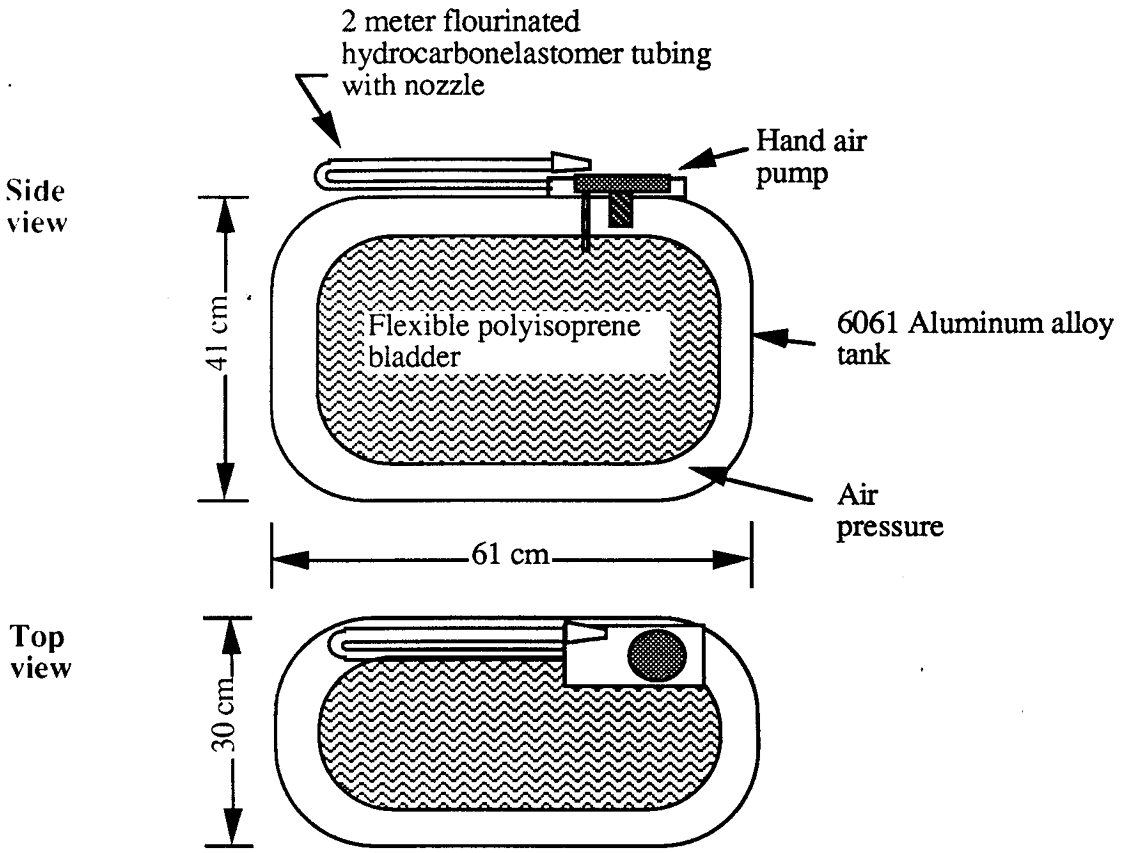

Figure 3.8 - EGRESS potable water tank with hand delivery pump and tubing assembly

In order to ensure that the potable water supply is safe to drink after a long period of storage, the EGRESS potable water will be monitored during periodic systems checks such that the NASA specified quality and sterility levels [3-4] listed in Fig. 3.9 are maintained.

Quality Requirement	Limit
Electrical conductivity	0.33 micro mho per cm
pH	6 to 8
Total residue	2 mg per liter

Fig. 3.9 - EGRESS water quality standards

Sterility, the absence of all viable organisms (yeast molds, E. Coli, etc.), can be preserved by the addition of small amounts of iodine or chlorine to the water supply. Because chlorine added to the water supply on several Apollo missions produced a noticeable taste and odor [3-4], 100 mg/liter of iodine as a biocide will be added to the EGRESS water supply during the initial loading of the tank. As iodine tends to degrade during long term storage, additional iodine will be added every six months to maintain an acceptable water quality. A bacterial filter,installed in the water nozzle, will further ensure the quality of the water delivered to the crew during an EGRESS mission.

3.2.6.2 Nutritional Support

Research and observations in human nutrition has shown that the human body can survive extended periods without food. However, the Project EGRESS Human Factors group has determined that the EGRESS crew will require a supply of food, based on the following considerations:

1. An active human being requires between 2000 to 3000 kilocalories of food per day (Fig. 3.1) in order to remain healthy [3-4].
2. Missions requiring the immediate evacuation of Space Station *Freedom* may result in an extended wait period on orbit to allow for correct positioning of the EGRESS spacecraft for reentry.
3. The possibility of a missed landing sight may require an extended wait for recovery.
4. The availability of food is psychological advantage to the crew.
5. Modern advances in food preservation allow for safe food storage for long periods of time.

The EGRESS ECLSS will provide enough food to keep a crew of five comfortable and alert during missions up to 48 hours long. The EGRESS ECLSS food supply items, listed in Fig. 3.10, are similar to those carried on previous Apollo [3-8], Skylab [3-9], and space shuttle [3-11] missions. These items were chosen because they have a long shelf-life, they are small and can be stowed easily inside the crew cabin, they don't need heating or rehydrating which would required additional equipment, and they provide an adequate amount of nutrition with good flavor.

Food Item	Quantity	Caloric Value
M & M Plain™ Candy	5 packs	240 kcal per pack
M & M Peanut™ Candy	5 packs	300 kcal per pack
High nutrient food bars	5 bars	400 kcal per bar
"Wetpak" fruit cocktail	5 packs	150 kcal per pack

Figure 3.10 - EGRESS ECLSS food supplies

For a crew of five sharing the items equally, these food items will provide a total of 1090 kcal of nutrition to each crew member on board the EGRESS vehicle. While this caloric value falls short of the 3000 kcal daily requirement, it is sufficient to help each crew member remain alert and oriented while performing their EGRESS mission tasks.

3.2.7 Waste Management System

An important aspect of environmental control is the ability of the EGRESS ECLSS to manage the various waste materials produced by the crew during an EGRESS mission. The EGRESS ECLSS Waste Management System provides means of controlling dry and wet wastes while also providing for the personal hygiene of the crew members.

Dry wastes, including used towelettes, empty food packages, and other litter will be collected and stored in a dry waste container located under the medical technician's couch (Fig. 3.22). Wet waste, including water, body secretions, or other fluids, will be drawn into a wet waste tank at the lower rear of the cabin with a suction pump. A 10 foot hose attached to the suction device allows crew members to remove loose fluids from anywhere in the cabin. A special nozzle attachment also allows the suction device to help clear a ventilated patient's airway (Section 3.3.1).

Personal hygiene supplies, including urine and feces collection bags and sanitary towelettes, are located in a small storage locker also located below the the medical technician's couch. Individual urine and fecal matter collection bags will be used on the EGRESS vehicle in lieu of the more complicated systems used on the Apollo or the space shuttle [3-11] due to volume limitations inside the EGRESS crew cabin.

Both the fecal matter and urine collection bags are plastic and will be disposed of after a single use. The fecal bags, shown in Fig. 3.11, are plastic, single-use bags designed for use by either male or female crew members [3-12]. The bags are attached by an adhesive cover which can folded and sealed for disposal. A finger thimble is used to clear the feces away from the body during use. The urine collection bags, on the other hand, have different designs based on the differences between male and female anatomy. Male urine bags have a roll-on cuff while female bags have an adhesive flange similar to the fecal bags. Both types of urine bags are plastic, for single-use only, and have a capacity of one liter. The EGRESS ECLSS waste management system contains 10 fecal bags, 10 male urine collection bags, 10 female urine collection bags, and 20 sanitary tissues.

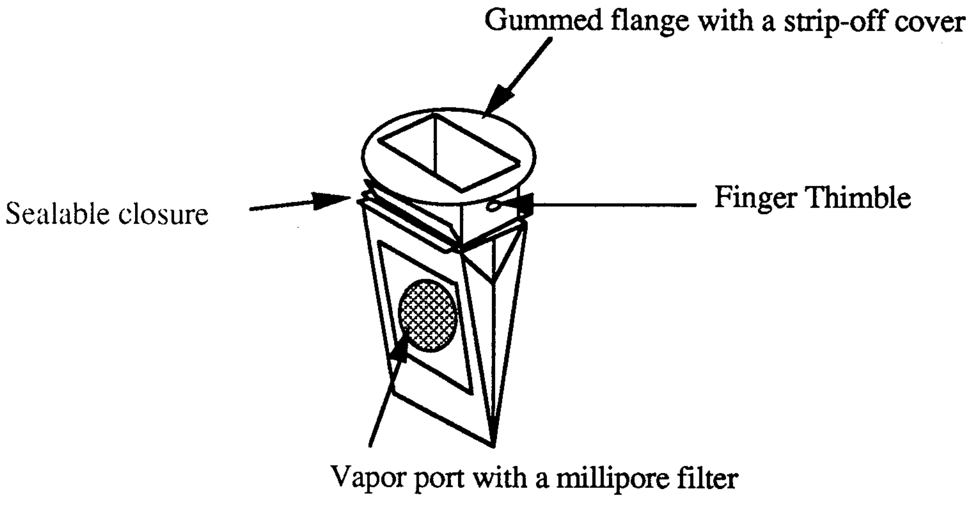

Figure 3.11 - EGRESS waste management fecal collection bag

3.3 Medical Systems and Provisions

While the EGRESS is designed to carry healthy crew members back to earth in an emergency, it is also designed with the capability of returning a critically ill or injured crew member to earth for more extensive treatment. As such, the EGRESS is equipped with basic monitoring equipment and consumable provisions to monitor and maintain one patient during a return to earth.

3.3.1 Medical Equipment

The medical equipment needed on the EGRESS vehicle was determined both from the needs of a critically ill or injured astronaut and from the types of illness or injuries that could occur on the space station. In order to allow for adequate care and monitoring of the EGRESS patient, the EGRESS vehicle will be equipped with a ventilator, a 0-g infusion device, a vital statistics monitor, and a defibrillator. These devices are portable versions of similar equipment used on the Space Station *Freedom's* Health Maintenance Facility. All EGRESS medical equipment will be located in the control panel above the patient and medical technician, as shown in Fig. 3.18.

Providing adequate tissue oxygenation for a critically ill patient unable to breath properly requires the use of a mechanical ventilation system. When necessary, the EGRESS spacecraft will provide mechanical breathing assistance with a portable, air powered ventilator, such as the OMNI-VENT Portable Ventilator which is presently used in emergency medical transport vehicles on earth [3-13]. This type of ventilator was chosen for the EGRESS vehicle because it is small, lightweight, simple to operate, and requires no electrical power. As well, the EGRESS will provide sensors to monitor critical respiratory parameters including inspired oxygen, expired carbon dioxide, tidal volume, and pulmonary resistance. These systems will all be hooked in-line with the PECS (Section 3.2.4).

In addition to adequate tissue oxygenation, critically ill patients generally require intravenous fluid therapy to prevent dehydration. Because fluids do not separate from air or "fall" in 0-g conditions, the EGRESS will utilize a special 0-g Intravenous Infusion Device, to deliver adequate amounts of fluid to a patient. This device, presently under development by NASA [3-1] for use on the space station, will also be necessary on the EGRESS vehicle to help maintain a proper patient fluid balance during an earth-return mission.

In order to determine if the oxygen, fluid, and other medical interventions are adequate to meet the patient's needs, continuous monitoring of a patient's vital signs will be required. Thus, the EGRESS will include a portable vital statistics monitor to record a patient's heart rate, blood pressure, and respiratory rate. Heart rate and respiratory rate will be monitored by leads connected to the patient's chest. Blood pressure will be monitored with an automatic pressure cuff - a device used in present-day emergency medical vehicles and operating rooms which automatically expands and contracts around a patients arm while sensing systolic and diastolic pressures.

Finally, the EGRESS will also have an automatic defibrillator on board for the treatment of dangerous arrythmias. Arrythmias, irregular heart beats cause by electro-chemical disturbances in heart, can be caused by electrical shock injuries or, in some cases, long term exposure the 0-g environment [3-8]. A defibrillator applies an electrical shock to the patient which temporarily interferes with the heart's own electrical activity, allowing the heart beat to return to normal. This device will be linked to a patient's chest through two adhesive paddles and will automatically deliver shocks when dangerous arrhythmias are sensed. The EGRESS defibrillator will be only be used on a patient who is experiencing dangerous arrhythmias during an EGRESS mission.

3.3.2 Medical consumables

In addition to critical care equipment for use during medical missions, the EGRESS vehicle will provide drugs and medical provisions for the care and comfort of both the patient and the other crew members.

A drug-pack located near the feet of the EGRESS medical technician (see Fig. 3.17), contains medications for treatment of a critically ill astronaut as well as for aches, pains, or nausea in any crew member. The oral and injectable medications that will be included in the EGRESS drug pack are similar to those used on the space shuttle. The EGRESS drug pack medications are listed with their functions in Fig. 3.12 (a) and Fig. 3.12 (b).

Oral Medications	**Use**
Dramamine	Prevents motion sickness
Aspirin	For headaches, fever
Nitroglycerin	Vasodilator, relieves angina
Digoxin, .25 mg	Treatment for arrhythmias
Dexedrine, 5 mg	Stimulant
Lomotil	Relieves diarrhea
Tylenol	For pain relief
Codeine, 15 mg	For stronger pain relief
Scop/Dex, .4 mg	Prevents motion sickness
Benadryl, 25 mg	Anti-histamine
Actifed	Anti-histamine/decongestant
Halcion, .25 mg	Relaxant

Figure 3.12 (a) - Oral medications

Injectable Medications	**Use**
Epinephrine, 1:1000	Treatment of allergic rx.
Benadryl, 50 mg/ml	Anti-histamine
Isoproterenol, 1:5000	Treatment of shock,cardiac arrest, arrhythmias
Atropine, 0.4 mg/ml	Reduce bronchial secretions Reduce GI spasms
Lidocaine, 40 mg/ml	Treatment of arrhythmias
2% Xylocaine/Epi.	Local anesthetic
Morphine, 10 mg/ml	Narcotic, for pain relief
Decadron, 4 mg/ml	Anti-inflammatory
Compazine, 5 mg/ml	Tranquilizer, prevents vomiting

Figure 3.12 (b) - Injectable medications

In addition to these medications, the EGRESS vehicle will supply the various medical instruments and supplies needed to treat both a patient and crew members during an EGRESS mission. Various needles, syringes, and a tubex injector are included to allow administration of the injectable medications. A circothyrotomy set with oral and tracheal airways will allow a medical technician to intubate or perform a tracheotomy if required. Tape rolls and bandages of various types are also available for patient or crew member use. These, and other emergency medical provisions are listed in the EGRESS Equipment/Provisions List in Appendix A.

3.3.3 Crew Medical Training

In order to properly utilize the EGRESS medical systems and supplies, the medical technician must be properly trained in both general medical procedures and in the use of the EGRESS equipment. Because present plans do not include a physician on the space station Freedom, NASA will require the following medical training for the space station crew members [3-14]:

1. All space station crew members shall be trained in basic first aid and Basic Life Support, including CPR.
2. Two crew members will have extensive medical training, such that:
    a. One crew member has specialized training equivalent to that of an emergency medical technician and an anesthetist/surgical assistant, and
    b. One crew member has at least 100 hours of general medical training.

In the event that the EGRESS vehicle is used to transport an ill or injured crew member to earth, an EGRESS medical technician will chosen from the two space station crew members who have had the most medical training and experience.

3.4 Interior Systems and Configurations

The EGRESS crew cabin is designed to provide adequate space for a maximum crew of five including one patient, the necessary crew provisions, and all necessary hardware. In order to maximize crew efficiency and comfort inside the EGRESS cabin, the interior systems were designed to meet volume, size, and acceleration requirements of the crew. This section describes the design and placement of the EGRESS interior systems, including the seats, the displays and controls, and the windows. As well, this section describes the placement of the crew provisions within the EGRESS crew cabin.

3.4.1 Basic Requirements

Depending on the length and type of task to be performed, a human being requires between 0.71 m^3 and 3.51 m^3 (25 ft^3 and 124 ft^3) to function comfortably and effectively [3-15]. Based on the volume and weight requirements for the EGRESS vehicle (Chapter 2), the crew cabin has a total volume of 7.1 m^3 (250 ft^3). Assuming that the interior systems make up 25% of the total volume of the cabin [3-15], the total usable volume for each of five crew members in the EGRESS cabin is 1.06 m^3 (37.5 ft^3). Although this volume is at the lower end of the functional range, this space will provide a comfortable and usable environment during a short duration EGRESS mission requiring minimal physical activity.

Within this volume, the EGRESS crew cabin is designed to accommodate five Space Station *Freedom* crew members who can range in size from a large "95th percentile male" to a small "5th percentile female." These percentiles are statistical measurement of human sizes which identify where in the total population a person of given size falls [3-16]. All measurements, including couch lengths, control panel sizes, and other dimensions are based on these sizes.

Finally, an important consideration for returning both healthy and ill or injured astronauts to earth is the deceleration loading (g-loading) that they must undergo during reentry and splashdown. Excessive g-loads beyond the normal 1-g on earth can cause blackouts, respiratory difficulty, and can be fatal if maintained for long time periods. Furthermore, the duration of which an ill or injured crew member can withstand high g-loading is substantially less than that of healthy crew members. The maximum allowable g-loading on the EGRESS crew, specified by the NASA ACRV Request For Proposal, is listed in Fig. 3.13.

Body axis	Reentry Load	Maximum impact load on crew	Maximum impact load on patient
Chest (+X)	4 g	15 g	10 g
Head (+Y)	1 g	10 g	3 g
Side (+Z)	0.5 g	5 g	2 g

Figure 3.13 - Maximum allowable g-loads

Higher g-loads through the chest than through the head or the side can be tolerated by crew members because forces in this direction have less effect on the pumping force of the heart. Based on a reentry angle of attack of 40° and a lift to drag ratio of 0.8 (Chapter 7), the maximum g-forces will be directed at 80° above the cabin floor, towards the rear of the craft. Therefore, as shown in Fig. 3.14, the EGRESS seats will face the rear of the craft at an angle of 10° above the cabin floor.

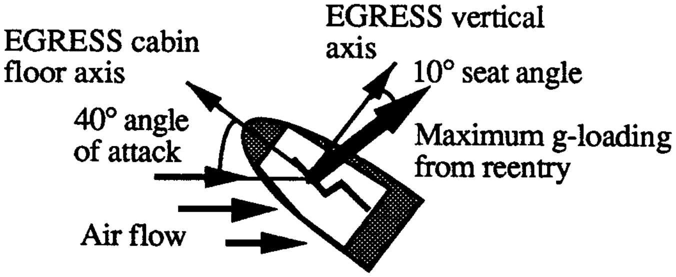

Figure 3.14 - The effect of maximum g-loads on crew orientation

3.4.2 Seats

The EGRESS vehicle will utilize three different types of seats to meet the specific requirements of each crew member. Two "command seats," permanently mounted on opposite sides of the EGRESS cabin, will be used by the pilot and medical technician. Two "jump seats" below the command seats will normally remain stowed and used only during EGRESS missions requiring a five person crew. The third type of seat, the "stretcher/chair," is mounted in the center of the EGRESS cabin where it can be removed easily when needed for patient transport. Each seat has an aluminum tubing truss structure across which sturdy cloth is stretched to support the crew members. This design, similar to one used on the Apollo spacecraft, has low material weight and requires a minimal amount of cabin volume. All EGRESS chairs utilize a common five point harness restraint system while the stretcher/couch also provides leg and head restraints for additional patient support.

Although the commands seats, shown in Fig. 3.15, are permanently mounted in the EGRESS crew cabin, adjustable head, foot, and arm rests allow the seats to accommodate crew members according to required size ranges (Section 3.4.1.1). Furthermore, the head rests can tilt down 90° to allow the occupants a better view through the EGRESS windows above their heads. Manual override controls are located on the arm rests of both chairs (Section 3.4.4). Two g-limiters [18], devices that help reduce sudden changes in g-forces through impulse-activated spring, are mounted and the main connecting joints between the seats and the EGRESS vehicle to help cushion the occupants during the flight.

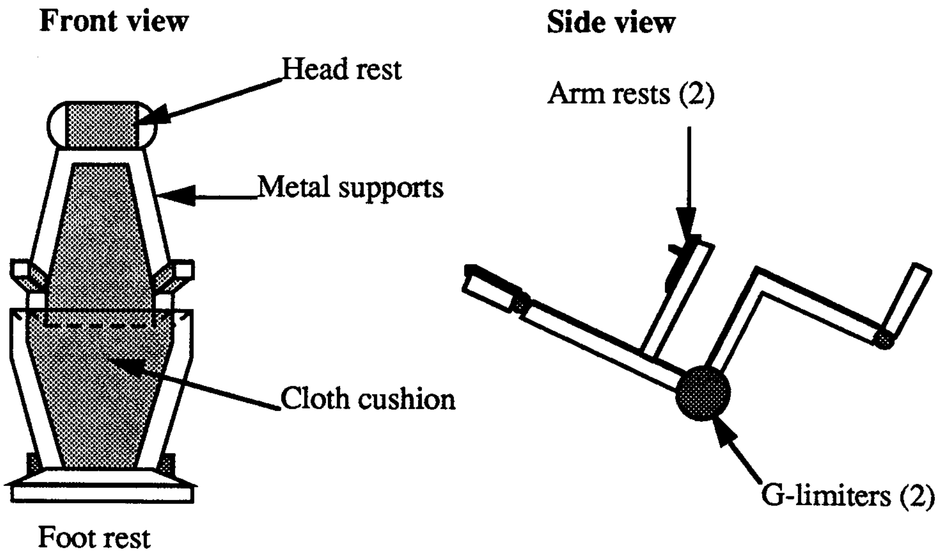

Figure 3.15 - Command seats

The two jump seats are attached directly to the base of the EGRESS cabin hull and remain stowed as shown in Fig. 3.16 when not in use. This design minimizes the space taken up by unused seats during a normal 3 person mission and allows more space in the cabin for the transport of packages and supplies from the space station, if necessary. The jump seats do not utilize a g-limiter due to the seats' locations and methods of attachment to the EGRESS frame.

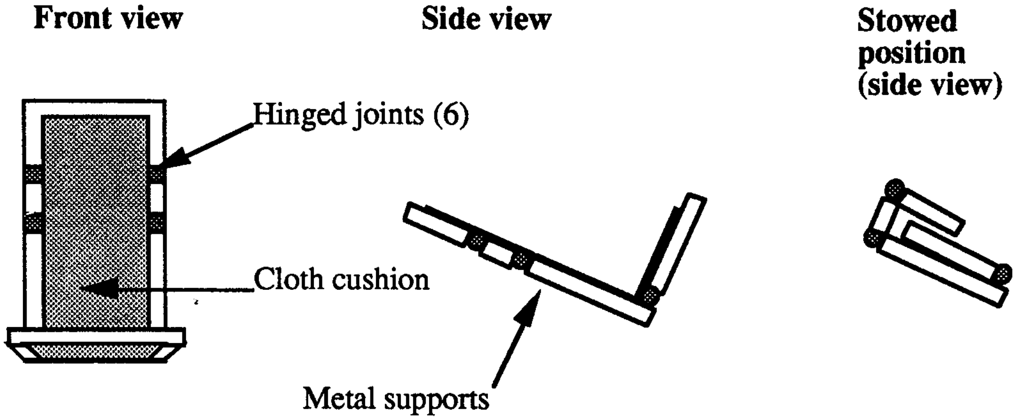

Figure 3.16 - Jump seats

The "stretcher/chair" (Fig. 3.17) can function as a patient stretcher during the entry and exit of the EGRESS cabin and as a normal chair during the EGRESS flight. During entry of the vehicle, a patient is moved into the vehicle on the "stretcher" after the pilot and medical technician have boarded. With the patient strapped to the stretcher, the pilot and medical technician then release pins in the two hinged joints and fold the stretcher into a chair, upon which it can be anchored in place at the normal 10° angle for the flight. During recovery of the crew, the stretcher/chair is unclamped from its cabin mountings, pulled and secured into the stretcher position, and removed from the vehicle. If a patient with back or pelvic injuries must be returned to earth in the EGRESS vehicle, the stretcher can remain straight during the mission through special attachments in the cabin. During missions not involving a medical emergency, the stretcher/chair can be left in the cabin in the chair position. G-limiters are also used at the stretcher/chair attachments to help reduce g-loading.

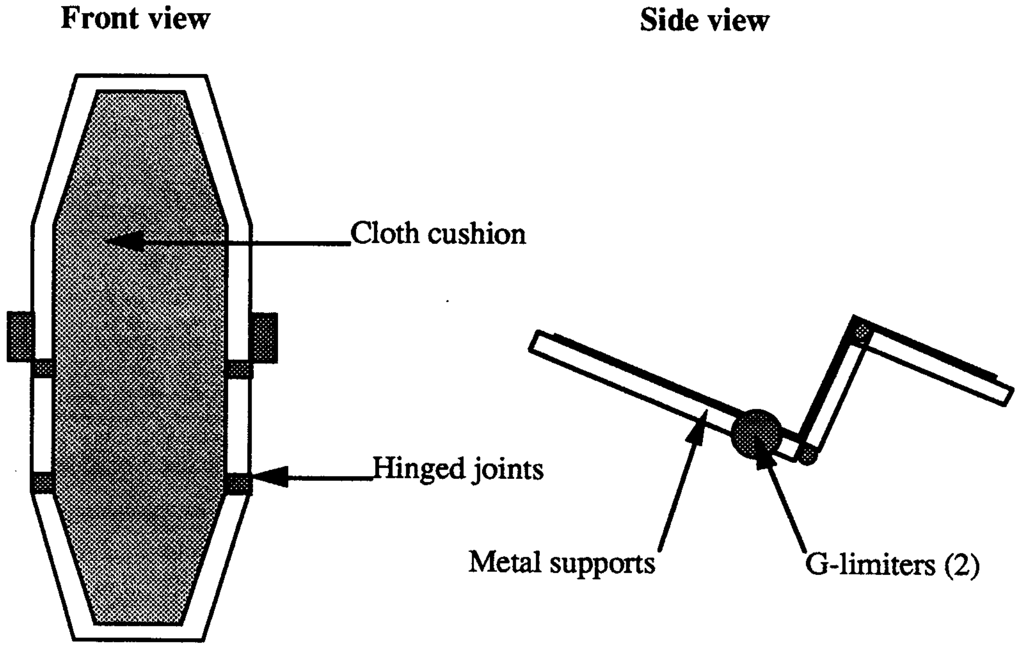

Figure 3.17 - Stretcher/chair

3.4.3 Crew Configuration

The configuration of a possible 5 member crew is based upon both the basic configuration requirements (Section 3.4.1) and the duties of the different crew members. The primary crew of a pilot, a patient, and a medical technician will be seated in the rear "top row" while the secondary crew members will sit in the jump seats in the "bottom row" of the cabin. These configurations will allow easy access to necessary controls and provisions, easy entry and exit of the vehicle, and maximum center of gravity stabilization during the flight. The crew configuration in the EGRESS vehicle is shown in Fig. 3.18.

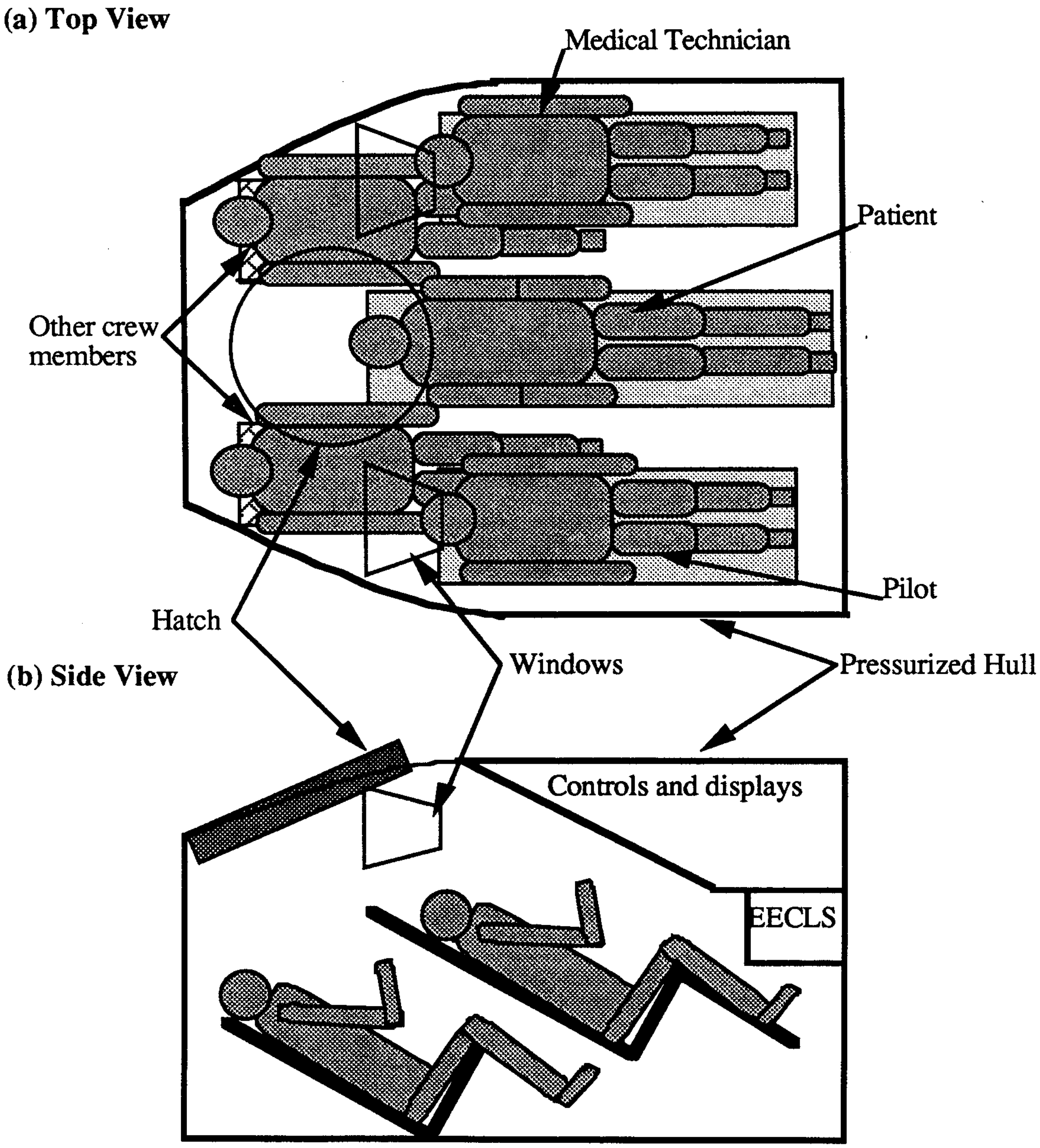

Figure 3.18 - Crew configuration

The command chairs and the stretcher/chair will be placed in a row facing the rear of the cabin at the appropriate 10° angle (Section 3.4.1) with the stretcher/chair placed between the two command chairs. This configuration will allow easy loading and removal of a patient on the stretcher/chair through the hatch in the center of the vehicle. The pilot and medical technician are seated such that all appropriate controls are within arms length. The patient is situated directly below the critical care equipment such that both the patient and the equipment are within easy reach of the medical technician.

The jump seats are located on the floor, centered behind the three primary seats and also angled at 10° above the floor. These seats, when not in use, will remain folded to allow space for the transport of supplies from the space station. Crew members seated in the jump seats will be in easy reach of the hatch and the provisions placed under the primary seats (Section 3.4.5).

3.4.4 Displays and Controls

The EGRESS vehicle contains many displays and controls which enable the crew to control the craft, monitor its performance, and care for an injured astronaut. The EGRESS displays and controls are divided between the medical technician and the pilot, as shown in Fig. 3.19.

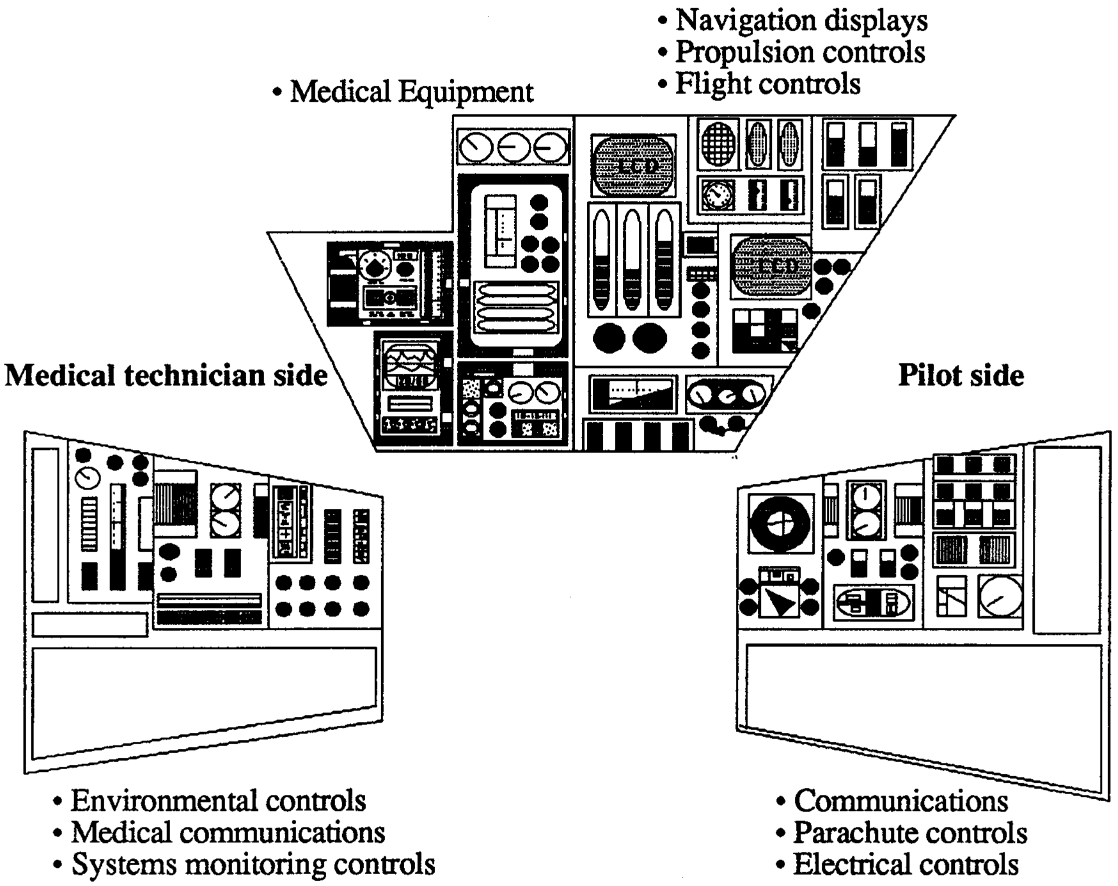

Figure 3.19 - EGRESS main displays and controls

Above and to the right of the pilot are controls for navigation, propulsion, flight control, communications, and power systems, while panels above and to the left of the medical technician contain medical equipment and controls for life support, medical communications, and systems checking.

The primary flight control panel, shown in Fig. 3.20, is located directly in front of the pilot and contains flight control information including manual override controls, indicators of velocity, attitude, and altitude, and three LCD computer screens. On the right of the panel, the RCS jet management and fuel monitors provide information on RCS fuel and oxidizer pressures, temperatures, and quantities. As well, the priority, selection, and availability of the rockets is monitored here. Atmospheric data such as pressure, temperature, and density will be placed on the lower center of this panel. Finally a caution and warning system to monitor critical conditions of most spacecraft systems will be placed at the top, center of the pilot's main display panel for obvious viewing. A malfunction or out-of-tolerance condition will result in the illumination of a status light and sounding of an alarm tone in the crew members' headsets that identifies the abnormality. The alarms will continue until a crew member resets the circuit. The caution and warning system will also include equipment to sense its own malfunctions.

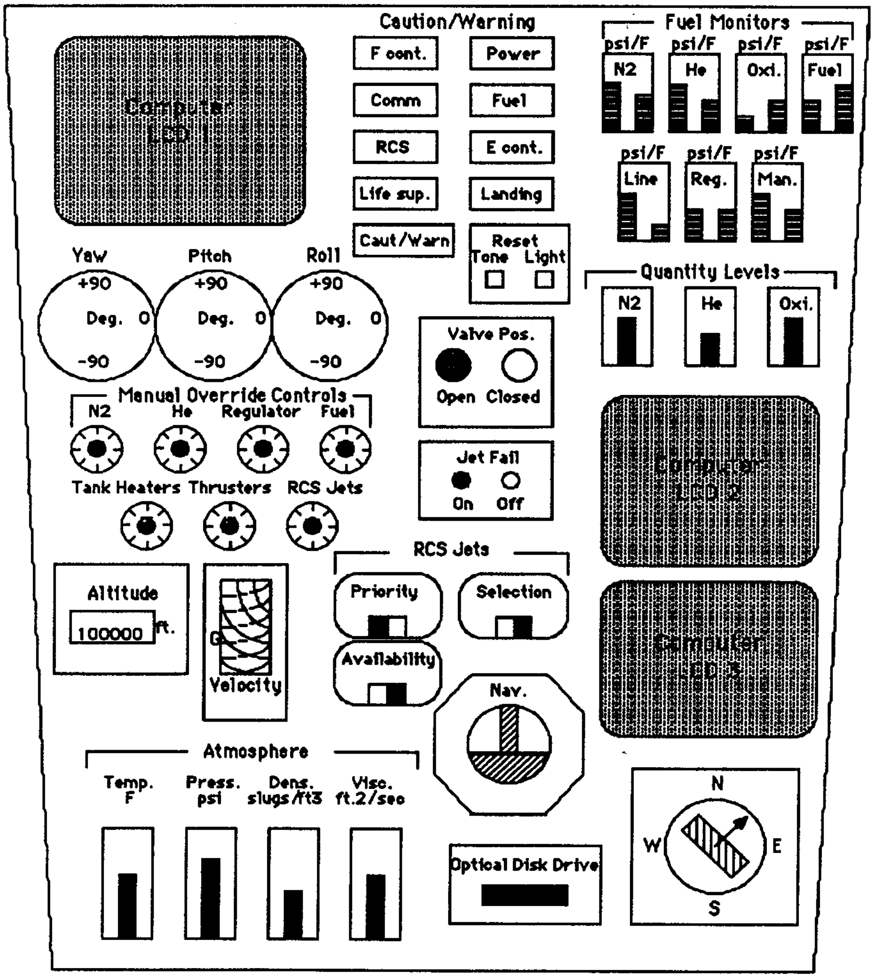

Figure 3.20 - Pilot controls and displays

To the right of the pilot, a panel provides landing information, communications data, parachute deployment status, and a power and circuit breaker board. The communication equipment includes the master and intercom volume meters and the S-band and VHF frequency meters. The power and circuit breaker board contains the EGRESS vehicle's main power switch, the power distribution system, current and total power consumption displays, and most of the EGRESS circuit breakers.

The portable critical care equipment (Section 3.3.1) is secured in cut-out areas of the control panel above the medical technician and the patient (Fig. 3.18). To the left of the medical technician, a wall panel contains the ECLSS controls and displays, a medical communication radio, and systems check information. The environmental controls will monitor the total cabin pressure, the partial pressure of oxygen and carbon dioxide, and the cabin temperature and humidity. An environmental caution and warning system will alert the EGRESS crew members of fire, pressure leaks, or system failures. The medical communications panel allows the medical technician to communicate directly with mission control flight surgeons during an EGRESS mission. Finally, the system check system will monitor the craft during dormancy system reviews.

The arm rests of the command chairs (Fig. 3.15) also have specialty controls to allow easy use. On the pilot's left armrest , a control stick will allow the pilot to manually control the yaw, pitch, and roll rates of the EGRESS vehicle with simple hand movements. A computer keyboard, stored on the side of the pilot's right armrest, can fold out across the pilot's lap, allowing the pilot access to the EGRESS computers. The pilots right armrest also contains controls for manual parachute deployment. The medical technicians armrests contain manual override controls for defibrillation and ventilatory parameter changes.

All the controls and displays are designed for easy reach and simple readability. The controls are predominantly of three types: toggle switches, rotary switches with click-stops, and push buttons. Critical switches are guarded so that they cannot be thrown inadvertently, while others are locked with mechanisms that must be released before the switch or button can be activated [3-18]. The three displays screens and many of the indicators use active-matrix liquid crystal displays (LCD's) rather than cathode ray tubes (CRT's) as used on previous spacecraft [3-15,3-19,3-20]. LCD's deliver the same brightness but are smaller, lighter, and more rugged than CRT's [3-21,3-22]. A thin plastic coating placed over all of the controls and displays will protect them from the corrosive effects of salt water after splashdown and will not interfere with use of the controls during the flight.

3.4.5 Windows

Two windows on either side of the EGRESS hatch above the command seats (Fig. 3.18) will allow viewing outside the spacecraft during possible space station rendezvous and redocking procedures or for navigation in the event of a computer navigation system failure. Windows are also essential for the psychological well being of the EGRESS crew.

The windows will be double paned with antireflective coatings on the external surface and a blue-red reflective coating on the inner surface to filter out most infrared and all ultraviolet rays.[3-18]. Straight sides and a grid pattern (reticle) fused onto the surface of the windows will help the pilot orient the EGRESS with a docking node of with the earth [3-23] . Rounded corners and the placement of the windows between spars in the EGRESS vehicle's structure will help decrease the structural impact of the windows. Finally, each window will be equipped with a shade to cut off outside light if desired [3-18]. A diagram of an EGRESS window is shown in Fig. 3.21.

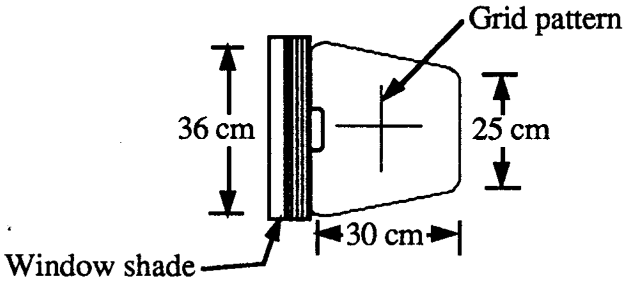

Figure 3.21 - EGRESS window design

3.4.5 General provisions and placements

The EGRESS vehicle will contain various general, medical, and emergency provisions that will help guarantee the safe flight and recovery of the EGRESS crew. Fig. 3.22 shows an interior view of the crew cabin showing the placement of these provisions with the seats and control panels removed. Appendix A provides a complete list of EGRESS provisions and systems, including their weights and volumes.

Pockets on the sides of the cabin will carry pressurized pens, clipboards, notepaper, and "cue cards" outlining flight and medical procedures for use during an EGRESS flight. Food will also be stored in these pockets. Flashlights and penlights will be provided for use during systems checkouts, EGRESS flights, and recovery. Waste management equipment and supplies are stored under the medical technician's seat on the floor of the crew cabin.

The majority of the critical care medical equipment, including on package of ventilator tubing, two liters or lactated ringers solution, and intravenous lines, will be stored in a medical supply kit on the floor of the crew cabin when not needed. Also stored in this kit, "trauma pants" with inflatable leg chambers will allow a patient to better withstand the g-forces of reentry. General use medical supplies, including bandages, alcohol prep-pads, needles, and syringes, are located in pockets on the wall of the crew cabin next to the medical technician.

Two fire extinguishers, one located within reach of the pilot and another in the rear of the craft, will give the crew members the ability to quickly control and put out fires in the crew cabin. An emergency supply kit will carry five automatically inflatable life jackets, a flare gun with flares, and other provisions needed to ensure the safety and survival of the crew during a wait for recovery. An automatically inflatable five person raft, stored behind the jump seats at the front of the crew cabin, will allow the safe exit from the EGRESS vehicle if required.

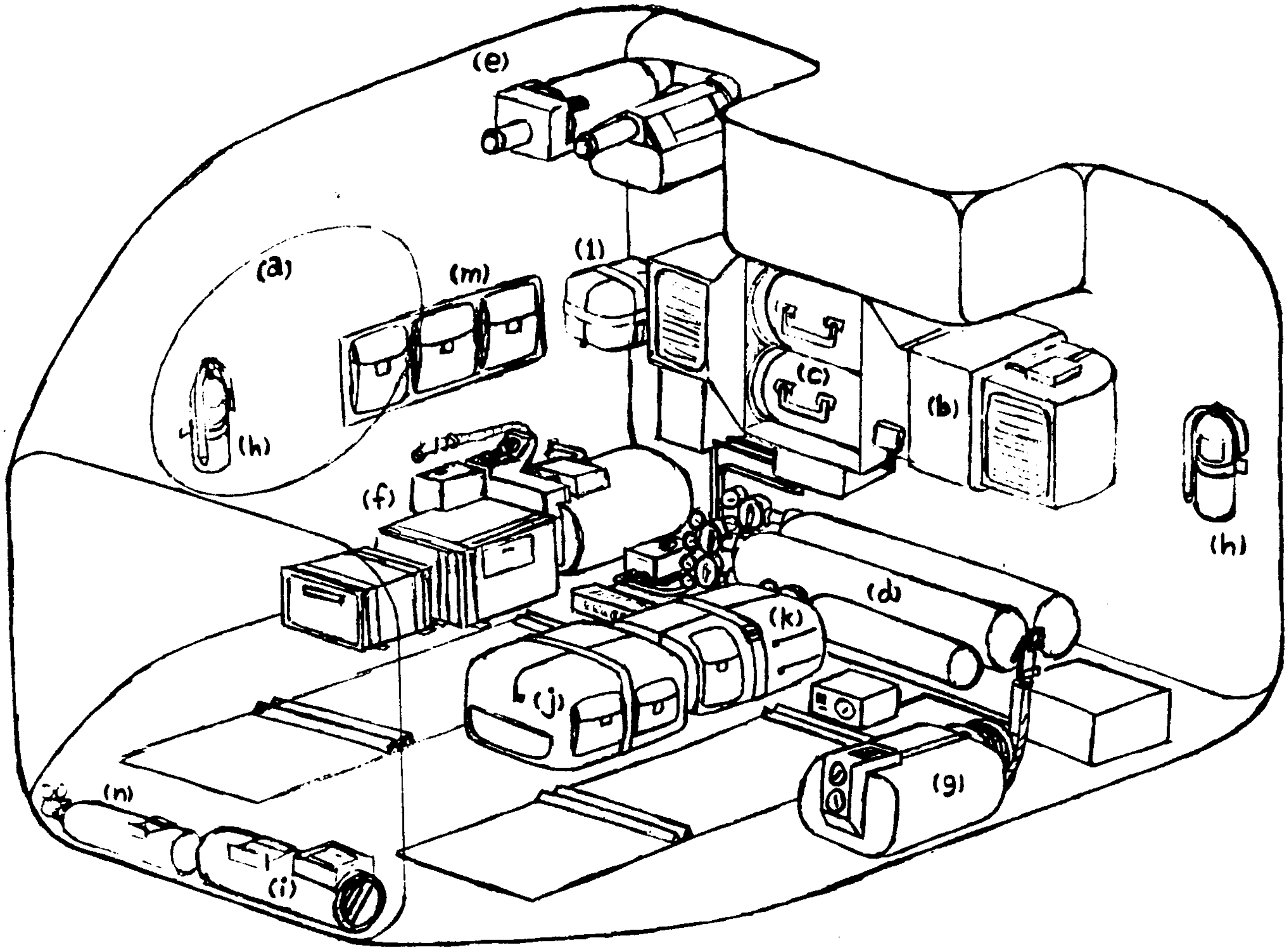

Figure	Provision or equipment description
(a)	Hatch
(b)	MECS
(c)	LiOH canisters
(d)	Oxygen and nitrogen tanks (ASPS)
(e)	EECS
(f)	Waste management systems
(g)	Potable water systems
(h)	Fire extinguishers
(i)	Life raft
(j)	Medical supply kit
(k)	General and emergency supply kit
(l)	Drug pack
(m)	Storage pockets
(n)	Emergency patient recovery oxygen tank

Figure 3.22 - Placement of provisions in the EGRESS crew cabin

Chapter 4

Power and Communications

4.0 Summary

4.1 Power System

4.2 Communications System

4.3 Computer System

4.4 Navigation System

4.5 Propulsion Module

4.0 Summary

The Power and Communication Group was responsible for designing all spacecraft systems requiring electronics expertise. Thus, the group's responsibilities were expanded to include not only power generation, power distribution, and communications, but also computer hardware, navigation, and avionics. These systems were designed in accordance with the RFP and the System Performance Requirements Document. A summary of the major features of these systems is presented below.

EGRESS is powered by primary (non-rechargeable) batteries during its operations. Power will also be provided to EGRESS from Space Station *Freedom* using a nickel-hydrogen (rechargeable) battery system as a reservoir. Power will be distributed to EGRESS systems using four main buses. Two major interface areas are present in the power distribution system, one between EGRESS and the propulsion module, and the other between EGRESS and the space station. Power will be distributed and monitored using state-of-the-art software in order to help detect problems before they develop, and isolate problems that do surface.

The communication system is primarily based on S-band radio transmissions. This system will use the Tracking and Data Relay Satellite System (TDRSS), which is currently used by the Space Shuttle, to relay signals to the ground. EGRESS will also use a Very-High Frequency (VHF) system to communicate with search and rescue forces. The VHF system could serve as a backup for voice communications if there are problems with the primary S-band system. L-band communications will also be used to receive signals from the Global Positioning System satellites in order to accommodate the navigation system described below.

The EGRESS computer system, which is in control of most of the EGRESS subsystems throughout a crew return mission, is designed for reliability. The processing units, high powered space rated IBM AP101S general purpose computers, are linked in a triple redundant configuration. The computers are connected to an optical disk mass storage device and the rest of the vehicles subsystems, through a 24 bit data bus. Under control of the EGRESS Automated Software Environment, the system is responsible for regulating the power and life support systems, as well as serving as the flight management system and controlling most of the vehicles operations.

In order for the EGRESS vehicle to accomplish its various missions, it is important that the vehicle have accurate navigation and guidance for control. The navigation system consists of a inertial navigation system (INS) that is augmented by the Global Positioning System (GPS). The Honeywell CG1320 INS, based on a ring laser gyroscope is used to provide highly accurate attitude information. By incorporating GPS into the system, precise position is determined to within 15 meters. Though the system is normally initialized while the EGRESS vehicle is docked, initialization can take place after separation in the rapid evacuation scenario.

Smaller scale systems very similar to those described above will be used on the propulsion module in order to allow for its recovery at a later time.

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4.1 Power System

The power system is divided into two categories: power supplies and power management and distribution (PMAD). This section contains the design details of both of these power system categories along with the reasons for discarding other possible alternatives.

4.1.1 Power Supplies

Power will be supplied to EGRESS by one of three sources:

1) Primary (non-rechargeable) batteries on EGRESS
2) Secondary (rechargeable) batteries on the airlock
3) The Space Station *Freedom* power system (through an electrical interface)

The specific system used depends on the mode of operation of EGRESS and on any other special circumstances which may make one of the three power sources unavailable. This section gives the design details on each of these three possible power supplies.

4.1.1.1 Primary Batteries

The only source of power on EGRESS from separation to recovery is its primary battery system. These batteries are located inside EGRESS and outside of the pressurized crew compartment. Refer to Figure 2.3 for details.

The primary battery system is divided up into four modules. Each module contains 25% of the total energy of the entire system. This design was chosen so that the failure of one module would not affect any of the other three modules. This setup will reduce the propagation of failures throughout the power storage system. In fact, three separate failures of power modules will not totally jeopardize the mission. One module alone is capable of getting EGRESS from Space Station *Freedom* to the ground within a four to five hour time frame depending on the conservation of electrical power.

The primary batteries consist of lithium thionyl chloride ($Li/SOCl_2$) cells. These batteries are state-of-the-art and can achieve very high power and energy densities [4-1]. Each cell has an open circuit voltage of 3.5 V. They will be configured in ten cell strings so that 28 V will be provided at the end of the four year maintenance cycle. One hundred twenty of these strings will be combined in parallel to form each storage module. This design allows the power system to be lightweight and compact. Since volume and weight were important constraints in the design of EGRESS, this type of battery was very attractive. Specifically, the lithium primary battery system on EGRESS has an energy density of 400 Wh/kg on a mass basis. On a volume basis, this corresponds to an energy density of 900 Wh/dm^3.

The sizing of the battery system developed from a study of all EGRESS systems that require power (see Figure 4.1). Using this data, a load versus time diagram was produced (see Figure 4.2). From this analysis, it was determined that EGRESS would require an average of 3 kW of power. Peak power consumption is 3.4 kW during deorbit burn and the minimum power consumption during operations is 2.5 kW. An EGRESS mission requires the primary battery system to operate for a maximum of three hours. However, in sizing the battery system, a 24 hour operational scenario was used. This provides EGRESS with the ability to stay on orbit at minimal power consumption for approximately

24 hours before commencing with the deorbit burn. Also, in the event of an early return to Space Station *Freedom* before the deorbit burn, EGRESS would still have a sizable portion of energy remaining to complete a mission at a later time.

EGRESS System	Max Power Req.
Computer System	1500 W
Navigation System	300 W
Communication System	350 W
Power Distribution	200 W
Displays and Controls	300 W
ECLSS	500 W
Attitude Control Jets	50 W
Deorbit Burn Engines	200 W
Visible Beacon	300 W

Figure 4.1 - EGRESS System Power Requirements

Operating a 3 kW system for 24 hours requires 72 kWh of energy. The energy of the EGRESS system, however, was increased another 50% to 108 kWh. The reason for this increase is twofold. The EGRESS battery system is scheduled to be replaced every four years. At the end of four years, it is desirable to still have some extra power available so that if the schedule is not met, the mission will not be endangered. The power system on EGRESS was, therefore, designed to have 120% capability after four years for a safety margin. In addition, another 30% was added to the system at the beginning of life to allow for the expected battery degradation over the four year maintenance period [4-2]. Allowing for battery support equipment and casing, the projected mass of the system is 324 kg (713 lb) and the projected volume is 160 dm^3 (5.6 ft^3).

The $Li/SOCl_2$ batteries must be stored at 0° ± 10° C for preservation. Also, during operation, the batteries must be cooled in order to keep their operating temperature under 65° C. The batteries are approximately 85% efficient. This means that they reject 15% of the electrical energy that they are providing as heat [4-3]. Under the peak conditions of operation, 3.4 kW of power consumption, the batteries generate 510 W of heat. The battery cooling system on EGRESS is capable of dissipating this maximum amount of heat and smaller amounts of heat as well. The battery cooling system is a part of the central EGRESS thermal control network which transports the heat from internal components of EGRESS to space. The batteries are mounted directly to coldplates that are serviced by the thermal control network. A separate heating system must also be run constantly while EGRESS is docked to Space Station *Freedom* in a dormant state to keep the batteries at the proper storage temperature. The batteries will be provided with redundant thermostats so that the battery temperatures can be monitored for irregularities.

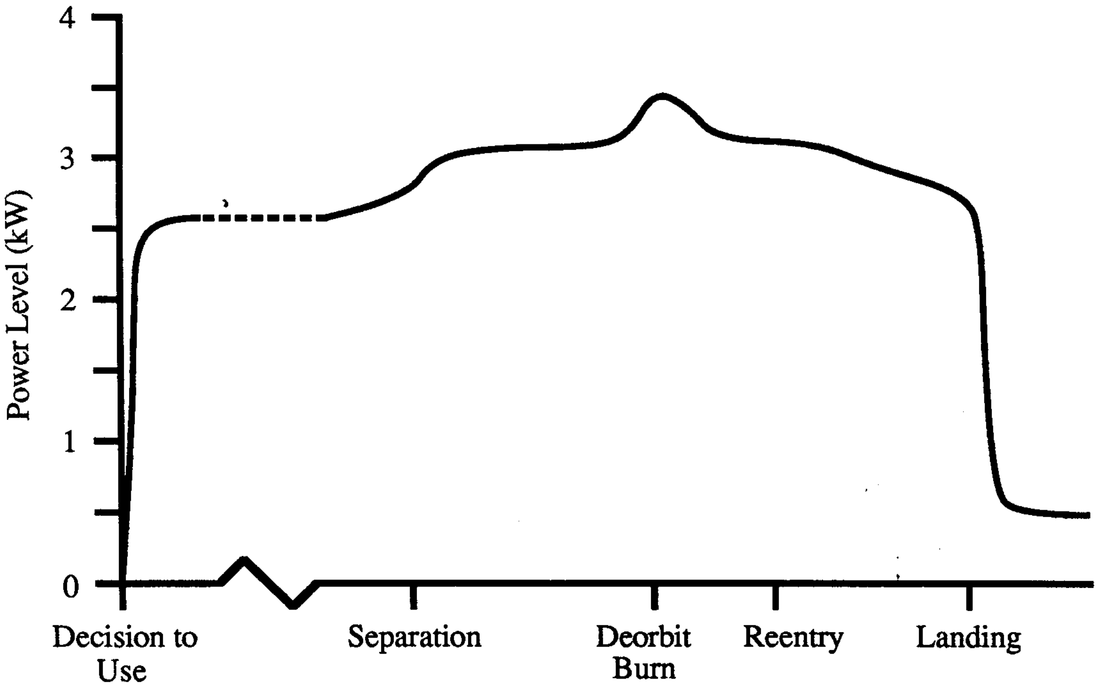

Figure 4.2 - EGRESS Power Consumption vs. Time

Several years ago there was much concern about the safety of lithium primary battery systems [4-4]. However, recent advancements at the Jet Propulsion Laboratory and elsewhere have made these batteries much safer. Nevertheless, safety features have been incorporated into the design of EGRESS to insure that a battery failure is not catastrophic. One of the failure modes of Lithium batteries that has been observed in the past is explosion. This is a relatively easy failure to protect against. On EGRESS it is accomplished by venting each of the cells to prevent pressure buildup. The vapors so emitted are ducted to space through vent openings near the rear of the vehicle. Diodes will also be used on the cell strings and modules to prevent the batteries from over-discharging or experiencing voltage reversal, which are the leading causes for pressure buildup [4-5].

Another problem exists with the activation of the lithium primary battery cells. After four years of quiescent storage, lithium batteries develop a layer of lithium chloride on the surface of the lithium anode [4-6]. Although this layer is one of the factors that gives the batteries a long life, it also delays the cells from reaching their working voltage immediately when a load is applied following a period of extended storage. The EGRESS batteries will circumvent this problem by using an electrolyte additive and a coating on the lithium anode. It is expected that these measures will allow full power-up within ten to fifteen minutes after initial activation. In an emergency, the power system should be given at least five minutes to warm up and only minimal systems should be used, before an attempt to depart the space station is made.

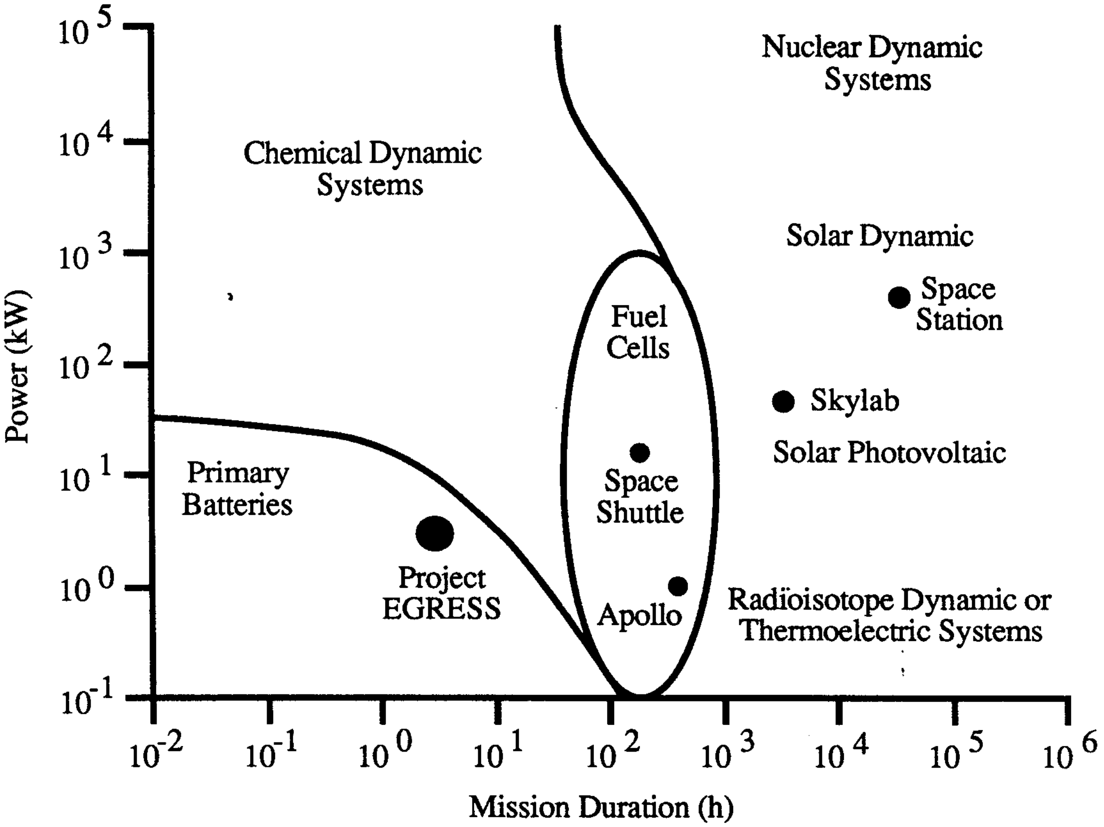

Figure 4.3 - Optimization of Power Systems

Other systems were considered for powering EGRESS. Statistical data compiled on missions in the past revealed that primary batteries are the optimum choice for EGRESS's main power supply (see Figure 4.3) [4-7]. Rechargeable power systems were ruled out because they are very large and heavy. Recharging is also a capability that EGRESS does not require. It is designed to be used only once, although some of its components may be salvaged. For this reason, rechargeable batteries in conjunction with solar panels or a Space Station *Freedom* interface were eliminated.

Fuel cells were also considered for powering EGRESS. The primary advantage of a fuel cell system over batteries is its low weight [4-8]. However, the volume required is very large due to the need for storing the hydrogen and oxygen reactants and redundancy considerations. Another problem with a fuel cell system is that its heat rejection is approximately four times greater than for the batteries. Thus, a much larger thermal control system would be required. The development costs for a fuel cell system are also much higher. Lithium batteries are commercially available which would fit EGRESS's needs, but a fuel cell system would have to be tailor-made for the vehicle. These factors led to the elimination of fuel cells as a power system for EGRESS.

The final alternative that was considered was nuclear power. This option was not ruled because of technological reasons, but by political reasons. There are, however, many technological difficulties such as shielding and heat dissipation. The political reasons are even more obvious. NASA has had many political problems with sending nuclear power sources to the outer planets. Putting a nuclear power source in orbit and then reentering with it would be likely to have enormous political implications. These factors led to the conclusion that nuclear power is not a viable option.

4.1.1.2 Secondary Batteries

EGRESS will also use secondary (rechargeable) batteries to carry out some of its functions. The secondary batteries will be located on the EGRESS airlock. They will be used to operate the airlock and its systems and will provide power to EGRESS for periodic system checkouts. The batteries are capable of providing enough power to operate all EGRESS systems at once for two hours while docked. This system was determined to be necessary in order to minimize the impact of EGRESS on Space Station *Freedom* operations. The rechargeable battery system will be charged during periods of low station activity. This will allow EGRESS to be monitored and checked out regularly without any need to schedule time for Space Station *Freedom* power usage.

The airlock secondary battery system will provide EGRESS with 5.2 kWh of energy before needing to be recharged, which is equal to a 50% depth of discharge. Simply stated, this means that the batteries could provide 10.4 kWh, but it is desirable to consume only one half of this before recharging the batteries. If the batteries are discharged too deep, they may suffer permanent damage. The battery system weighs 227 kg (500 lb) and has a volume of 234 dm^3 (8.2 ft^3). These figures also allow for battery support equipment and casing.

The best rechargeable battery for space applications is currently the nickel hydrogen (NiH) battery. The specific energy density of nickel hydrogen batteries is much greater than that of any other battery currently available [4-9]. In this analysis, it was assumed that the nickel hydrogen battery system on the airlock has specific energy densities of 55 Wh/kg and 60 Wh/dm^3. A second reason for using NiH batteries is that they will be used on Space Station *Freedom*. Thus, choosing a nickel hydrogen system increases the compatibility of EGRESS and the Space Station.

4.1.1.3 Space Station *Freedom* Interface

Although not a regular operating procedure, EGRESS has the capability of being powered directly by Space Station *Freedom*. This is an important feature of the EGRESS power system. It could be utilized in the event that the secondary batteries in the airlock fail. The interface also provides EGRESS with much more flexibility. This flexibility may be needed in a space station emergency. For instance, if EGRESS does not have quite enough power to complete an entire mission, the space station interface could possibly be used to power the start-up sequence. This may then allow EGRESS to fully complete the mission.

The Space Station interface will be used on a routine basis, however, by the airlock battery system. The secondary batteries on the airlock will have to be recharged regularly through the interface. The routine use of the interface by the airlock batteries will help to insure that the Space Station interface is working properly in time of need.

Many precautions are built into the interface mechanism. It is very important to insure that any electrical problems on Space Station *Freedom* do not carry over to EGRESS. For this reason, the interface mechanism will contain sophisticated equipment to isolate problems such as power surges and short circuits to Space Station *Freedom*. Although the space station's power system is designed to prevent any of these situations from happening, EGRESS will further protect against them by using more advanced hardware and greater redundancy than that used on Space Station *Freedom*.

4.1.2 Power Management and Distribution

The EGRESS power system architecture is presented in Figure 4.4. This figure contains four primary areas of interest: 1) Power storage (top left), 2) Main EGRESS systems (top right), 3) Airlock/Space Station (bottom right), 4) Propulsion module (bottom left). These four components are all connected together by power lines and power distribution electronics. This is what is known as the EGRESS power management and distribution (PMAD) system.

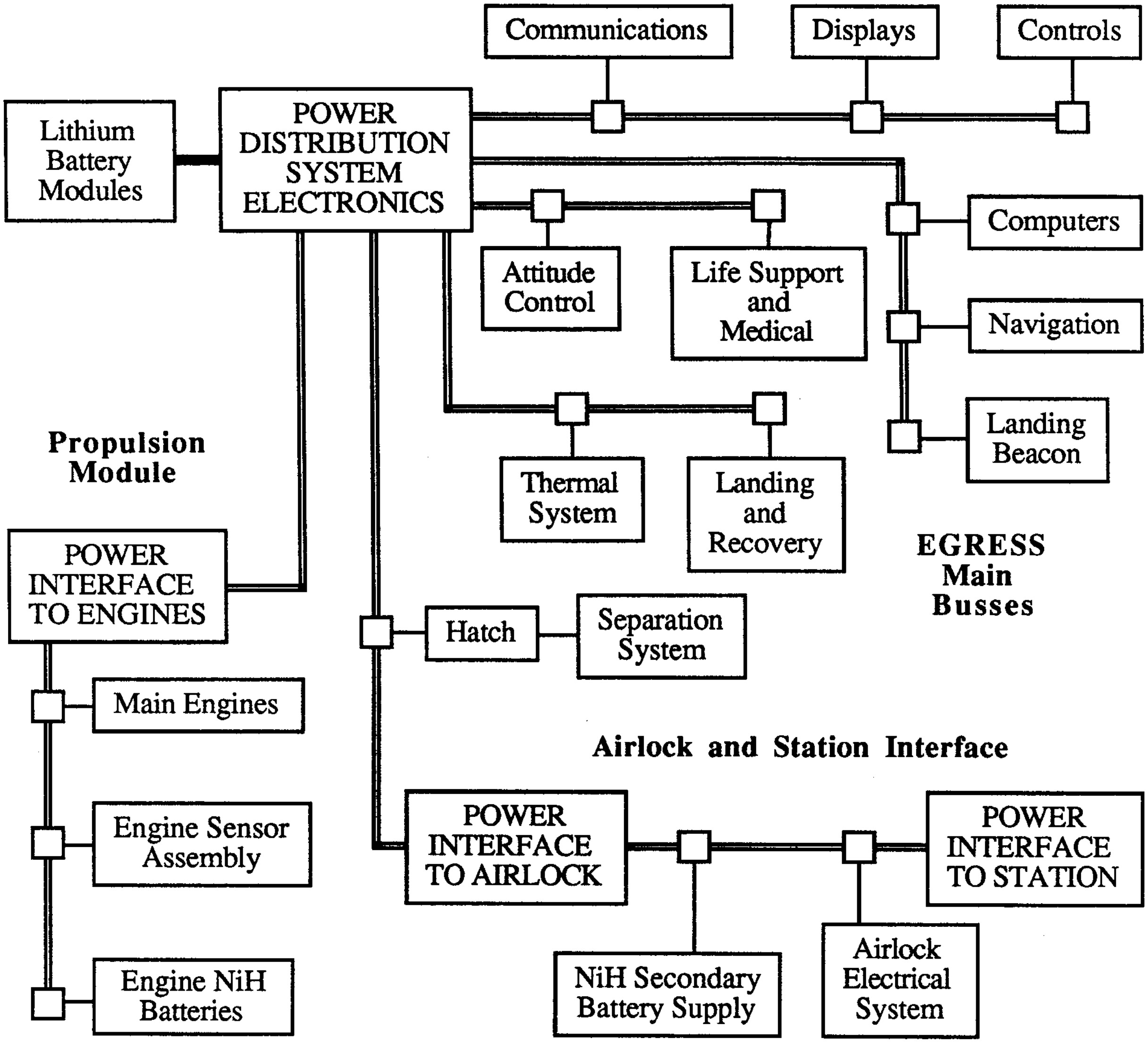

Figure 4.4 - EGRESS Power Distribution Network

The EGRESS power cables indicated in Figure 4.4 are drawn as dual lines. This is to show that for the major power lines, redundant lines are present. The power cables are made of copper and very in gauge depending on the maximum loads they must carry. Each system was placed on a power bus keeping two things in mind, the proximity to other equipment and the size of the load. Putting equipment in close proximity to one another on the same line is important because it reduces cable lengths. We also desired to have each power bus carry approximately the same wattage. In the end, proximity was the most important factor in assigning systems to the various busses.

Power distribution electronics are spread throughout the entire system. They are located at the battery feed, at all interfaces, and at all nodes with EGRESS systems. These electronics regulate voltages, measure the status of the electrical system (voltage, current, etc.), isolate faults and surges, and route the electrical current through alternate paths if the primary path is unavailable. All measurements made by these controllers are forwarded to the computer system for use by the power management and distribution system software. In turn, the PMAD software uses the data to issue commands to the power distribution electronics. The software is capable of handling many more situations than just normal operations. Contingency situations are designed into it for many different types of problems that may evolve; for instance, a scrubbed mission, a mission on minimal power, or a mission involving malfunctioning systems.

The EGRESS power management and distribution system allows for a high level of automation. This will help to decrease the training time required by the astronauts. In addition, many electrical problems must be responded to very quickly and should be monitored closely. The EGRESS crew may not be able to respond to such a problem in order to prevent great damage. An automated system, however, is capable of making split second decisions which may prevent great harm from coming to the spacecraft. This is the justification for choosing an automated system over a manually controlled power system. EGRESS will, however, be equipped with manual override switches in case the need should arise for the crew to direct the distribution of power throughout the craft.

4.2 Communication System

There are two important aspects of the EGRESS communication system: communication links and communication hardware. The design details of both of these aspects of the communications system are summarized below along with the reasons they were chosen over other possible options.

4.2.1 Communication Links

This section includes details on the number and frequencies of the communication channels, specific lines of communication that will be used during operations, and the type of data that will be received and transmitted by EGRESS.

4.2.1.1 Lines of Communication

It is important for EGRESS to maintain radio contact with the ground throughout its mission. To accomplish this, EGRESS will have five lines of communication. Three will be with other personnel, and two with satellite networks.

1) NASA Ground Spaceflight Tracking and Data Network (GSTDN)

NASA uses a system of ten ground stations scattered around the globe to monitor the missions of all spacecraft. Information is relayed between these ground stations and mission control in Houston, Texas.

Immediately after EGRESS is powered up, all voice, telemetry, and positioning information will be sent to mission control using the EGRESS communications system. The communications system will remain operational until EGRESS has landed and the crew is safely recovered by ground forces. All communications with mission control will be done using S-band radio frequencies in conjunction with the Tracking and Data Relay Satellite System or through direct radio contact with NASA ground stations.

2) Tracking and Data Relay Satellite System (TDRSS)

TDRSS will provide S-band radio communication services for EGRESS throughout its mission. TDRSS consists of three satellites in geosynchronous orbit that relay signals between a spacecraft and the ground. Two of the satellites serve TDRSS full time. One is positioned over the Atlantic Ocean (41° W. Long.) and the other is positioned over the Pacific Ocean (171° W. Long.) [4-10]. The third satellite is and on-orbit spare positioned over eastern South America (79° E. Long.) [4-11]. TDRSS provides radio coverage over 85% of the globe excluding a narrow region over the Indian Ocean (55° E. Long. and 95° E. Long.) known as the *zone of exclusion* [4-12]. The current system of ground stations only provides partial radio coverage. For the space shuttle, it amounted to only 20 minutes of communication during a 90 minute orbit [4-13]. With TDRSS, EGRESS will only experience 10 minutes of radio silence as it passes over the Indian Ocean. This can be reduced by communicating directly with the ground station at Diego Garcia using S-band.

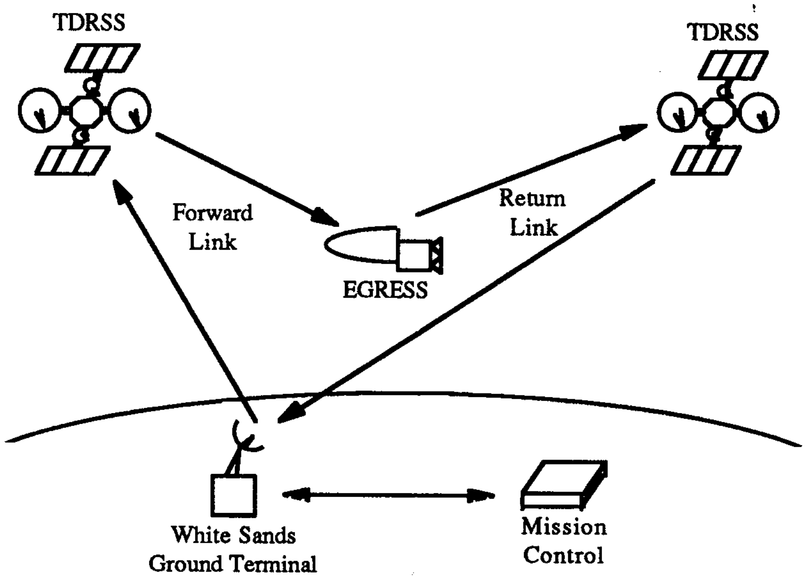

Figure 4.5 - TDRSS Satellite Network

Figure 4.5 shows how signals are relayed between EGRESS and the ground. All radio communication with mission control from the moment of ingress until parachute deployment will be done using the S-band single access mode through TDRSS. Signals sent by way of a TDRSS satellite to the ground are return link communications, while all signals received by way of a TDRSS satellite from the ground are forward link communications. The two way transmission time will amount to 270 ms [4-10]. Signals sent to the ground, are received by the TDRSS ground terminal at White Sands, New Mexico [4-10]. There, the signal is processed and the information is sent to mission control.

Using TDRSS, EGRESS can eliminate the period of radio blackout experienced during reentry [4-14]. This was a problem for the Apollo programs and also for the Space Shuttle. During reentry, heating on the outside of the spacecraft ionizes the atmosphere and the radio antennas. The ionized antennas cannot transmit any signals temporarily eliminating radio communication with mission control. However, the temperatures achieved on the upper surface of EGRESS will not be as high, allowing the crew to transmit back out through the atmosphere to a TDRSS satellite. This way, EGRESS will be able to maintain open communications with mission control throughout reentry.

3) Space Station *Freedom*

Besides maintaining open communications with the ground, EGRESS will also be able to communicate with Space Station *Freedom.* Current designs for Space Station *Freedom* require open communications and tracking of all spacecraft within a defined zone. This zone extends 9 km on either side, and extends 37 km radially along Space Station *Freedom's* orbital path [4-15]. The link will remain open from the moment EGRESS is powered up to the time of deorbit burn. While still docked, EGRESS will use on-board audio terminal units to maintain voice communications; while after separation, EGRESS will use S-band radio communications. In the event the entire crew is evacuated from the Space Station, this link is broken and EGRESS will only communicate with the ground.

4) Internal Communications

Inside EGRESS, the crew will be able to communicate with the Space Station and the ground with headsets that are connected to audio terminal units located by each seat. The audio terminal units will be equipped with multi-channel capability to allow the crew to switch communications between Space Station *Freedom* , mission control, and ground recovery forces. These were chosen over wireless headsets for simplicity. Wireless headsets, similar to those on the shuttle [4-16], allow the crew freedom of movement around the cabin. The crew of EGRESS will remain in their seats during the entire mission. Secondly, the headsets operate on rechargeable batteries. Should the batteries fail, a backup hard-wired system would be required for the crew to maintain voice communications with the ground. Therefore, hard-wired headsets are the simplest and most reliable.

5) Global Positioning System (GPS)

GPS will be used to determine the position and velocity of EGRESS at all times. EGRESS will only receive information from GPS. Once position and velocity have been determined, this information is relayed to Space Station *Freedom* and the ground. Attitude will be determined separately using a laser gyroscope. EGRESS will transmit its position, velocity, and attitude to the Space Station during separation and docking maneuvers using S-band radio communications. In turn this information can be relayed by the Space Station to mission control. After separation and just before the deorbit burn, EGRESS will transmit this information to the ground using S-band communications through TDRSS. Lastly, after parachute deployment and for the rest of the mission, position will be transmitted to recovery forces using the VHF communications system.

4.2.1.2 Radio Frequencies

EGRESS will require three separate radio frequencies in order to satisfy all of its communication needs.

1) S-Band Phase Modulated Subsystem (S-band PM)

EGRESS will use S-band phase modulated radio frequencies (1550 - 4000 MHz) to transmit and receive all communications with the Space Station and the ground. This subsystem is very similar to the Space Shuttle's S-band communications system. After separation and while still within the vicinity of the Space Station, EGRESS will communicate directly all voice and telemetry information to the Space Station; but, will require TDRSS to communicate with the ground. When on orbit, all communications will be with the ground through TDRSS.

EGRESS will have two carrier frequencies for forward link communications and two carrier frequencies for return link communications. The second carrier frequency is necessary to allow a second EGRESS to communicate with either the Space Station or the ground without radio interference from the first. If only one EGRESS is needed to return injured crew to the ground, then the second carrier frequency acts as a backup. Figure 4.6 shows the S-band radio frequencies EGRESS will have available.

	Primary Frequency	Secondary Frequency
Forward Link	2074.2 MHz	2035.8 MHz
Return Link	2269.0 MHz	2234.0 MHz

Figure 4.6 - EGRESS S-band PM Radio Frequencies

These frequencies will not interfere with the frequencies reserved for the Space Shuttle nor will they interfere with any other S-band frequencies that NASA is currently using. This is just a precaution in the event EGRESS is used while the Space Shuttle is still in orbit performing a mission.

EGRESS will use three channels during S-band operation to relay all information between the crew and mission control. Two channels are for voice communication. These are divided between the pilot and the medical technician on board EGRESS, allowing both of them to communicate with mission control without interference from each other. The pilot can receive instructions from mission control, and in turn, keep them informed of all flight operations. Likewise, the medical technician can receive instructions from the flight surgeon on the ground and inform the surgeon of the patient's condition.

The third channel is used for command and telemetry. During forward link communications from the ground, this channel carries command information. This allows mission control to send data or instructions back to EGRESS governing its control. Three main systems can be controlled from the ground:

A) Operation of the general purpose computers on board EGRESS. Mission control can "command" the computers to monitor specific systems; or, to activate or deactivate these systems.

B) Operation of the reaction control system. Mission control can automatically operate the deorbit burn engines and the attitude control thrusters.

C) Operation of the environmental control and life support system (ECLSS). In addition to the ability to automatically pilot EGRESS, mission control can operate the life support systems in case the crew becomes incapacitated.

During return link communications to the ground, the third channel relays telemetry. Telemetry is data that describes the status of EGRESS during its mission. Figure 4.7 is a table showing the breakdown of the telemetry from EGRESS. Telemetry on the power distribution system will include the breakdown of the power supplied and used on each of the four main buses of the electrical system. Atmospheric sensors will include pitot-static probes and temperature sensors which are used during atmospheric flight.

Computer System	Reaction Control System	ECLSS
Position, Attitude, & Velocity	Pressure Transducers (He)	Total Pressure
Available Power	Pressure Transducers (Prop)	Partial Pressure O_2
Power Used	Temperature Sensors	Partial Pressure CO_2
Power Distribution System	Quantity Gaging	Tank Pressure
Decisions by the Voter	Atmospheric Sensors	Temperature and Humidity
		Inspired and Expired O_2
		Expired CO_2
		Heart and Respiratory Rates
		EKG and Respiratory Patterns
		Blood Pressure

Figure 4.7 - EGRESS Telemetry Requirements

2) Very-High Frequency Subsystem (VHF)

EGRESS will use VHF radio frequencies (30 - 300 MHz) to communicate with search and rescue forces and recovery forces. The VHF subsystem will also act as a backup system for voice communications with mission control in case there are any problems with the S-band subsystem. The actual range of EGRESS's VHF subsystem will vary from 225 - 400 MHz [4-17], which takes it into the UHF radio spectrum (300 - 3000 MHz). This will allow EGRESS to communicate with the Navy and the Air Force on UHF frequencies.

This subsystem is very similar to the one used by the Apollo [4-18] and the Space Shuttle [4-19] programs. EGRESS will have two VHF frequencies for voice communication with mission control. In addition, EGRESS will be able to communicate on an international distress channel. These frequencies are listed in Figure 4.8.

	VHF Frequencies
Primary	296.8 MHz
Secondary	259.7 MHz
International Distress Channel	243.0 MHz

Figure 4.8 - EGRESS VHF Radio Frequencies

These channels are only used for voice communication. In case the entire crew of the Space Station *Freedom* needs to be evacuated, the second EGRESS will use the secondary radio frequency (259.7 MHz). This will prevent interference between two EGRESS vehicles during communications with either mission control or with recovery forces. Secondly, this also allows the two vehicles to communicate with each other. One EGRESS can transmit information on one frequency and receive information on the other.

The VHF subsystem will switch on during the mission right after the parachutes have been deployed. This way, EGRESS will be able to communicate with recovery forces and relay its position. The computer will also send the position, altitude, and velocity of EGRESS to the VHF subsystem, which will transmit this information over the International Distress Channel. This way the International Distress Channel will also act as a radio beacon for EGRESS.

3) L-Band Subsystem

EGRESS will be equipped with an L-band receiver to receive positioning and velocity information from GPS. The frequencies are 1227.6 MHz and 1575.2 MHz [4-20]. This information will then be relayed either to the Space Station or to the ground using S-band or VHF communications. The S-band will be used to relay this information to mission control during on orbit flight and during reentry as part of the telemetry signal. After the parachutes are deployed, this information will be relayed to recovery forces using the VHF International Distress Channel.

4.2.2 Communication Hardware

Each communications subsystem described above has its own hardware. However, only the L-band subsystem is independent from the other two. Both the S-band and VHF subsystems are linked together by the Audio Central Control Unit. The Audio Central Control Unit (ACCU) relays analog voice signals between the crew and the S-band and VHF subsystems. Figure 4.9 shows the EGRESS communications system and how information is transferred between the crew and the various subsystems.

Each crew member will be able to wear a headset that is connected by a cable to an Audio Terminal Unit (ATU). In order to talk, a crew member simply presses a button, otherwise the headset receives. One ATU will be placed by each seat allowing the crew to plug in the headsets with ease. Each ATU in turn is connected directly to the ACCU. A separate hardwire interface between EGRESS and the Space Station *Freedom* will allow individual crew members to talk to the station during ingress and before separation.

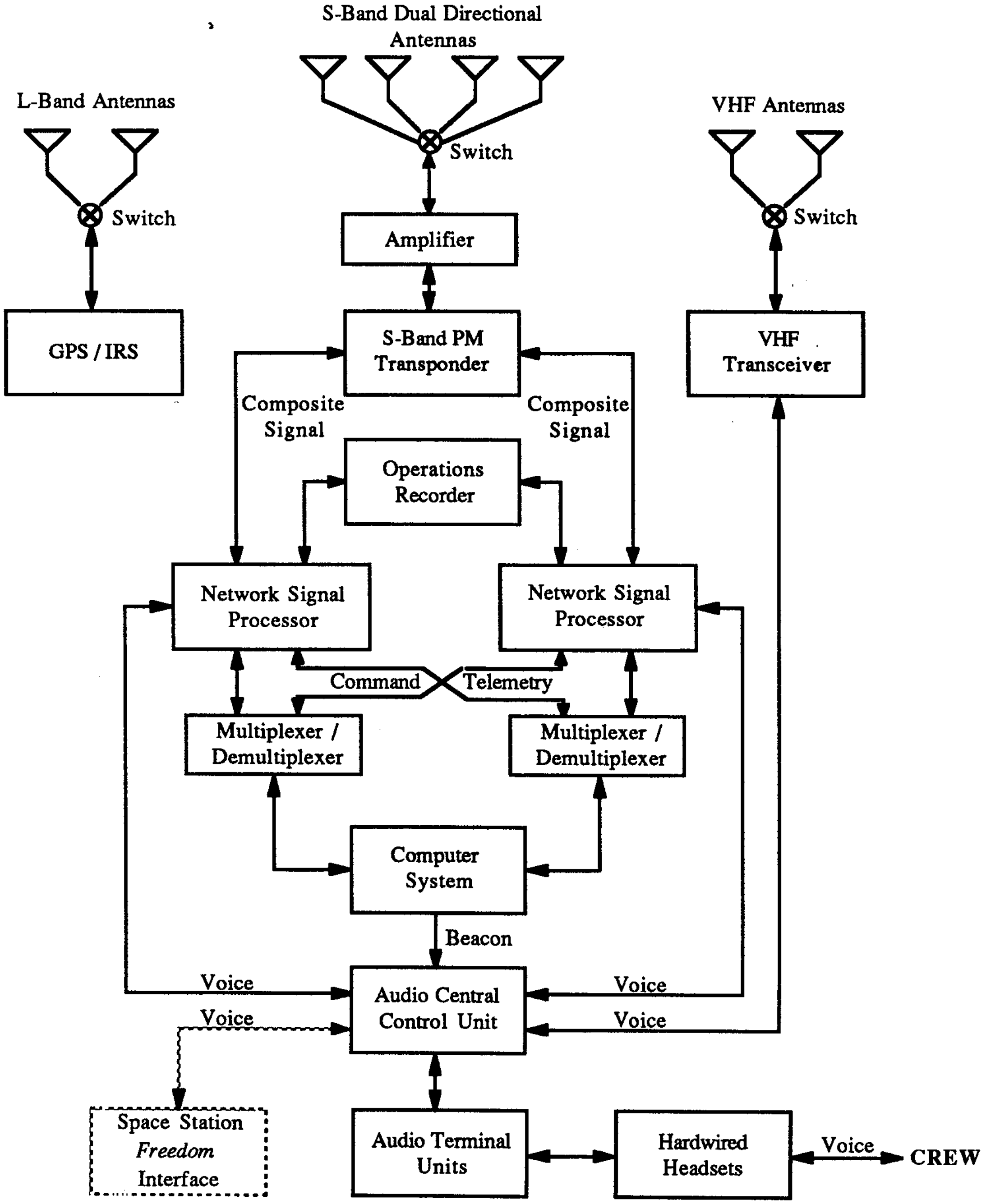

Figure 4.9 - EGRESS Communications System

1) S-Band Subsystem

The S-band PM subsystem is the workhorse of the EGRESS communications system. It is connected to the ACCU through the Network Signal Processors (NSPs). EGRESS will have two NSPs that are cross-strapped to the ACCU and to the main computer system through the Multiplexer / Demultiplexers (MDMs). Only one NSP operates at a time, the second one is a backup. All signals either transmitted or received by EGRESS are processed by the NSP. When transmitting, two separate voice signals (one from the medical technician and one from the pilot) are received from the ACCU and converted from analog to digital by the NSP. Digitized signals are faster and less susceptible to noise than analog signals. The digitized voice signals are then combined with one telemetry signal from the computer system into one composite signal. The composite signal is then sent to the transponder for transmission. When receiving, just the opposite occurs; the NSP separates the composite signal into the two voice signals and one command signal. The voice signals are converted from digital to analog and sent to the ACCU. The command signal is sent to the computer system where it is processed.

EGRESS will have two MDMs connecting the communications system to the computer system. The second system, again, is for redundancy. The MDM translates commands from the main computers so that the computer system can automatically operate and monitor the communications system.

The S-band PM transponder is composed of a transmitter and receiver together. The S-band system can simultaneously transmit and receive information between mission control and EGRESS, or between TDRSS and EGRESS. When communicating with mission control through TDRSS, the signal has to be amplified in order to prevent a significant decibel loss as the signal is transmitted to a TDRSS satellite.

The transponder and the amplifier, in turn, are connected to four dual directional antennas. The antennas are spaced 90° apart around the body of EGRESS on the plane passing through the hatch. Each antenna has compound curvature and has to be molded to the surface of the body. These antennas are rectangular (12 in by 16 in) and weigh 17 lbs. However, promising advancements in the design of these antennas may bring the size down to 6 in by 7 in [4-21]. These smaller antennas would be patch antennas and not the more complicated compound curvature antennas. But, unlike the compound curvature antennas which lie on the surface of the vehicle, the patch antennas are placed within the surface of vehicle (3 to 4 in deep). In either case, these antennas would be mounted to the body beneath the Thermal Protection System (TPS).

Each antenna can transmit and receive in the forward or aft directions and essentially has a 140° field of view [4-21]. Dual directional antennas as opposed to hemispherical antennas allow for higher gain in the transmitted signal. The higher gain is desirable for transmitting to a TDRSS satellite (since it is located in geosynchronous orbit) [4-21]. Only the antenna that has a direct line of sight to a satellite is used at any given moment. Antenna switching is handled by the computer system. Contingency operations would allow the antennas to be switched either manually by the pilot or automatically with a command signal from mission control.

Lastly, an optical disk operations recorder will be cross-strapped to both NSPs. The operations recorder will record all data during the mission. This device is also used as a backup for radio telemetry during periods of radio silence when EGRESS passes into the TDRSS zone of exclusion over the Indian Ocean. Once EGRESS regains contact with mission control, all data recorded by the operations recorder will be sent to the NSP for transmission to the ground.

2) VHF Subsystem

The VHF subsystem transceiver is connected directly to the ACCU. It does not transmit or receive digitized signals and hence does not need to be connected to the NSPs. The transceiver can transmit and receive information, but it cannot do both simultaneously. Two hemispherical antennas are mounted on the upper and lower surfaces of EGRESS beneath the TPS. The upper antenna is required since the lower antenna of EGRESS will be submerged or possibly damaged during landing. The antennas are annular slots 2 ft in diameter. One foot is the antenna, while the other foot is for a mounting ring. The depth of the antenna is 5 to 6 in at the center [4-21].

3) L-Band Subsystem

Two L-band hemispherical antennas are mounted on the upper and lower surfaces of the EGRESS beneath the Thermal Protection System. These antennas only receive signals from GPS. They are 1 ft in diameter and 3 in deep. They are fairly flat and don't require a compound contour for mounting. The information is sent directly to the Inertial Reference System where it is processed and used in conjunction with the laser gyroscope to determine position, velocity, and attitude of EGRESS.

4.2.3 Other Systems Considered

Three other systems were considered for EGRESS. These were the Fleet Satellite Communications System (FLTSATCOM), the Ku-band radio, and the S-band Frequency Modulation (FM) radio.

1) FLTSATCOM

The Fleet Satellite Communications System is a worldwide military communications system. It provides 23 UHF channels that are shared by the U.S. Navy, the U.S. Air Force, and the Department of Defense. Half the channels are dedicated for naval fleet relay and the other half are dedicated for U.S. Air Force satellite communications. It consists of a system of four satellites placed in geosynchronous orbit around the globe. These four satellites provide global communications coverage for a user between 70° North and South Latitudes [4-22]. The primary reason EGRESS will not rely on this system is the fact that it is a military satellite system. Since the Space Station is an international project, using a military satellite system was considered a risk to national security. Secondly, telemetry rates with a UHF system are slower than with an S-band system, because UHF is lower in frequency than S-band. S-band communications are flight proven and have been used in both the Apollo and Space Shuttle programs. The S-band system provides EGRESS with the high telemetry rates that may be needed in case the vehicle needed to be piloted remotely from the ground.

The Space Station *Freedom* will use TDRSS in conjunction with an S-band system for most of its communications. It will not be using FLTSATCOM. EGRESS requires the ability to communicate with the Space Station while in orbit, and in case the mission should be scrubbed. During this contingency, EGRESS will be able to return and dock with the Space Station using S-band communications.

2) Ku-band Communications System

The Ku-band (12.5-18 GHz) operates at a much higher frequency than S-band. This is excellent for sending high telemetry rates but it is a far more complicated system than an S-band communications system. TDRSS operates at both S-band and Ku-band frequencies; however, the Ku-band has a narrower beam width requiring an external gimballed antenna.

The Space Station *Freedom* is currently designed to use Ku-band communications as its primary communication system while its S-band system is used as a backup. It will require the high telemetry rates provided by Ku-band in order to transmit and receive information from all free-flyers and orbital maneuvering vehicles (OMVs). EGRESS is not classified as a free-flyer or an OMV. EGRESS is an emergency vehicle designed with simplicity in mind. It can communicate with the Space Station using S-band and will not need the Ku-band.

3) S-band FM

The only difference between the S-band FM system and the S-band PM system is the way information is sent on the signal. The S-band FM system transmits information by modulating the frequency of the carrier wave. The S-band PM system transmits information by phase shifting the carrier wave. Both have a low susceptibility to noise, however the S-band PM system uses power more efficiently. Lastly, TDRSS does not use S-band FM for communications. Only NASA STDN ground stations can operate with S-band FM communications. If EGRESS was equipped with S-band FM as its primary communications system it would only be able to communicate with the ground when it passed over one of these ground stations. This would severely reduce the radio coverage provided for EGRESS.

4.3 Computer System

The main computer system interacts, in at least some fashion, with all of the EGRESS subsystems, as well as with the Space Station and Ground Processing Facilities (at mission control). The computer system controls the operation of EGRESS, monitors its systems, and, while EGRESS is dormant, runs diagnostic checks on the vehicle. The computer system is designed with the power to run as autonomously as possible, with the flexibility to handle a variety of missions, the reliability to perform when needed, and with the redundancy to minimize single point malfunctions.

4.3.1 Hardware

The core of the EGRESS computer system is the AP101S General Purpose Computer (GPC), which is part of the IBM System Advanced 4π family [4-23] and was designed specifically for the National Space Transportation System (NSTS). The system is broken into two functional units, the central processing unit (CPU) and the input/output processor (IOP) .

The central processing section of the system consists of a 32 bit, 1.2 million instruction per second (MIPS) processor, a memory managing unit (MMU) and 256K (kilobytes) of battery backed CMOS random access memory. These units, as well as the IOP, are linked high-speed synchronous bus. The pipe-lined architecture allows for high speed processing and execution of macro instructions.

SIZE	10.2 x 7.625 x 19.52 in.
WEIGHT	64 lbs.
POWER	500 watts
MEMORY	256 k CMOS / battery backed
SPEED	1.2 MIPS
DATA BUS	24 bit serial, 1 MHz

Figure 4.10 - AP101S System Specifications

The CPU is connected to the rest of the EGRESS computer system through the input/output processor. The IOP is a digital, programmable, time-shared processor that allows data transfer between the CPU and the EGRESS subsystems. In addition to providing a 1 Mhz, 24 bit interface to the EGRESS subsystems, the IOP handles instructions and data requests from main memory and has limited processing capabilities.

The AP101S GPC was chosen for the EGRESS system primarily because it is already rated for manned space flight and is flight proven. In addition to being used on the Space Shuttle, similar units (the AP101F) are used in the B-1 bomber and the F-16 eagle. The AP101S is also sufficiently powerful enough to provide nearly autonomous flight and to aid in variety of tasks from mission planning to assistance in EGRESS maintenance.

Mass storage will be provided by a 300 megabyte read/write/erasable optical disk, using an a solid state laser diode. Though magnetic tape recorders have been used for a long time in space operation, the optical disk is more reliable, because an optical disk is mechanically simpler and more radiation resistant, and has an order of magnitude more storage capabilities [4-24].

4.3.2 System Architecture

Reliability is the most important consideration in designing a computer architecture for space operation. With all aspects of the mission utilizing the computers and their supporting hardware, failures that would only cause a delay in a ground environment, could be catastrophic in space. The EGRESS computer system will be made up of three AP101S GPCs in a Triple Modular Redundancy configuration [4-25]. In essence, all three computers will run the same software using the same data. Before a command is executed, a voter will compare the outputs of the three systems, and produce output of its own based on their majority. This system can tolerate failure in any one of the three main computers, and one computer is designated as the prime and is weighted higher than the others if the three computers generated three different answers.

The three AP101S GPCs are connected to the rest of the computer system via a 24 bit, 1 Mhz data bus (see Figure 4.11). Through the data bus, the processors have access to the information stored on the optical disk drive, guidance information from the navigation system, EGRESS subsystem telemetry, and commands from the controls. Information can then be sent to various displays, and commands to specific systems, including those on the engine assembly.

The computer system has direct access to both the communications system and the space station's data management system. The computers can send (and receive) information to (and from) mission control through a buffered interface, directly to the communication system's Network Signal Processor (see Section 4.2.2). Additionally, telemetry information, which enters the system through a telemetry processing unit, is sent unprocessed directly to the communications system. When EGRESS is docked, commands and information can be placed directly onto the space station's fiber optic data system.

4.3.3 Software

Software for the EGRESS vehicle falls into two distinct groups, system software and operation software, and these two groups jointly form the EGRESS Automated Software Environment (EASE). The system software is responsible from supervising the vehicle's subsystems. The operations software provides the computer system with capabilities for flight operations, diagnostics, mission planning, and system expandability. The software running under EASE is written to provide assistance in a variety of operational modes, to be easily updated and modified from either the vehicle or from the ground, and adaptable to unusual situations.

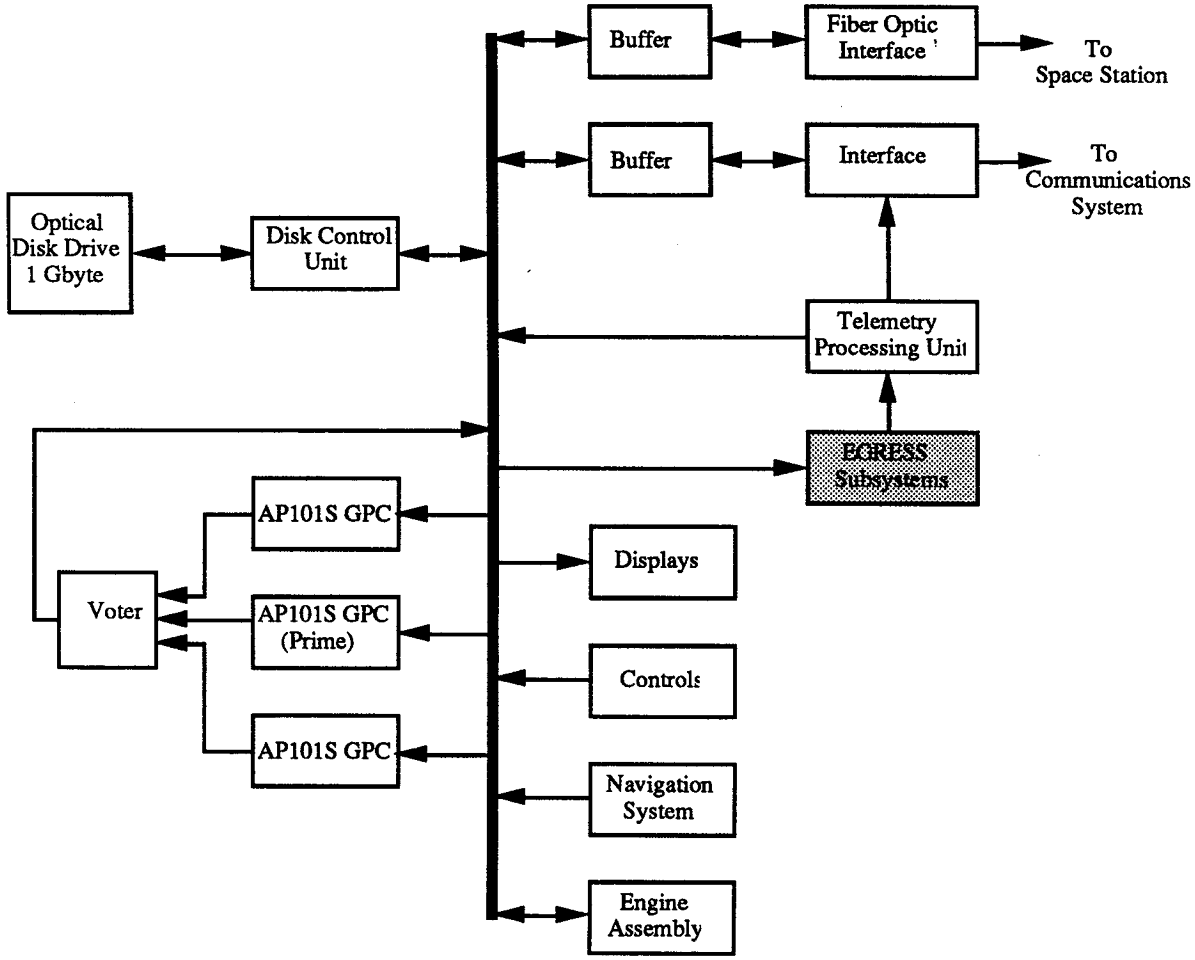

Figure 4.11 - Computer System Architecture

The EASE software is designed to meet the needs for two distinct user groups. When an experienced pilot is commanding EGRESS, the astronaut needs to be able to tell when the system is malfunctioning and manual override capabilities must be incorporated. Unfortunately, due to the nature of this vehicle, it is possible that an astronaut inexperienced as a pilot will fly EGRESS. In this case, the system needs to be sufficiently autonomous to compensate for the astronaut's lack of knowledge and experience.

The following are the major packages that make up the systems software:

- **Power Distribution** - this package is responsible for regulating the voltage and currents of the various battery supplies, power buses, and distribution circuits of the electrical power system. The software is also tasked with monitoring the entire system, selecting between redundant power buses, and re-routing power when overloads or shorts occur.

- **Atmosphere Regulation** - this software package will monitor the EGRESS environmental control and life support system. From sensor inputs of oxygen and carbon dioxide content, humidity, temperature, and pressure, the system will regulate the ECLSS so that these conditions are properly maintained. The system will also monitor the patient and emergency systems.

The following are the major packages that make up the operations software:

- **Primary Flight System** - this single program is tasked with all segments for a normal EGRESS flight. This includes: trajectory determination, attitude control, deorbit burn control, telemetry monitoring and relay, and landing system deployment.

- **Diagnostics Software** - the primary responsibility of this package is to verify the operational readiness of the EGRESS system. In addition, it will collect information on system performance periodically while docked. This information will allow NASA engineers to learn more about the long duration exposure of spacecraft systems in low earth orbit.

- **Flight Path Planning** - in case communications with mission control is impossible when it is necessary to use EGRESS, this expert system will allow the astronauts to work out the departure time and flight path necessary to land at a primary site.

- **Special Flight Software** - several special purpose software packages will also be available for possible use. These include: return to station capabilities, spacecraft rendezvous, and EGRESS maintenance assistance.

4.4 Navigation System

Navigation, both the determination of position and attitude, is an essential part of all space missions. Project EGRESS has a two part navigation system. An on-board inertial navigation system (INS) provides information about both position and attitude. While attitude, with only using the INS, is more than sufficient for navigation needs, the error in position accumulates with time and is therefore not accurate enough to provide the navigational information necessary for an autonomous flight. For this reason, the INS system is augmented by the Global Positioning System (GPS). The navigational system of EGRESS is made up of a redundant pair of the INS/GPS system.

4.4.1 Inertial Navigation System

The Inertial Navigation System consists of two types of sensors and the supporting electronics. Translational motion is measured by three orthogonal accelerometers and rotational motion is measured by three orthogonal gyroscopes. These six together measure the vehicles accelerations in 6 directions, and this information is integrated to provide velocity and position information.

The Inertial Reference System for Project EGRESS is built around the Ring Laser Gyroscope (RLG). The RLG has several advantages over a gimbaled system, including half the power consumption, increased accuracy, and a complete lack of moving parts. The RLG is a reliable system in that after several years of dormancy it's accuracy will not deteriorate. Specifically, two Honeywell CG1320 Ring Laser Gyroscopes (specifications given in Figure 4.12) will be used in the EGRESS INS.

SIZE	10.25 x 8.5 x 6.5 in.
WEIGHT	24.9 lbs.
POWER	90 watts
GYROSCOPE	
Random Walk	0.008 deg / hr
Bias	< 0.03 deg / hr
Scale Factor	< 0.05 ppm
Frequency Response	> 200 Hx
Max. Input Rate	> 720 deg / sec
ACCELEROMETER	
Bias	50 μg
Scale Factor	< 175 ppm

Figure 4.12 - Honeywell CG1320 Specifications

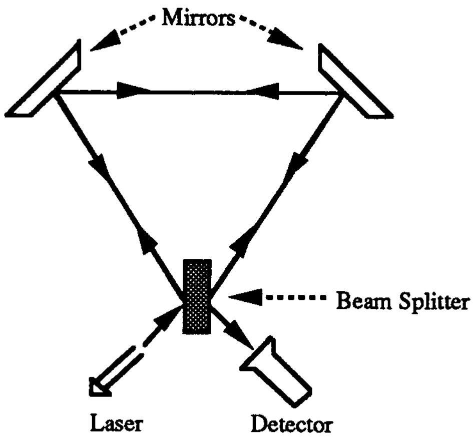

Figure 4.13 - Ring Laser Gyroscope

In a Ring Laser Gyroscope [4-26], a single laser beam is split and sent in opposite directions around the ring (see Figure 4.13). As the gyroscope is rotated, the effective path taken by one beam is shorter in comparison to the other. This has the effect of setting up a fringe shift proportional to the angular speed of rotation when the two beams are recombined. By measuring these fringe effects the navigation system can make a accurate determination of the gyroscope's motion. Three orthogonally positioned RLGs allow the determination of pitch, roll, and heading.

4.4.2 Global Positioning System

The Global Positioning System (GPS) [4-27], also known as Navstar, is a satellite radio-navigation system that is designed to provide worldwide highly accurate three dimensional position and velocity measurements, as well as precise time. The fully operational constellation consists of 18 satellites, and three active spares, in six orbital planes inclined at 55 degrees. Each plane consists of three equally spaced satellites that have a 12 hour orbit. Each GPS satellite continuously transmits navigational signals on two separate frequencies (1575.42 MHz and 1227.6 MHz).

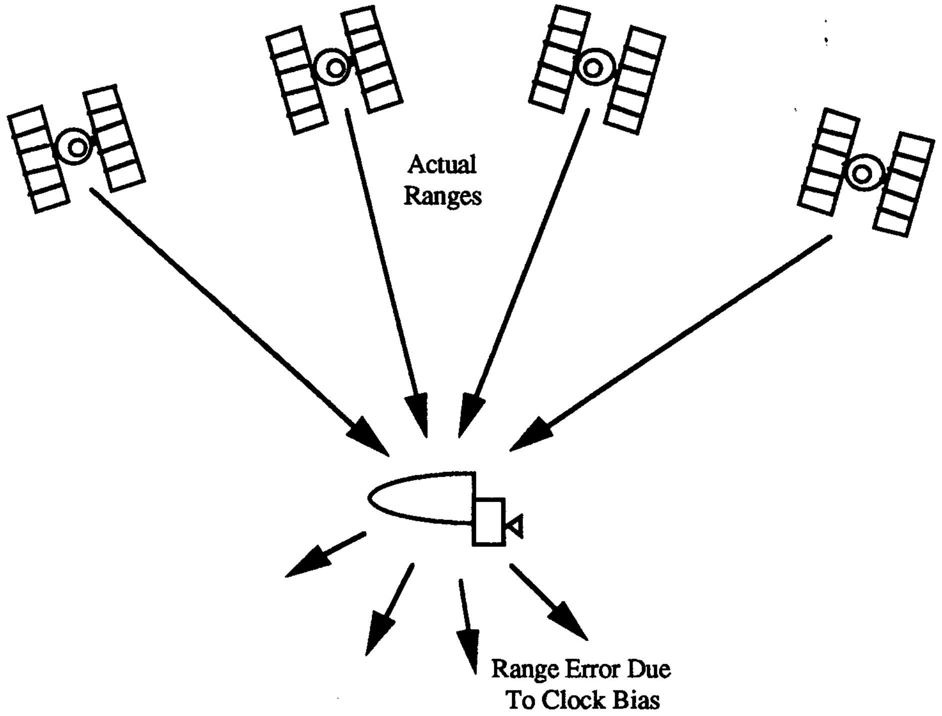

Figure 4.14 - Global Positioning System

Each EGRESS navigation unit will have a GPS receiver which will passively calculate the vehicle's position and velocity. The navigation unit receives a signal from at least four of the Navstar satellites (see Figure 4.14). By using information transmitted in the signal, in conjunction with an internal clock, the pseudo-range to each satellite is calculated. The pseudo-range is determined by calculating the time difference between transmission and reception of the signal and dividing by the speed of light. Slight errors occur in this calculation from a difference in clock bias between the navigation system and the satellite.

By knowing the precise position of the four satellites, which is contained in the GPS signal, and estimating errors in range calculation due to atmospheric conditions, triangulation is used to pinpoint the vehicle's position within 15 meters spherical error probability (SEP). In addition, by monitoring the phase change in the navigation signal, velocity can be determined within 0.1 m/s.

4.4.3 Navigation System Accuracy

The EGRESS navigation system is based on the ring laser gyroscope and is supplemented in position and velocity by the Global Positioning System. The accuracy of this system is shown in Figure 4.15. Note that with the gyroscope alone, the system accuracy degrades with time of operation.

CHARACTERISTIC	RING LASER GYROSCOPE	AUGMENTED GPS SYSTEM
POSITION	0.8 nm (per hour off operation)	15 m (spherical error)
VELOCITY	2.5 feet per second	0.3 feet per second
PITCH	0.05 degrees	0.05 degrees
ROLL	0.05 degrees	0.05 degrees
TRUE HEANDING	0.10 degrees	0.10 degrees
MAGNETIC HEADING	0.20 degrees	0.20 degrees

Figure 4.15 - Navigation System Accuracy

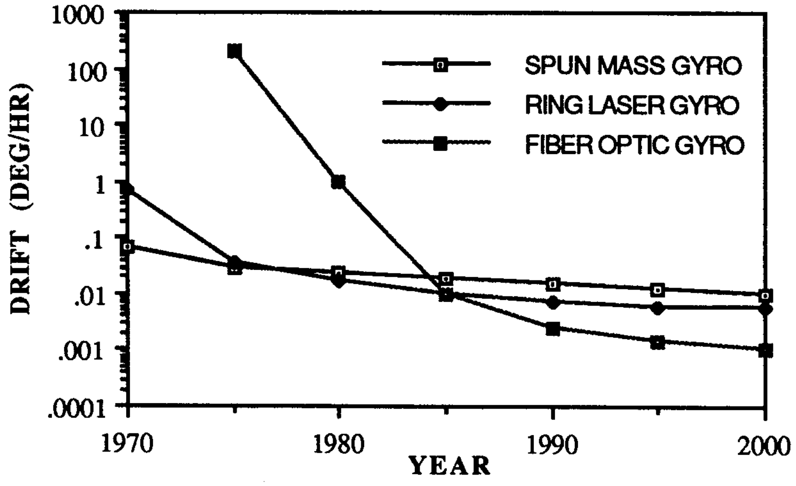

Figure 4.16 - Gyroscope Comparison

4.4.4 Other Navigation Systems Considered

In addition to the Ring Laser Gyroscope, two other systems were considered. The first of these was the conventional spun mass gyroscope. The spun mass gyro, while being a well proven technology, has the lower accuracy (as measured in drift, see Figure 4.16), is bulkier, and requires more power than the RLG [4-28]. In addition, because the spun mass gyro relies on moving parts, its reliability after up to four years of dormancy is questionable. The second system considered was the fiber optic gyroscope. While the fiber optic system is the most accurate (by an order of magnitude) and lowest power unit, it is still in the laboratory testing stages and is therefore not proven enough for the EGRESS mission.

4.4.5 Use of the Navigation System

In a typical mission, when the station is still operational and stable, the navigation system will be initialized from Space Station *Freedom*, while the Egress vehicle is still docked. After separation, the two redundant systems will continually use the GPS data and will send their compared information to the flight software to update the position of EGRESS. In addition, after parachute deployment, the navigational signal will be converted to an audio signal and transmitted as a distress beacon over the Search and Rescue communication channels.

When Space Station attitude and position are unknown, as in the case of a space station catastrophe, the system will be initialized after separation. Once the EGRESS vehicle is on its own, three separate GPS measurements will be taken. From these three position fixes, the flight computer will be able to interpolate the vehicle's orbital trajectory [4-29]. This information is then used to initialize the inertial navigation system, which will take over for the rest of the mission as normal.

4.5 Propulsion Module

After EGRESS completes it's deorbit burn, the propulsion module will detach and complete a posigrade burn that will place it in a safe orbit for later recovery (see Section 5.4.3). In order to accomplish this, the module must have its own power, communications, navigation and computer systems. These system are provided by two identical avionics packages that are part of the module (see Figure 5.12).

4.5.1 Power

Prior to separation the engines on the propulsion package will be powered from the EGRESS main power distribution network. Upon separation, power will be provided for internally. The propulsion package requires approximately 45 minutes to place itself in a safe orbit. During this procedure, each avionics package uses approximately 100 watts of power, the majority of which is used for the navigation system. The avionics boxes will each hold batteries containing 200 Wh of usable energy.

After being retrieved, the propulsion module will be returned to the space station, refitted, and then used again on the next EGRESS. For this reason, the power for the system will be provided by secondary cells. Secondary cells can only be discharged to 50%, therefore each battery pack is fitted for 400 Wh of energy. As with the airlock system, the propulsion module will use NiH cells. Each of these battery packs weighs 19.2 lbs and requires 0.35 cubic feet of space.

4.5.2 Communications

The engine assembly will have a small VHF communications transceiver and antenna to transmit and receive information from mission control. The communications transceiver which is connected to the command sequencer will transmit position and attitude information to the ground whenever it passes over a ground station. It will also receive commands from mission control for guidance.

4.5.3 Computers

The computational needs of the propulsion module are very primitive and therefore are based around a simple processor. Before separation, the EGRESS computer system will initialize all of the modules systems and then load the computer pack with the necessary commands to reach a safe orbit. The propulsion processor will simply sequence through these commands, using navigational information and engine telemetry as variables. Commands can also be added to the sequencer via the communications system.

4.5.4 Navigation

After separation the propulsion package must reorient itself for the posigrade burn that will place it into a safe parking orbit near the space station. In addition, the system module location must monitored both by the computer system and the ground. Navigation and tracking for the module will be accomplished both externally and internally. NORAD currently tracks over 7,500 orbital objects, though most are debris, many are functioning spacecrafts. The resolution of the NORAD radar is 10 centimeters, so the propulsion module is easily tracked. By relaying this information to the module, it is able to determine its position (altitude) with more than sufficient accuracy. However, position is second in importance to the module's attitude. Each avionics packet will contain a Ring Laser Gyroscope, which is similar to the gyroscopes in the EGRESS vehicle. However, in order to save cost, mass, and weight, these gyroscopes are not as accurate as those on EGRESS. These packages, with the ground supplementation, will provide the guidance for the module after separation from the EGRESS vehicle.

Chapter 5

Propulsion

5.0 Summary

The propulsion group was responsible for selecting propulsion systems for each phase of the mission. These systems can be broken down into three main areas:

- a system for separating from the station
- a reaction control system (RCS) for attitude control
- a system to perform the deorbit burn.

Some additional thought was given to providing a ramjet for atmospheric flight. All systems were subject to the constraints of the RFP and the needs of other design teams.

EGRESS will use a gaseous nitrogen system to separate from the station. Two clusters of two 1 lbf cold gas thrusters will be placed on either side of the vehicle to allow separation at 1 ft/s from either node 1 or node 2. This system will need to be refurbished annually.

For on orbit maneuvers, EGRESS will be equipped with 42 reaction control jets. There will be one cluster of 16 across the nose of the vehicle and two clusters of 11 each in the aft section of EGRESS. The two aft modules also contain two 65 lbf thrusters capable of providing attitude control once the craft has entered the atmosphere.

In order to insure proper fuel flow to the engines, a rubber bladder pressurization system will be used. This system employs rubber "bags" inside spherical tanks to totally separate the fuel (or oxidizer) from the pressurizing gas. This design will allow up to 99% fuel expulsion from the tanks in a zero-g environment.

EGRESS will use the Marquardt R-40 engine to deorbit. The R-40 is a liquid bipropellant engine using monomethyl hydrazine as the fuel and nitrogen tetroxide (N_2H_4) as the oxidizer. The vehicle will have three engines, but will be capable of deorbiting using only one.

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5.1 System for Separation from the Space Station

Following ingress of the vehicle, the crew of EGRESS will start their journey earthward. The first phase of this journey will be a 1 ft/s separation maneuver up and away from the station. In order to accomplish this task, a system was developed that could supply the necessary change in velocity while minimizing impact on the station. Three types of systems were researched. They are:

- a pneumatic system
- an electromagnetic repulsion
- a mechanical device (i.e. a spring)

5.1.1 Pneumatic Gaseous Nitrogen System

The system finally chosen for separation from the space station was a pneumatic gaseous nitrogen system. This system stores pressurized nitrogen gas in tanks and expels it through thrusters in order to provide the upward thrust to separate. There are four clusters of two 5 lb thrusters very similar to the thrusters utilized for attitude control, with two clusters on each side of EGRESS. Each cluster on one side is aligned either perpendicular or parallel to the slope of the airlock and passes through the center of gravity in order to provide separation from two possible node configurations. These nodes are located on the top and on the side of the station. The thrusters will always provide motion in the positive Z direction from the station in order to avoid complications caused by the presence of the solar arrays.

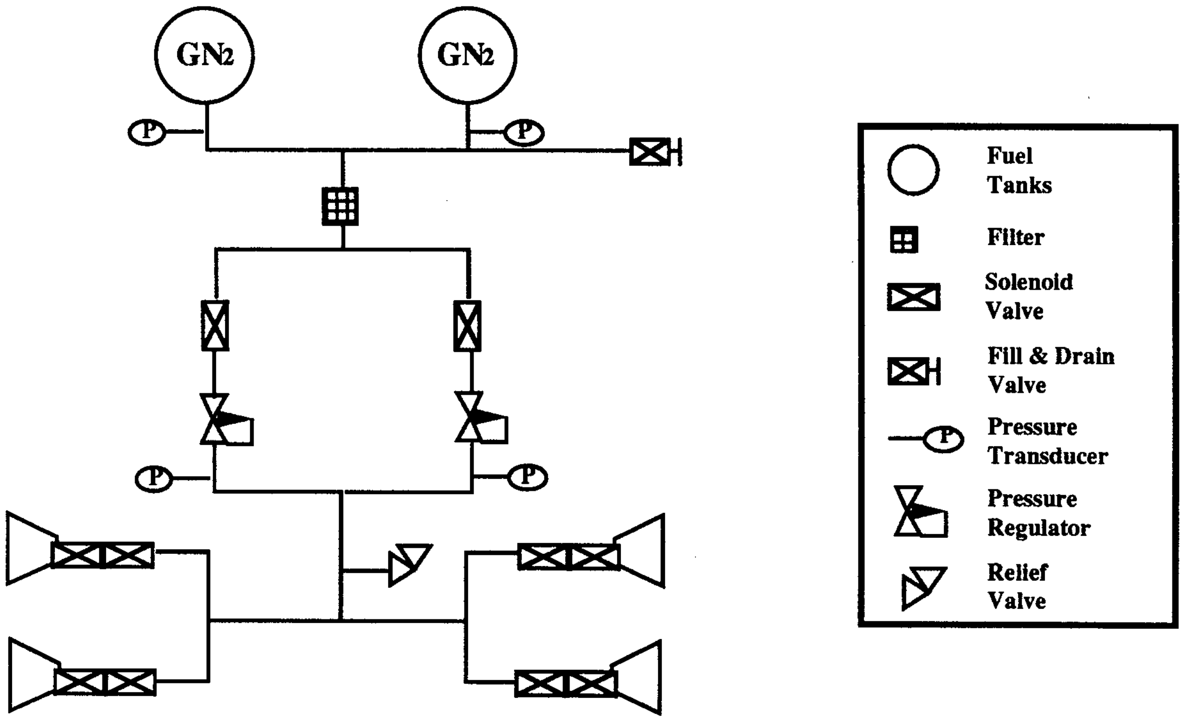


Figure 5.1 - Pneumatic Gaseous Nitrogen System Schematic

5.1.1.1 System Configuration

A schematic of the system is shown in Figure 5.1. The nitrogen is stored under a nominal pressure of 4100 psia in two 0.3 ft^3 tanks, each of which must be kept at a nominal temperature ranging from -90°F to 30°F [5-6]. The tanks are heated using an active heating system provided in the interior of EGRESS. Pressure transducers monitor the pressure in the lines immediately outside the tanks in order to detect any possible failures. Two tanks are provided for redundancy.

From the tanks, the nitrogen flows through a filter and and a pressure regulator. The regulator reduces the pressure from 4100 psia to approximately 315 psia. Again, two are provided in case one fails. In case of a double regulator failure, emergency relief valves are included to prevent damage to the system. Between the regulators and the filter are latching valves to isolate the tanks from the rest of the system.

After the nitrogen is regulated to a working pressure, it passes through two more valves before being exhausted out the thruster nozzles. Each nozzle provides a thrust of 5 ± 0.5 lbs over the entire range of operating pressures.

5.1.1.2 Determining Fuel and Burn Time

The amount of nitrogen necessary to perform a 1 ft/s change in velocity is 5.16 lbs. This was determined based on an initial vehicle mass of 10,800 lbs using:

$$\Delta V = g_o I_{sp} \ln\left(\frac{m_i}{m_f}\right) \qquad (5\text{-}1)$$

where:
m_i is the initial vehicle mass
m_f is the final vehicle mass
g_o is a gravitational acceleration constant (32.2 ft/s^2)

The mass of fuel necessary is simply the difference between the initial and final masses. In this case it was 5.16 lbs. Dividing this by two, it is necessary to provide 2.58 lbs of nitrogen on each side of EGRESS. To provide a safety factor of two, a duplicate tank is added on each side as well. The volume of the tanks can be determined using

$$PV = mRT \qquad (5\text{-}2)$$

With worst case values for the pressure (4500 psia) and temperature (90°F), the required tank volume is 0.12 ft^3 [5-2].

The burn time, or in this case the time the thrusters will be open, is determined by

$$I_{sp} = \frac{T\,t_b}{W_{pb}} \qquad (5\text{-}3)$$

where
I_{sp} is the specific impulse (worst case is 65 s)
W_{pb} is the weight of propellant used (5.16 lbs)
t_b is the time the thrusters are open.
T is the thrust provided (20 lbs).

Equation 5-3 determines t_b, showing that it will be necessary to fire the thrusters for approximately 17 s in order to get a velocity change of 1 ft/s.

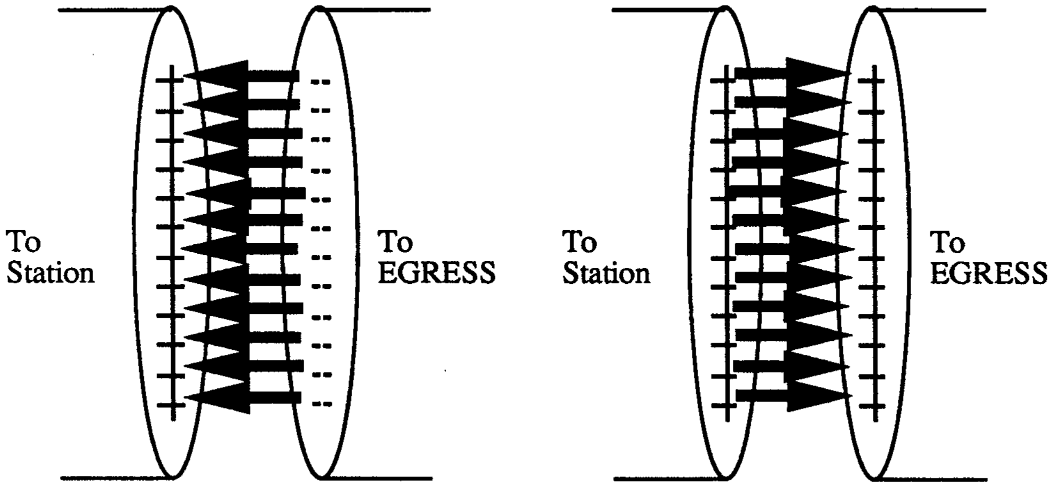
5.1.1.3 Maintenance

Whenever propellants are being stored for an extended period of time, bleed off becomes a concern. In the case of the pneumatic nitrogen system, each valve has a specified leakage rate of 5 scc/hr or about 1.54 ft^3/yr at standard pressure, which at first glance may seem outrageously high. However, the nitrogen is not at standard pressure, but rather is stored at 4100 psia. Therefore, 1.54 ft^3/yr must be divided by a factor of 15 in order to relate this system to standard conditions, giving a loss of 0.10 ft^3/yr. This assumes only one valve when in reality the gas would be forced to flow through three valves. This will reduce this number considerably, making bleed off negligible.

The system will need to be recharged about once a year. This can be done from the station using the fill and drain valve shown in Figure 5.1. In case of some abnormal bleed off conditions, the pressure transducers immediately outside the tank should be monitored periodically to insure system integrity.

5.1.2 Alternatives

The other types of systems considered, electromagnetic propulsion and propulsion by a mechanical device, were not chosen because they were difficult to incorporate into the system. Both systems would require the airlock to pass directly through the center of gravity. Since this was not feasible, neither system would provide pure translation, but rather would cause EGRESS to rotate.



Before separation plates are oppositely charged and EGRESS is attracted to the station.

To separate, polarity on one plate is reversed, creating a repulsive force pushing EGRESS away from the station.

Figure 5.2 - Electromagnetic Separation System Concept

The concept of electromagnetic propulsion is graphically illustrated in Figure 5.2. Basically, there are two charged plates-- one on EGRESS and one on the station. Initially, both plates are oppositely charged, creating an attractive force between EGRESS and the station. The charge on one plate is then instantaneously reversed, causing both plates to be of like charge. This creates a repulsive force which pushes the spacecraft away [5-1].

A problem with this system aside from that mentioned above lies in the fact that a capacitor capable of providing such a charge would be enormous. Because of the large size and the proximity of the operations, it is quite likely that the capacitor would arc long before sufficient charge was built up to repel EGRESS away from the station. The arc would at least burn out the system and could potentially destroy EGRESS and cripple the station.

Another problem is created when the charge reverses polarity. An electromagnetic pulse (EMP) would be created powerful enough to disturb any system on the station or EGRESS that has not been properly shielded. Since delicate experiments will be in progress on the station, this EMP would be highly undesirable.

The initial concept of a mechanical system was something similar to the device used by the Apollo capsule to separate from Skylab. Little data was available on this type of system, and for reasons mentioned above, it was discarded as a viable option.

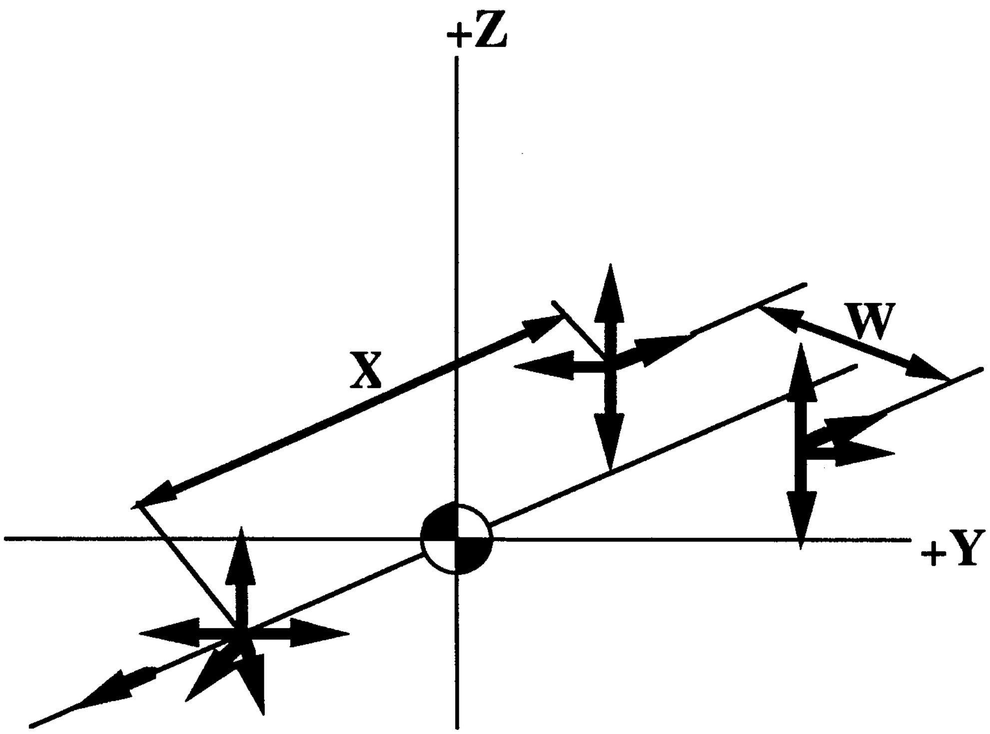


Figure 5.3 - RCS Thruster Placement (X=10 ft, W=6ft)

5.2 Reaction Control System (RCS)

The EGRESS Reaction Control System (RCS) Thrusters are located in the forward reaction control subsystem and the aft propulsion subsystem. These thrusters provide the thrust for vehicle attitude control and 3-axis translation on orbit. The thrusters are designed to provide high reliability, minimum weight and minimum maintenance and servicing. The thruster used is a Hughes 5 lbf hydrazine monopropellant rocket engine [5-3]. The Hughes thruster has a demonstrated specific impulse of 229 seconds at a thrust of 5 lbf.

During atmospheric flight EGRESS will require the use of a 65 lbf thruster rather than a cluster of Hughes 5 lbf engines in order to provide adequate roll control in the atmosphere, thus resulting in the addition of four Marquardt R-30A hydrazine monopropellant rocket engines. There will be two placed in each aft propulsion subsystem and will only be used during atmospheric flight. The R-30A has a demonstrated specific impulse of 225 seconds at a thrust of 65 lbf The thrusters employ a multiple tube penetrant injector, a catalytic decomposition chamber packed with shell catalyst and a 23 to 1 ratio expansion nozzle. Hydrazine flow to the thruster injector is controlled by a balanced poppet, solenoid operated injector valve mounted integrally to the injector mounting plate.

5.2.1 RCS Number and Placement

The reaction control system of EGRESS provides vehicle attitude control and 3-axis translation on orbit, and during entry phase of the flight. There are three separate reaction control subsystems in each EGRESS. As shown in Figure 5.3 and Figure 5.4, the forward system is located in the nose of the vehicle, and each of the two aft systems are located before the deorbit module in the rear of the craft on each side. There are a total of forty-two 5 lbf thrusters in the on orbit reaction control system and four 65 lbf thrusters in the atmospheric reaction control system. Sixteen 5 lbf thrusters are in the forward module and provide impulse in the ±Y axis (6 thrusters), combination of -Z and ±Y axis (4 thrusters), the +Z axis (3 thrusters), and the -X axis (3 thrusters). The 5 lbf thrusters that are a combination of -Z and ±Y axis in the forward module are angled down at 75 degrees from the Y axis in the Y-Z plane. Each of the two aft modules contain thirteen 5 lbf thrusters which provide impulse capability in the ±Y axis (4 thrusters), combination of -Z and ±Y axis (4 thrusters), the +Z axis (3 thrusters), and the +X axis (2 thrusters). The 5 lbf thrusters that are a combination of -Z and ±Y axis in the two aft modules are angled down at 60 degrees from the Y axis in the Y-Z plane. The two aft modules also contain two 65 lbf thrusters each, which provide impulse capability for a combination of -Z, -X, and ±Y axis (combination of pitch, yaw, and roll). The 65 lbf thrusters are angled down at 60 degrees from the Y axis in the Y-Z plane and angled back at 15 degrees from the Y axis in the X-Y plane.

The thrusters are buried and the exit nozzles are contoured to the EGRESS fuselage. There are fifteen different configurations for the thruster chambers. The control and instrumentation components of all thrusters are identical except for different heater wattages.

5.2.2 Design Requirements

The design requirements, demonstrated life, and performance of the EGRESS Reaction Control System Thruster, Hughes 5 lbf engine, are shown below in Figure 5.5 and Figure 5.6.

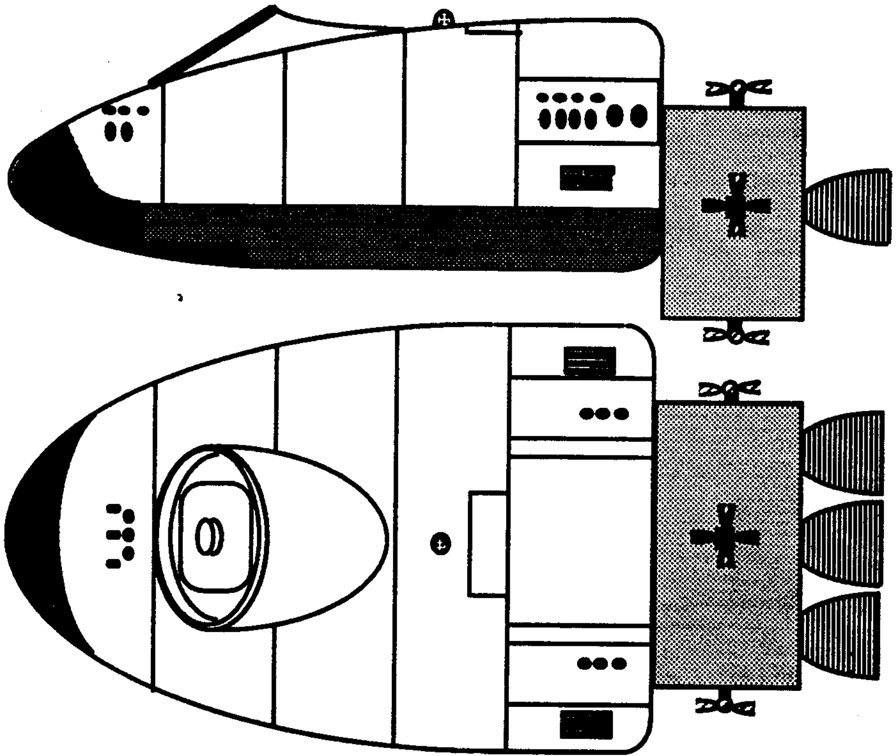


Figure 5.4 - RCS Thruster Placement

Operating pressure range:	285 to 90 psia
Pulses:	34,000
Steady state duration:	21,600 seconds
Total starts:	290
Injector temp. at hot restart:	1000°F
Min. operating temp.:	Valve, 40°F catalyst bed and injector, 15°F
Propellant consumed:	500 lbm

Figure 5.5 - Demonstrated Life and Performance of Hughes 5 lbf thruster

Thrust:	5.0 lbf nominal
Valve inlet pressure:	300 psia nominal
Specific Impulse:	229 sec nominal
Nozzle type:	Conical, 15 degree half angle
Thrust coefficient, C_F:	1.70
Throat area, cold:	0.0256 square inch
Nozzle area ratio:	40:1 nominal
Catalyst type:	Shell 405, ABSG grade
Weight (with valve):	1.2 pounds

Figure 5.6 - Hughes Thruster Design Requirements

The design requirements and performance for the EGRESS Reaction Control System Thruster, Marquardt R-30A are as follows. The R-30A operates at a thrust level of 65 lbf with specific impulse of 225 sec. This engine operates in the pulsing mode with pulse widths down to approximately 30 ms. The engine normally operates with feed pressure of 180 psia. Both 50,000 lb-sec of total impulse and a steady state continuous burn time of 220 seconds were demonstrated with no significant decrease in performance of the R-30A.

5.2.3 Attitude Control System Configuration

A schematic of the system is shown in Figure 5.7. All fuel and helium tanks use the rubber bladder system (see Section 5.3.3) and are constructed out of titanium to provide a high strength and durability. Each of the three spherical helium tanks has a volume of .5 ft^3 and all three subsystems contain a level of redundancy of one for the fuel. A level of redundancy of one means that the system will still operate after one failure. Each system caries twice the amount of fuel needed and is split between two spherical fuel tanks. The forward RCS fuel tanks each have a diameter of 10.1 in. and a volume of .59 ft^3. Both aft RCS systems contain two fuel tanks, each with diameter of 12.73 in. and volume of 1.19 ft^3. As seen from the Figure 5.7, both the 65 lbf and the 5 lbf thrusters use the same helium and fuel tanks; however, only one system can operate at a time.

The forward RCS contains a level of redundancy of two for the ±Y direction, the -X direction, and the +Z direction cluster of thrusters. The level of redundancy is only one in the combination of -Z and ±Y direction cluster. Both aft RCS systems contain levels of redundancy of one, two and three. Level of one in the +X direction cluster, two in the -Z direction cluster, and three in the ±Y direction cluster and the combination of -Z and ±Y direction cluster of thrusters. The RCS for atmospheric flight has a redundancy of one.

The volume of each engine and equipment is .05 ft^3 with each engine spaced 1.5 in. apart. Therefore the total volume for the forward RCS thrusters is 1.18 ft^3 and the total volume for each on orbit aft RCS thruster cluster is 0.98 ft^3. The total volume for each atmospheric aft RCS thruster cluster is .59 ft^3.

5.2.4 Attitude Control Performance

The 5 lbf thrusters were chosen because they allow for on orbit attitude control in a reasonable amount of time without maneuvering too quickly. This was determined based on a maximum angular velocity of 5 RPM and the fact that the distance from the center of mass to the forward RCS is 6 to 7 ft, and the distance from the center of mass to the aft RCS is 3 to 4 ft. The equations used are:

$$T = F_f d_f + F_A d_A \tag{5-4}$$

$$\frac{d^2\beta}{dt^2} = \frac{T}{I} \tag{5-5}$$

$$t = \frac{d\beta/dt}{d^2\beta/dt^2} \tag{5-6}$$

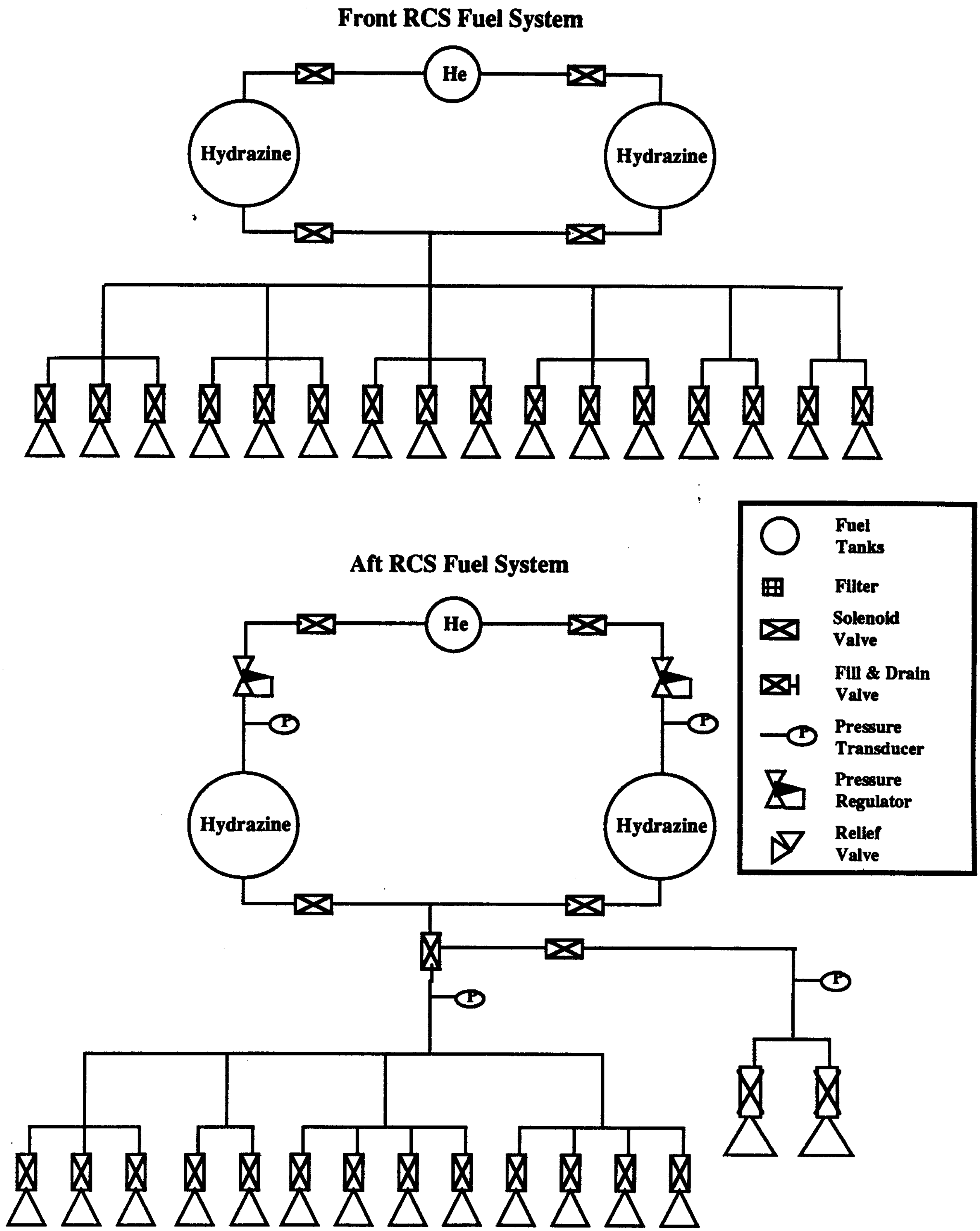


Figure 5.7 - RCS Fuel System Schematic

where F_f = Thrust in forward cluster (lbf)
F_A = Thrust in aft cluster (lbf)
d_f = Distance from c.g. to forward RCS (ft)
d_A = Distance from c.g. to aft RCS (ft)
I = Moment of inertia (lbm ft^2)
$(d^2\beta/dt^2)$ = Angular acceleration (rad/sec^2)
$(d\beta/dt)$ = Angular velocity (rad/sec)
T = Torque (lbf ft)
t = Time to reach maximum angular velocity (sec)

5.3 Fuel Pumping system

The engines that are being used for the deorbit burn require a pressure fed propellant system. This system must be able to feed the fuel and the oxidizer at 238 psi.

Because the propulsion system will be used in zero gravity conditions, there are several items that must be considered. The first item is the propellant distribution in the tanks. Under zero gravity conditions the fuel may be distributed in two different ways depending on the fluid properties of the liquid [5-5].

The first method uses a wetting fluid. Here the fluid forms separate droplets in the tank. An example of this is shown in Figure 5.8. Once these droplets form, there is no way to guarantee that the fuel will be at the inlet to the engine when it needs to be started.

The second method uses a non-wetting fluid. Here the fluid will spread itself over different areas of the tank, also shown in Figure 5.8. This method also has the problem that it is not possible to ensure the location of the fuel when it is necessary to start the engine.

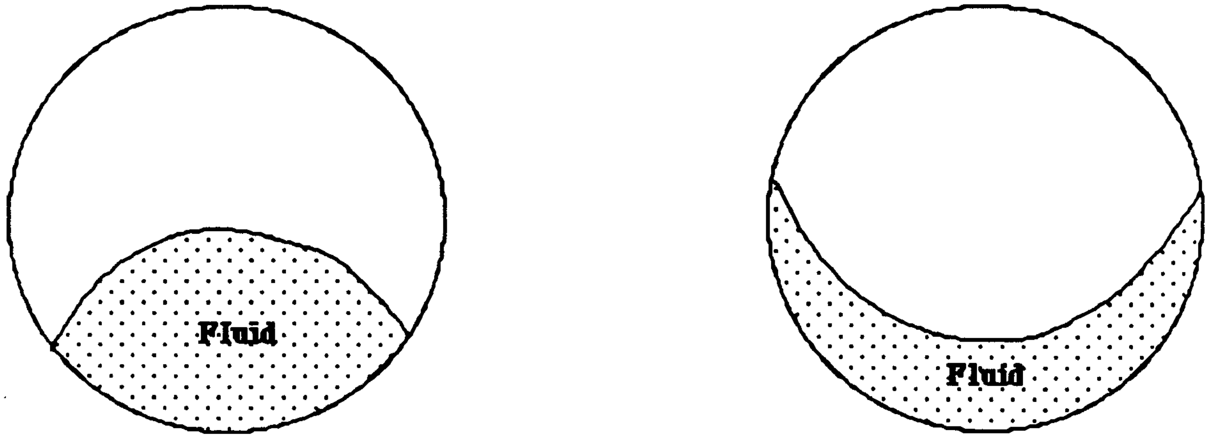


Figure 5.8 - Wet Versus Non-Wet Fuel Tanks

5.3.1 Choosing a System

Several different pressurization systems were considered for use on EGRESS. One system uses a piston that forces the fuel or oxidizer from the tank under pressure. It has two major drawbacks: (1) it tends to have a larger mass, and (2) it is nearly impossible to insure a 100% seal between the piston and the sides of the tank.

Another method involves the use of a surface tension screen at the engine inlet. When a pressurizing gas is forced into the tank, the surface tension will pull the fluid towards the screen and keep it separated from the pressurizing gas. Problems with this system include the possibility of the fuel being dislodged by sudden movement, causing undesirable fuel flow into the engine creating complications.

A method similar to the rubber bladder system chosen makes use of metal membranes or plastic films. The major difficulty with this system is in fatigue. It is so easy to fatigue these types of systems that failure may occur during testing.

Still another system uses rubber diaphragms to separate the fuel (or the oxidizer) from the pressurizing gas. As the gas is forced into the tank, it exerts a pressure on the diagrams which in turn pushes the fuel into the engine inlet. This system is also advantageous in that it is possible to achieve up to 99% efficiency for fuel expulsion. Figure 5.9 shows an example of this configuration.

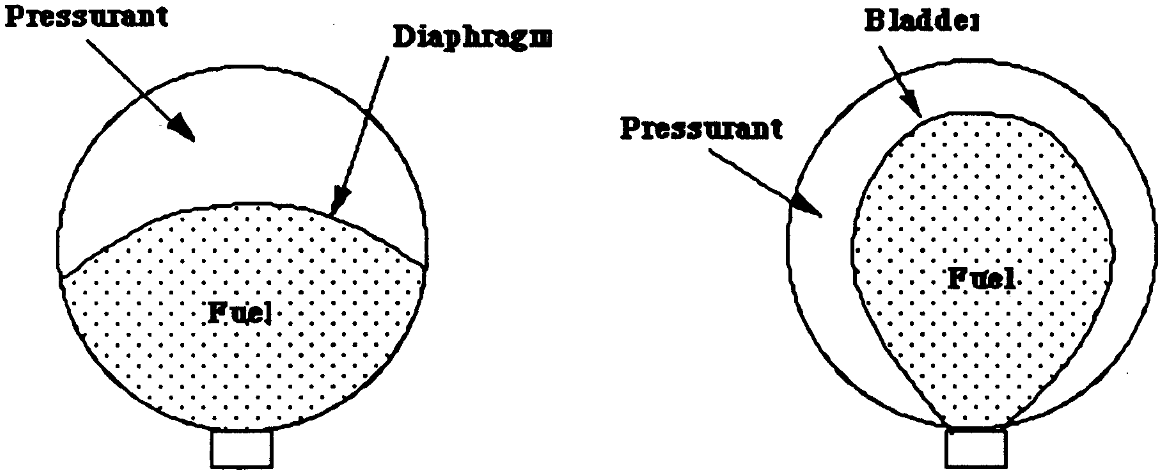


Figure 5.9 - Diaphragm and Bladder Systems

5.3.2 The Rubber Bladder System

The system employed on EGRESS utilizes a rubber bladder, as shown in Figure 5.9. The concept is similar to a rubber diaphragm except that the fuel is totally enclosed in a rubber bag. This method has all the advantages of the diaphragm in addition to helping reduce fuel bleed off over time. By separating the fuels from the tanks, it also eliminates the chemical interactions between the fuel and the tanks providing longer tank life.

Another major advantage of the rubber bladder system is that it has a long life cycle. It can sustain a large number of refill and empty cycles. Since the EGRESS system is reusable this is an important consideration.

The bladders in the MMH tanks will be made of TRW's AF-E-332. This material has been used in many satellites and has proven to be reliable for a extended durations in space. In the oxidizer stage a newly developed elastomer for oxidizers will be used. This elastomer is TRW's AF-E-124R. It is one of the first elastomers to be oxidizer compatible and can be used to initiate expulsion bladders in bipropellant systems.

In this system, Helium will be used as the pressurizing gas. Helium was selected because it has a low weight, it is inert, and it is highly compressible [5-5].

5.3.3 Tank Design

The propellant tanks will be spherical in shape, because this shape has a very high volumetric efficiency, and it is also the most efficient design for the expulsion bladders. The propellant tanks will have a diameter of 23 inches. This gives a volume of 3.8 ft^3. They will be constructed of titanium to provide high strength and durability. Each tank will weigh 16.2 lbs.

The tanks used to hold the helium will also be spherical. These tanks will have a diameter of 11.2 inches and a volume of 1.6 ft^3. The dry weight of the tanks will be 10.0 lbs.

5.3.4 System Configuration

A schematic of the system is shown in Figure 5.10. This systems provides many levels of redundancy. The first valves are from the helium tanks. This consists of two different valves in parallel for redundancy. In case one of the valves malfunctions, it will still be possible to open a passage, thereby preventing the whole system from being inoperable. The next level is the pressure regulators. This stage is necessary because the oxidizer and the fuel will need several different pressures. This provides the different pressures without having a separate helium tanks for the oxidizer and the fuel.

The third level of valves leads into the tanks themselves. This makes it possible to stop pressurizing the tanks if the helium tank valves are stuck open.

5.4 Deorbit Burn Engine

A deorbit burn engine configuration is necessary to allow EGRESS to slow down and begin descent to Earth. Performance criteria were derived from the requirements of space operations and a desire for fuel and cost efficiency.

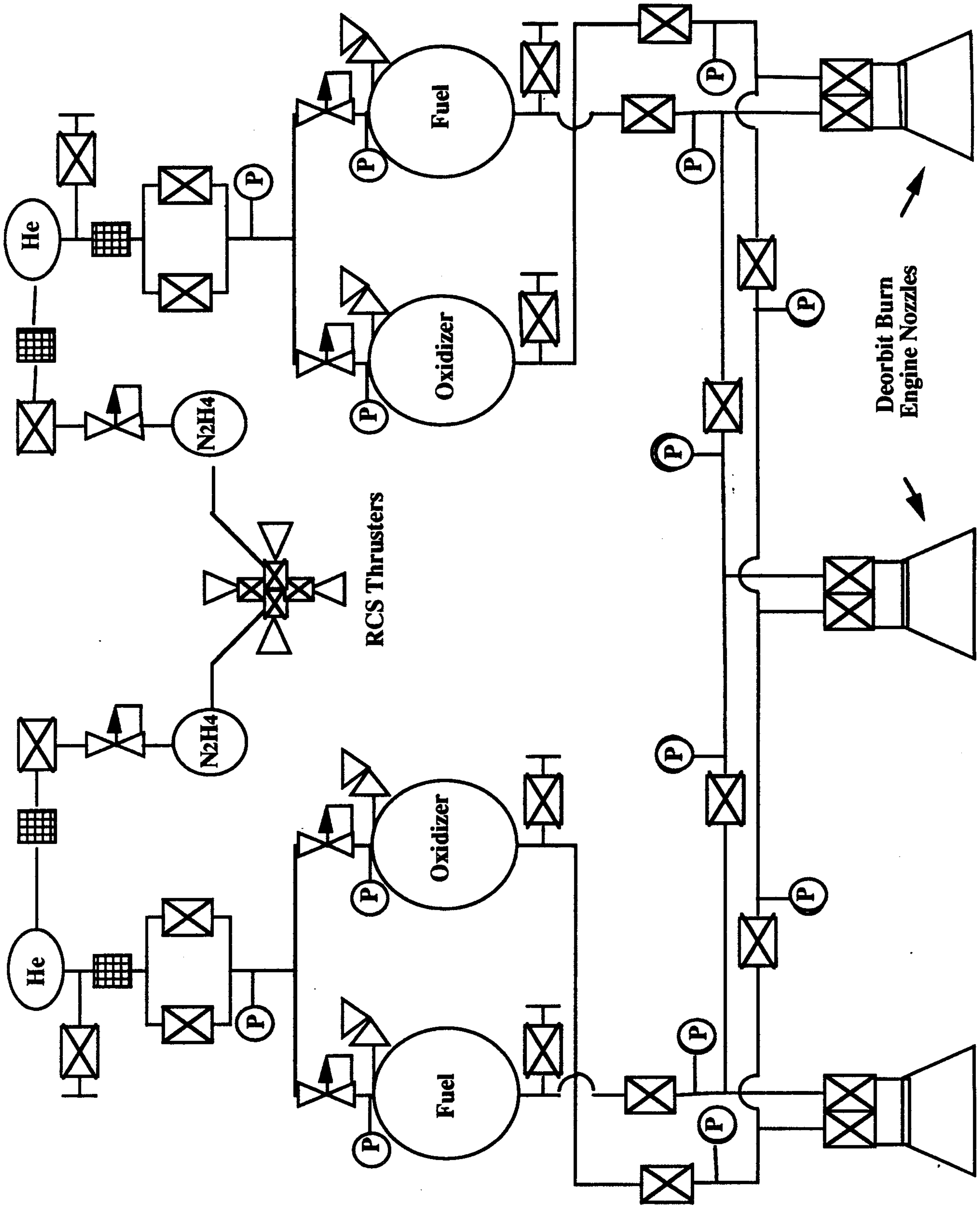


Figure 5.11 - Pressurization System Schematic

5.4.1 Selection Criteria

The deorbit maneuver requires a maximum velocity change of approximately 390 ft/s. The following criteria was used to select the engine:

- A liquid propellant
- a large specific impulse to decrease the amount of fuel necessary
- multiple engines in order to provide several levels of redundancy
- a moderately large thrust to make the burn reasonably short
- A short nozzle size

A liquid propellant was chosen instead of a solid for several reasons. Most importantly, a solid rocket provides only one set burn time. Since the space station will be in orbit at varying altitudes, it is necessary to be able to vary the burn time in order to accommodate the various starting points. Moreover, a failure in one engine would require a longer burn time from the remaining engines. A solid propellant could not accomplish this.

To obtain a given amount of thrust two configurations were available: first a large engine providing all the thrust, or second, several small engines which, taken together, provide the total thrust needed. With several small engines, the possibility of engine failure is not a disaster because the deorbit burn could still be performed on time with fewer engines. With one large engine however, a failure would totally disable any deorbit capability. These criteria led to the selection of the Marquardt R-40 bipropellant engine as the deorbit burn engine.

Size was also a consideration since EGRESS will be put into orbit using the space shuttle. A very large engine would not allow EGRESS to fit into the shuttle bay. Alternative engines had nozzle lengths of up to 6 ft.

5.4.2 Marquardt R-40 Rocket Engine

The Marquardt R-40 engine has the technical specifications shown in Figure 5.11.

Fuel	MMH (Monomethyl hydrazine)
Oxidizer	N_2O_4
Thrust	870 lb
I_{sp}	300 s
Inlet Pressure	238 psia
A_e/A_t	40
Maximum Burn Time	800 s
Mass flow rate fuel	1.2 lb/s
Mass flow rate ox	1.9 lb/s
Electric Requirements	27 V DC
Length	18 in
Width	13 in
Weight	16.0 lb

Figure 5.11 - R-40 Technical Specifications

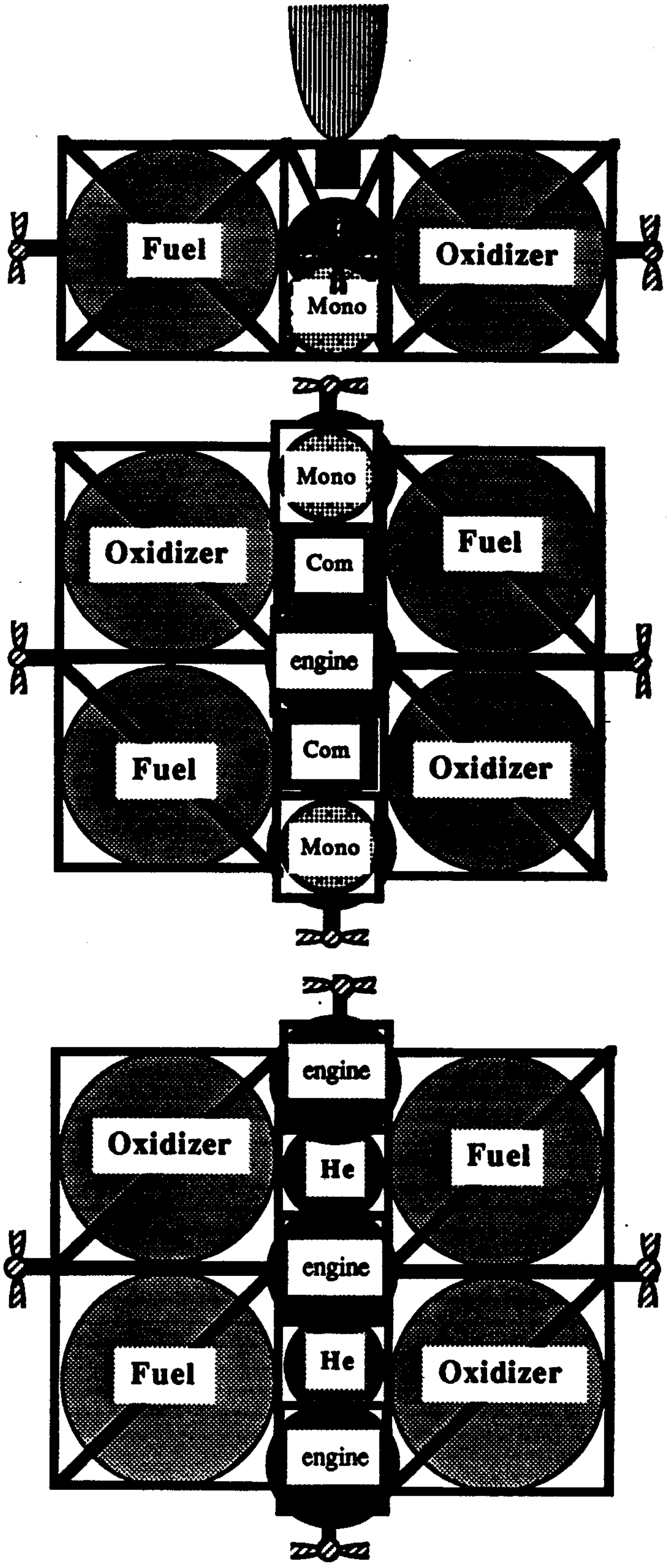


Figure 5.12 - Deorbit Burn Module Configuration

5.4.3 Configuration

We decided to use three R-40 engines in a straight line. With this arrangement a normal burn would be performed with all three engines. In case of a center engine failure, the two outside engines could be ignited. In case of a end engine failure, two options exist: burning only the center engine or burning the center and remaining extreme engine while compensating for induced moments by RCS jets.

The engines, their fuel, and pumping systems will be contained in a jettisonable structure separate from the main body of EGRESS, as shown in Figure 5.12. This structure will be jettisoned following the burn for several reasons. First of all, dumping the propulsion pack will decrease both the mass and the drag of the vehicle. Secondly, by placing the propulsion pack in a safe orbit, the pack can be reused. EGRESS will perform a small separation maneuver after which the structure will use some of the remaining fuel to put itself in a safe orbit where it can be retrieved later.

5.5 Atmospheric Flight

In order to aid atmospheric flight during the entry phase of flight, the propulsion group considered the possibility of powered flight using a ramjet.

5.5.1 Air-Breathing Propulsion

As shown in Figure 5.13, the ramjet would be operational between Mach numbers of 1 and 5. Use of the ramjet would increase both the crossrange and downrange capabilities of the vehicle [5-2]. We researched the amount of downrange increase versus the amount of fuel burned. In order to study this, we assumed the following:

- Level flight
- Vehicle dry mass of 10,300 lb
- Lift-to-Drag ratio of .8
- Mach number of 4.0
- Operational altitude of 98,500 ft
- Thrust Specific Fuel Consumption of 0.18 kg/N-hr

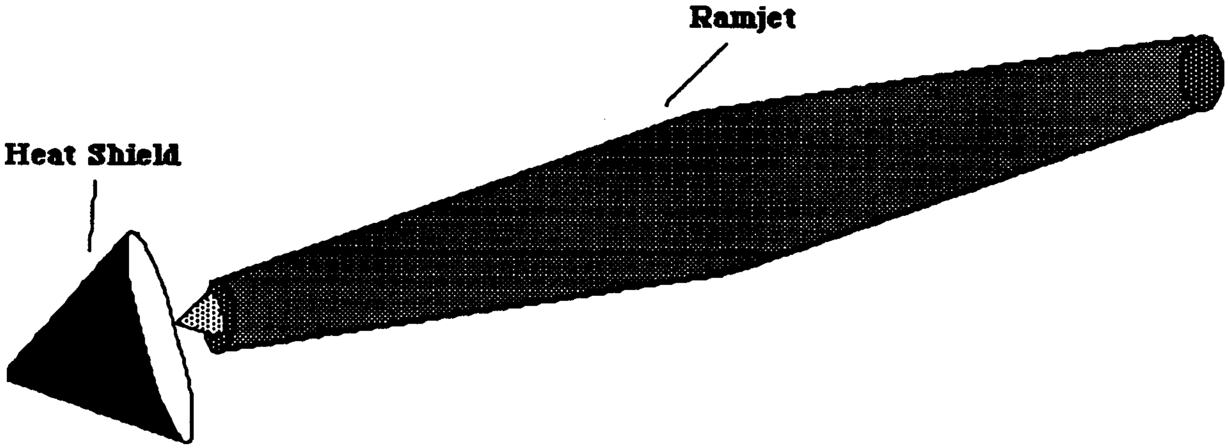


Figure 5.13 - Ramjet with Heat Shield

5.5.2 Benefits and Problems

Although using a ramjet would increase the vehicle's downrange capability, several disadvantages are present.

For example, a ramjet would be mounted on the underside of the vehicle. This means that it would require a protective heat shield during reentry that would have to be "blown off" before initiating ramjet operation. Constructing a device to reliably perform such a difficult procedure was a major concern. Additionally, to attain any downrange capability, the ramjet would need additional fuel, meaning additional tanks, increasing the vehicle's weight. Effective use of the ramjet would also require advanced aerodynamic control surfaces, which may not be flight proven. Another important factor is that the vehicle will be in the operational Mach 1-5 range for only about 2 minutes.

The ramjet itself cannot be considered flight proven, and because the Request For Proposals (RFP) specifically states that EGRESS use flight proven hardware, the propulsion group decided that the ramjet would not be feasible.

Chapter 6

Space Operations

6.0 Summary

Responsibilities for the Space Operations group revolved around planning the return of the EGRESS vehicle to earth. The necessary orbital maneuvers between Space Station *Freedom* (altitude of 140 to 270 nautical miles) and 400,000 feet were determined. These altitudes specify, respectively, the height of the Space Station and the height at which the atmosphere was assumed to begin. The determination of these maneuvers yielded time lines for the various sample missions. In planning these sample missions, appropriate landing sites had to be selected in order to substantiate the guarantee that the project EGRESS vehicle will be able to land at one of the sites within twenty-four hours of the deciding time to use the EGRESS.

The EGRESS vehicle's mission will begin with separation from the Space Station. This separation will consist of two phases. The first phase is a 1 ft/s positive radial burn that will consume approximately three minutes. When EGRESS reaches a height of 150 ft above the station, the second phase of separation will begin. This maneuver will consist of a 2 ft/s retrograde that will put the EGRESS in proper position for the deorbit burn after approximately 40 minutes.

The deorbit burn will be a retrograde burn, and the transfer will resemble a Hohmann transfer. The retrograde will allow the EGRESS vehicle to transfer from the station's orbit to the 400,000 ft atmospheric boundary. The time and velocity change required for the maneuver depends on the station's altitude. At the minimum altitude of 140 nm, the required ΔV is 227 ft/s, and the maneuver will take 24.4 minutes. At the maximum altitude of 270 nm, the required ΔV is 391 ft/s, and the maneuver will take 36.6 minutes.

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6.1 Proximity Operations

After leaving Space Station *Freedom*, the EGRESS vehicle must be able to safely maneuver around the station. The station's solar arrays extend 104 feet from the main truss and pose a threat for potential collisions; therefore, a safe distance must be reached before any sudden movements are made by EGRESS. Additionally, contamination from the RCS jets and deorbit burn engines must be avoided. Several different methods exist to allow EGRESS to safely maneuver away from the station. The possible maneuvers to be considered are as follows: a radial burn, a posigrade burn, and a retrograde burn.

The first type of maneuver consists of a radial change in velocity, or a radial ΔV. This type of burn is fired along the radius vector of the vehicle. The radial ΔV may also be negative, ΔV towards the earth, or positive, a ΔV away from the earth. The vehicle's trajectory after a radial ΔV is shown in Figure 6.1. The motion for both cases begins at the origin of the coordinate system. The coordinate system is centered on the Space Station and is moving with the Space Station's velocity, in this figure the station is moving to the right. The motion for this maneuver looks similar to a football and has the same period as the Space Station.

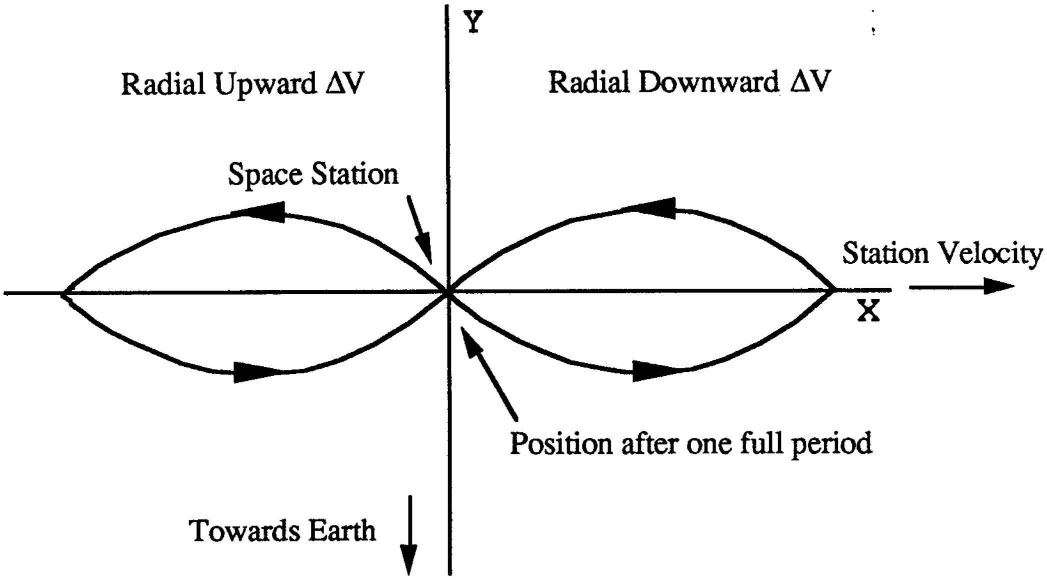

Figure 6.1 - Motion after Radial Burns

The second and third types of maneuvers consist of a velocity change along the same line as the Space Station's velocity vector. If the ΔV is in the same direction that the Space Station is traveling, the maneuver is called a posigrade. When the ΔV is opposite to the station's velocity, the maneuver is referred to as a retrograde. The motion for both posigrade ΔV and retrograde ΔV are illustrated in Figure 6.2. The motion for both cases begins at the origin of the coordinate system. The coordinate system is centered on the Space Station and is moving with the Space Station's velocity, in this figure the station is moving to the right. This motion also has the same period as that of the Space Station. However this maneuver differs from the radial ΔV in that after the retrograde or posigrade the vehicle will not return to the Space Station.

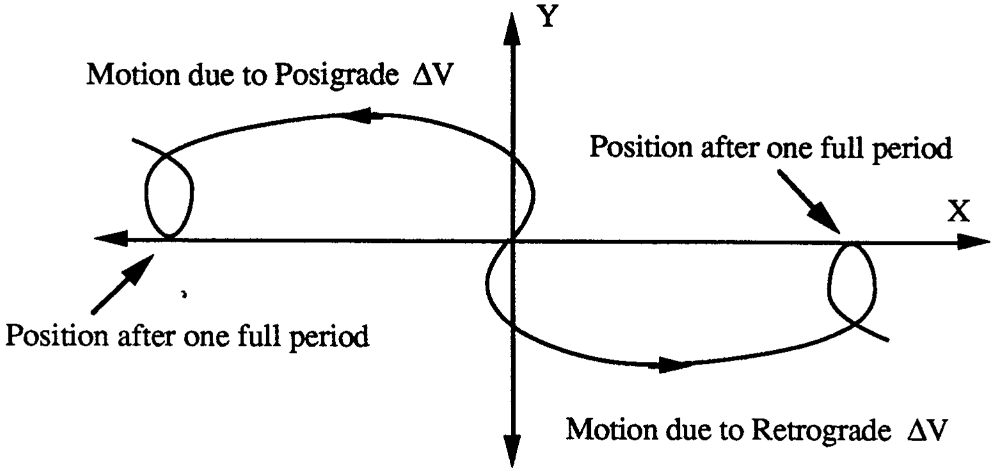

Figure 6.2 - Motion after Posigrade / Retrograde Burn

A computer program was written that evaluated different combinations of these maneuvers. Rather than using only a radial ΔV, a retrograde or a posigrade, EGRESS will utilize a combination of two maneuvers. The first phase of separation is shown in Figure 6.3 and will consist of a positive radial burn via EGRESS' cold gas system. The velocity change will be 1 ft/s, and this maneuver will take the EGRESS to a distance of 150 feet above the station, thus, clearing the solar arrays and avoiding contamination of the panels from the RCS jets. At this point, phase two of separation will begin.

The phase two maneuver [6-1] can be calculated by

$$x(t) = \left[x(0) - \frac{2\,\dot{y}(0)}{\omega}\right] + \left[-\,3\,\dot{x}(0) - 6\,\omega\,y(0)\right] t + \left[2\,\frac{\dot{y}(0)}{\omega}\right] \cos \omega t + \left[4\,\frac{\dot{x}(0)}{\omega} + 6\,y(0)\right] \sin \omega t \tag{6-1}$$

$$y(t) = \left[\frac{2\,\dot{x}(0)}{\omega} + 4\,y(0)\right] + \left[\frac{-\,2\,\dot{x}(0)}{\omega} - 3\,y(0)\right] \cos \omega t + \left[\frac{\dot{y}(0)}{\omega}\right] \sin \omega t \tag{6-2}$$

For safety purposes, the distances x(t) and y(t) were assumed to each be approximately 1 nautical mile. The variables in this case were the x- and y- components of the velocity. Based on the calculations, phase two will consist of a 2 ft/s retrograde. As shown in Figure 6.4, this retrograde will decrease the vehicle's orbital velocity so it can enter a small elliptical orbit about the Space Station, which is centered at the origin in Figure 6.4. When EGRESS reaches a distance of approximately 1 nm ahead and 1 nm below the station, the vehicle will safely begin the deorbit burn. The vehicle will leave this small elliptical orbit and enter a larger elliptical orbit that will eventually allow EGRESS to reenter the atmosphere.

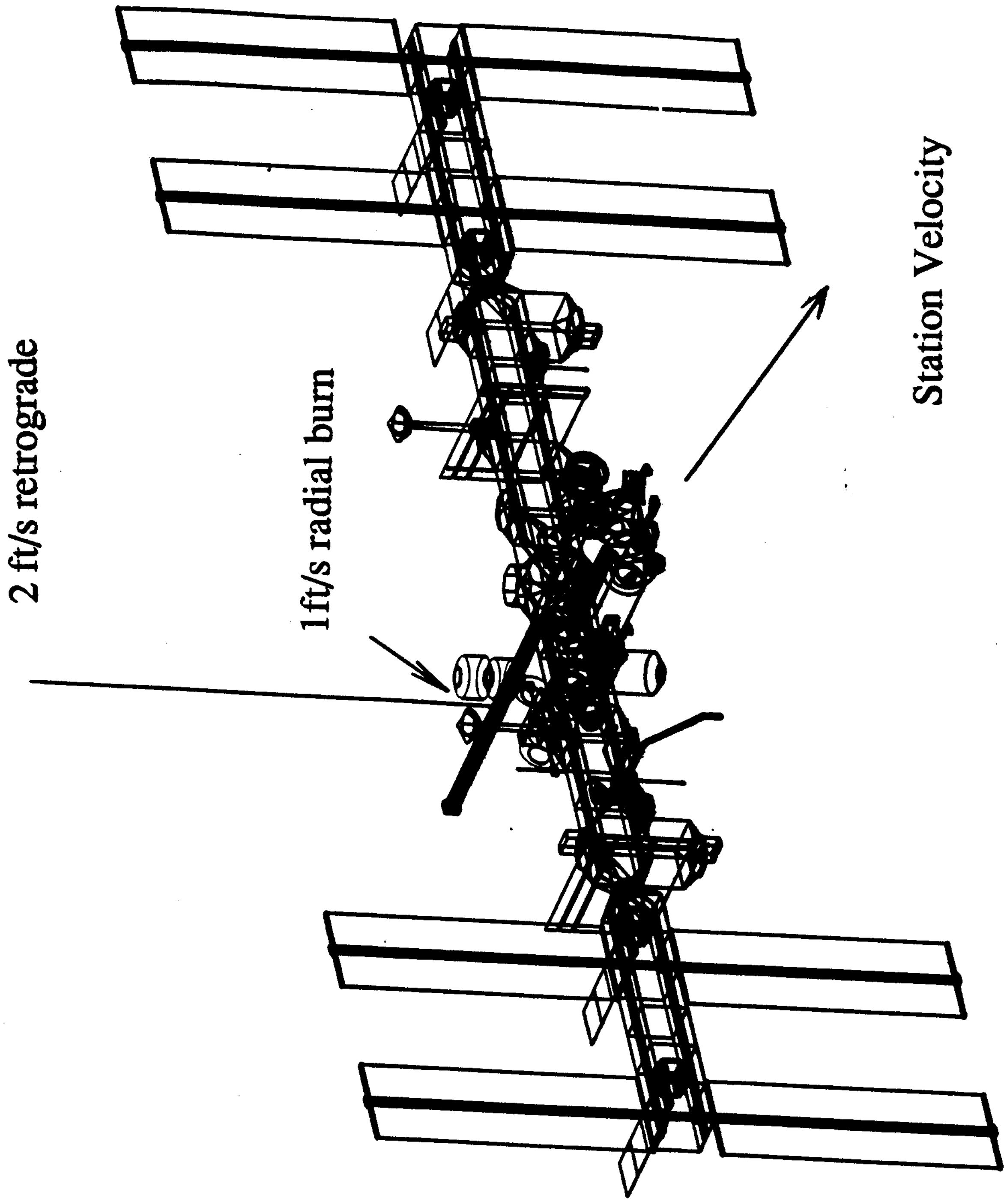

Figure 6.3 - First Phase of the Separation Maneuver

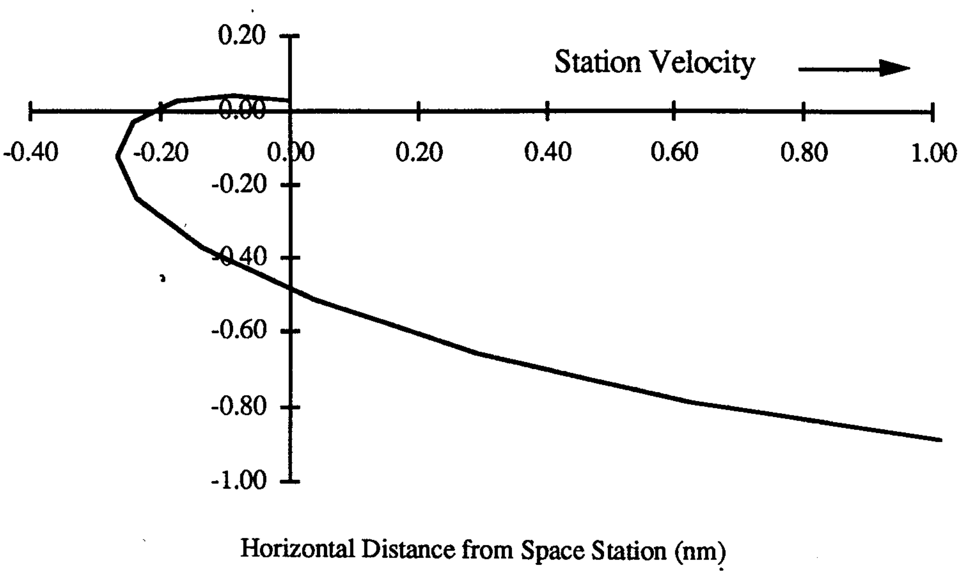

Figure 6.4 Phase Two of the Separation Maneuver

6.2 Deorbit Maneuver

The mission plan for project EGRESS' atmospheric reentry requires a coplanar orbital transfer from the Space Station altitude to the upper edge of the atmosphere (400,000 ft) where atmospheric flight will begin. This deorbit maneuver is based upon the classic Hohmann Transfer maneuver.

6.2.1 Hohmann Transfer

The Hohmann transfer [6-2] is used in orbital mechanics to transfer between two co-planar circular orbits of different altitudes. This is a fuel efficient method of co-planar orbital transfer. An example Hohmann maneuver is shown in Figure 6.5.

If the vehicle is originally in the higher orbit and needs to transfer to the lower orbit, the vehicle must first perform a retrograde burn (position 1). This burn places the vehicle in an elliptical orbit with its apogee at the point of the first burn. The second burn (position 2) is used to recircularize the orbit at the lower altitude. This burn is also a retrograde and is performed at the perigee of the elliptic orbit. The magnitude of these retrograde burns depends on the altitudes of the two circular orbits. The higher the orbit, the lesser the required retrograde since vehicles travel slower at higher altitudes. The time to complete a Hohmann transfer is half the period of the elliptic orbit.

6.2.2 Maneuver of Project EGRESS

The maneuver that EGRESS will use to deorbit is based upon the Hohmann Transfer and is shown in Figure 6.6 (not drawn to scale). At position 1, EGRESS will perform a retrograde maneuver that will place it in an elliptical orbit. The vehicle will intersect the 400,000 foot atmospheric boundary with a negative flight path angle (γ) at position 2. Unlike the Hohmann Transfer, however, no retrograde will be needed at this point since the vehicle will be entering the atmosphere. The angular distance traveled from the deorbit burn position to entrance of the atmosphere is shown as Θ. The elliptic orbit is arranged so that the vehicle will enter the atmosphere at a given negative flight path angle. By entering the atmosphere at a non-zero flight path angle, the maneuver will not take as long as a true Hohmann Transfer to radius R_2, but will require an additional retrograde velocity change.

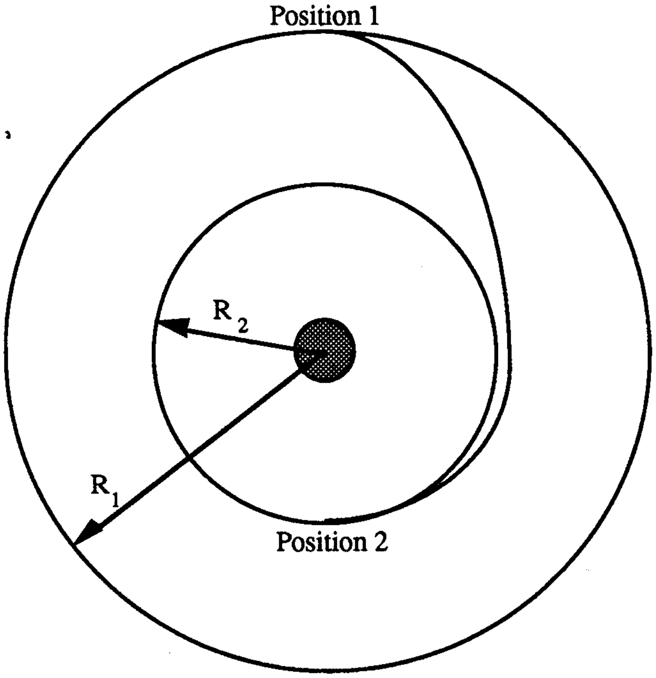

Figure 6.5 - Hohmann Transfer

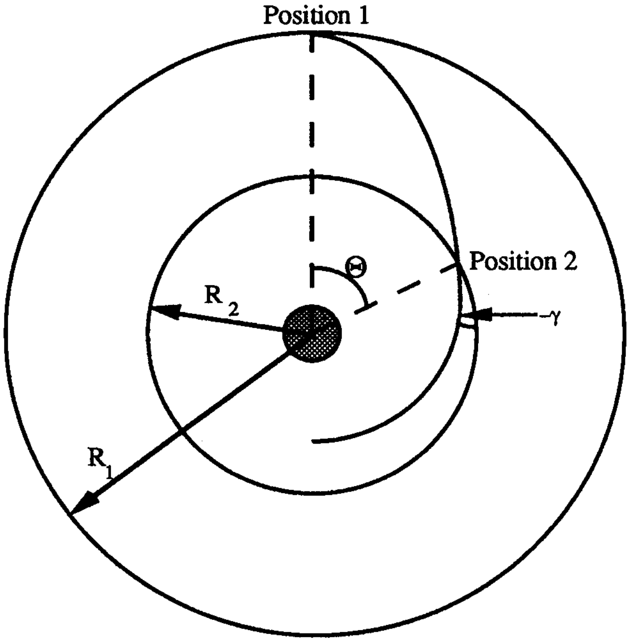

Figure 6.6 - Deorbit Burn Maneuver

The information for this maneuver is derived by using the Conservation of Energy and Angular Momentum laws. Through these relationships, data such as required change in velocity, angular distance to complete maneuver, and velocity of the EGRESS when it reenters the atmosphere can be determined.

The change in velocity (ΔV) required by the retrograde burn at position one of the maneuver is given by the following formula:

$$\Delta V = \sqrt{\frac{\mu}{R_a}} - \left(\frac{R_1}{R_a}\right) V_1 \cos\gamma \qquad (6\text{-}3)$$

R_1 = radius of the orbit at the point of reentry (position 2)
R_a = radius of the orbit at the retrograde burn point (position 1)
V_1 = velocity of the EGRESS at position 1
μ = Gravitational parameter of Earth
g = negative flight path angle at position 2

The retrograde required for this maneuver increases as the flight path angle increases. Although the retrograde increases with increasing flight path angle, the time required for the maneuver decreases with increasing flight path angles.

The equation to determine the eccentricity (e) of the maneuver's elliptical orbit is as follows:

$$e = \sqrt{\frac{2EH^2}{\mu^2} + 1} \qquad (6\text{-}4)$$

E = Energy of the Orbit
H = Angular Momentum of the Orbit

The angular distance (θ) required from the initial retrograde burn at position one to the beginning of the reentry at position 2 is given by:

$$\theta = \arccos\left\{\frac{1}{e}\left(\frac{1}{r} - 1\right)\right\} \qquad (6\text{-}5)$$

l = semilatus rectum of the elliptical orbit
r = radius of the orbit at the point of reentry

The time required for the deorbit burn maneuver is found by dividing the angular distance by 360° and then by multiplying this fraction by the orbital period.

The flight path angle of the EGRESS vehicle at 400,000 ft will be -1°. Based upon this flight path angle, the following values for the deorbit maneuver were obtained.

	140 n.mi	200 n.mi	270 n.mi
Retrograde Velocity Change:	227 ft/s	290 ft/s	391 ft/s
Angular Distance for Maneuver:	77°	129°	145°
Time Required for Maneuver:	18.7 min	32 min	36.6 min

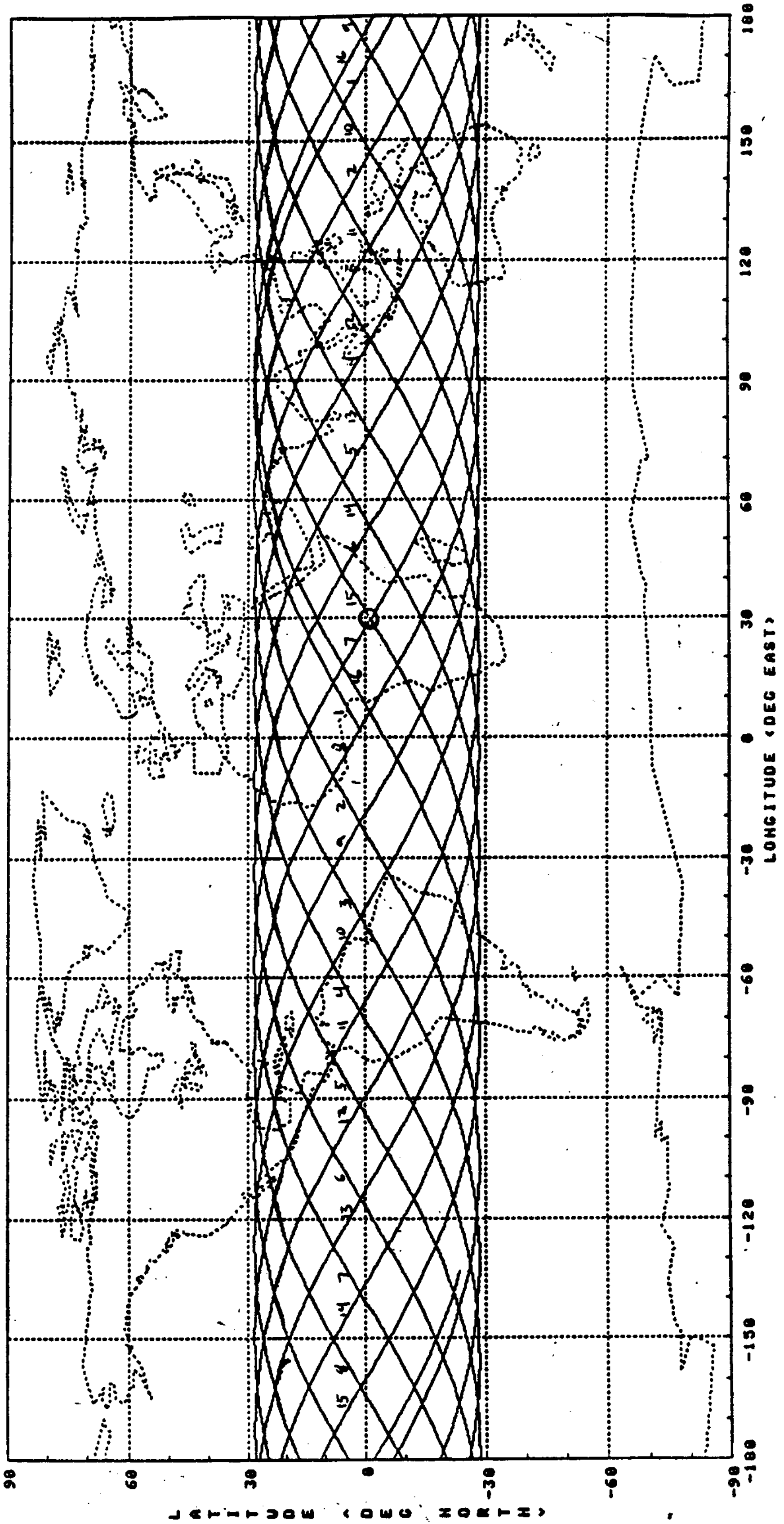

Figure 6.7 - Space Station Ground Track:
h = 200 nm and inclination = 28.5°

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These three station heights (140 n.mi, 200 n.mi, and 270 n.mi) represent, respectively, the station's minimum altitude, a mid-range altitude, and the station's maximum altitude. These numbers indicate that the station's altitude will not appreciably affect the maneuvering time. This twenty minute range is negligible compared to the twenty-four hours allotted for the mission.

6.3 Mission Time Lines

While in orbit, Space Station *Freedom* 's orbital height will vary between 140 n.mi and 270 n.mi. Because of this wide variation, a single position for the Space Station was chosen for a sample mission. The sample mission will occur at 200 n.mi above the earth's surface (about midrange) at an inclination of 28.5 ° to the equatorial plane (standard for Space Station *Freedom*). A typical orbit in this sample mission has a period of 92 minutes and a local circular velocity of 25,220 ft/s. A randomly generated, 24 hour ground track for the sample station height is illustrated in Figure 6.7.

The Space Station completes approximately 16 orbits within each 24 hour period. Theoretically, the station's ground track should retrace the same orbital lines, with respect to the ground, after every day. Realistically, however, this will not happen. Due to the oblateness of Earth, the line of nodes (the axis along which the orbital plane intersects the equatorial plane) regresses approximately 7° each day. This regression prevents the station's ground track from repeating itself after 24 hours. Since neither the periodic cycle of the Space Station's orbit nor the regression of the line of nodes are synchronized, the ground track will never exactly repeat itself.

As seen in Figure 6.7, the ground track for Space Station *Freedom* passes predominantly over water. This fact was one of the main reasons for selecting the following three primary landing sites for Project EGRESS' water landing: Hawaii, Cape Canaveral, and Okinawa. All of these sites have the necessary rescue facilities, and their locations along the ground track will guarantee a landing at one of these sites within 24 hours of the decision point. This is true regardless of the station's position at the decision point. The time required for EGRESS's orbital maneuvers is independent of the station's position in a specific orbit; however, since the EGRESS vehicle must be in the proper position over the earth before it can leave the station, landing at a primary site from a particular point in the orbit will require different wait times before separation. Hence, the choice of a landing site may be heavily dependent upon the amount of allowable wait time before, for example, the emergency escalates.

In determining the mission times for the various sites, a landing site and a particular orbit on the 200 nm ground track that passed directly over or very near the site were chosen. Space Operations then proceeded to work backwards from a desired "daytime" landing time to calculate all of the individual maneuver times and, eventually, the amount of wait time needed. Since Hawaii is the main landing site for EGRESS, this location was chosen for the initial calculations. Orbit 13 on the 200 nm ground track passes directly over Hawaii; therefore, this is the orbit that was chosen to land on. Then, for example, if a decision to use the EGRESS were made above Africa on orbit 7, the sample mission time line for the Hawaii scenario would be as illustrated in Figure 6.8 and outlined in Figure 6.9.

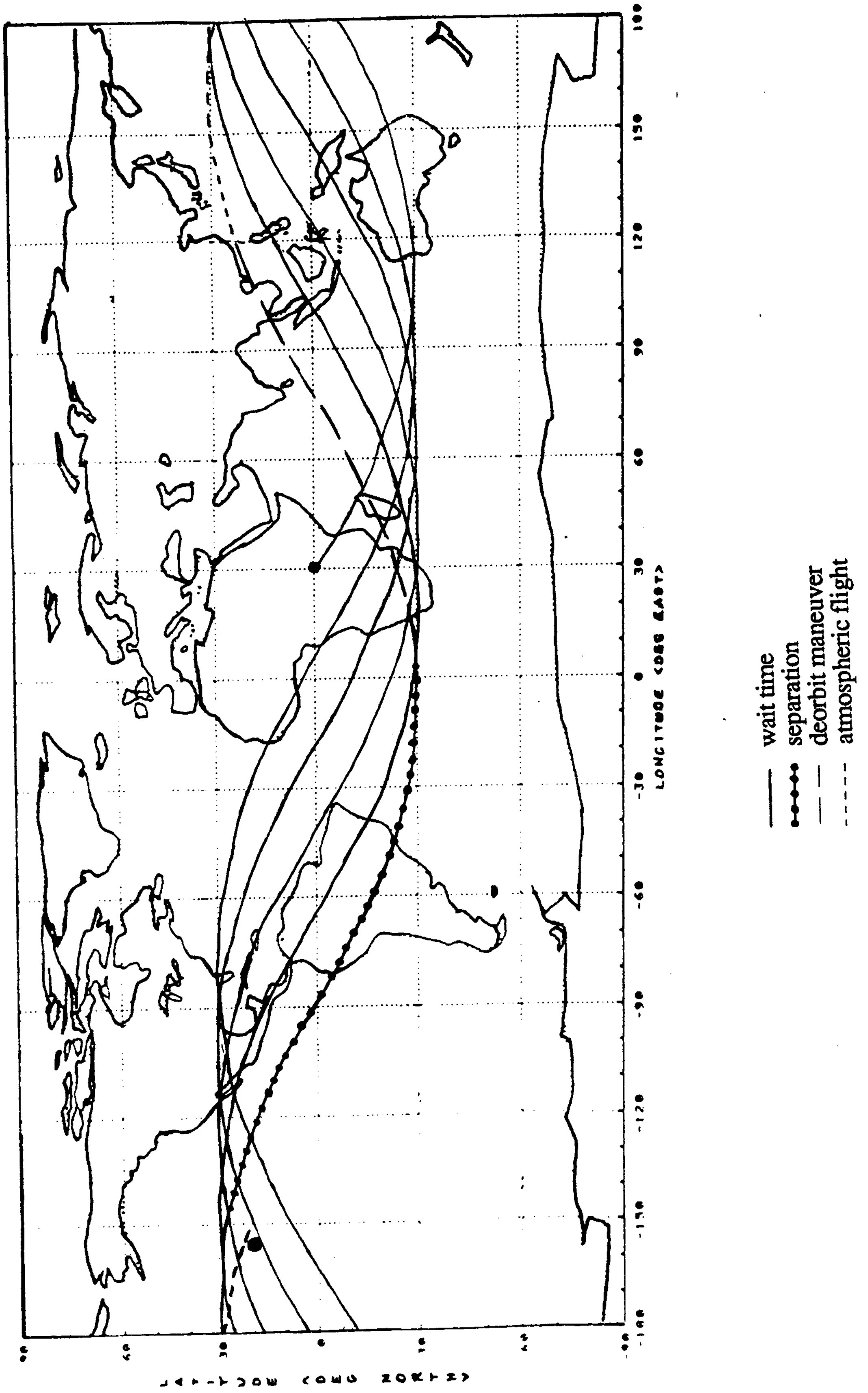

Figure 6.8 - Ground Track for Mission to Hawaii

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	Mission Time	Segment Time	Angular Distance
Decision	0:00	6:31	-
Separation I	6:31	0:03	11.0°
Separation II	6:34	0:40	132.0°
Deorbit Burn	7:14	0:32	121.0°
Reentry	7:46	0:30	82.5°
Landing	8:16	-	-

Figure 6.9 - Mission Time Line For Hawaii (h = 200 nm)

For this particular scenario, the wait time is 6 hours and 31 minutes with a total mission time of 8 hours and 16 minutes. As seen in Figure 6.9, the decision point is over Africa. After waiting approximately four-and-a-half orbits, the first phase of separation can begin. The second phase of separation can begin three minutes later, and the deorbit maneuver can begin 40 minutes after the second phase of separation begins. The reentry flight consumes almost a quarter of an orbit and ends at splashdown near Hawaii.

The EGRESS crew is allowed up to eighteen hours of wait time before ingress; thus, in order to be able to land at Hawaii, the decisions to use the EGRESS and land at Hawaii may be made anywhere on orbits 1 through 10 1/2. This takes into account various issues which include time to prepare the EGRESS for separation, wait time to reach orbits that allow a landing close to Hawaii, and the fact that a particular site can be reached from more than one orbit. In a 24 hour period, the only orbits from which project EGRESS cannot make a decision to land at Hawaii are the last half of orbit 10 and orbits 11 through 16.

In order to guarantee the ability to land during any given 24 hour period, Space Operations repeated calculations (similar to those above) for the other two primary landing sites. Okinawa is the second primary location for landing. Orbit 14 passes directly over the island; therefore, this was the orbit chosen for landing. Again, using orbit 7 as the decision point, a time scenario was generated and is outlined in Figure 6.10.

	Mission Time	Segment Time	Angular Distance
Decision	0:00	8:43	-
Separation I	8:43	0:03	11.0°
Separation II	8:46	0:40	132.0°
Deorbit Burn	9:26	0:32	121.0°
Reentry	9:58	0:30	82.5°
Landing	10:28	-	-

Figure 6.10 - Mission Time Line for Okinawa (h = 200 nm)

This particular mission took 10 hours and 28 minutes. The times required for the orbital maneuvers remained the same; however, the wait time increased from 6 hours and 31 minutes for Hawaii to 8 hours and 43 minutes. The eighteen hour wait time limit still applies; thus, for this case, the decision may be made anywhere on orbits 1 1/2 through 12. Many of these orbits overlap those of Hawaii, but the missions simply have different wait times. Even with the addition of Okinawa as a primary landing site, a landing still could not be guaranteed from orbits 13 through 16.

The third primary landing site is Cape Canaveral. Once again, the arbitrary decision point was orbit 7, but in this case, orbit 10 passed near the site and was, therefore, the orbit chosen to land on. A possible scenario for landing at Cape Canaveral is outlined in Figure 6.11.

	Mission Time	Segment Time	Angular Distance
Decision	0:00	2:30	-
Separation I	2:30	0:03	11.0°
Separation II	2:33	0:40	132.0°
Deorbit Burn	3:13	0:32	121.0°
Reentry	3:45	0:30	82.5°
Landing	4:15	-	-

Figure 6.11 - Mission Time Line for Cape Canaveral (h = 200 nm)

This particular mission has a short wait time of 2 hours and 30 minutes and a total mission time of 4 hours and 15 minutes. According to the maximum eighteen hour wait time, the decision to use EGRESS can be made on orbits 10 through 16 and orbits 1 through 4 1/2 of the following day.

The addition of this third site guaranteed that EGRESS would always be able to land at one of the primary sites within a 24 hour period of time. In some cases, the crew would even have a choice of landing sites. Basically, the wait time required for a specific mission would govern the choice of site. The luxury of choosing a landing site is also desirable if bad weather or a night landing needs to be avoided.

The above mission time lines are based on a station height of 200 nm, and similar calculations for the mission times can be made for the 130 nm range of station heights. The separation times remain the same for the altitude range; however, the times for the deorbit maneuver change. As mentioned in Section 6.2, a twenty-minute difference arises between leaving the station at 140 nm and 270 nm altitude. Essentially, the station's varying altitude will have a negligible affect on project EGRESS' mission.

In summary, these calculations have shown that given an arbitrary ground track and an arbitrary landing time, EGRESS will be able to land from any orbit at at least one of the three primary sites. Although the times and positions of EGRESS along the orbits can vary infinitely, there will always be the possibility to land within 24 hours. Ample time was allowed for crew ingress and preparation of EGRESS before separation. Very little, if any, of the cross-range available to EGRESS was utilized in these initial calculations. If the 500 nm cross-range is taken into account, more orbits may be considered to cross over the landing sites. This will allow a wider range of decision points per site. Even so, it does not seem probable that EGRESS will be able to land 100% of the time at a given site within a 24 hour mission.

6.4 Return to Station Capability

There are several scenarios which would require project EGRESS to return to the station after the separation maneuvers rather than continuing with the deorbit maneuver. One such scenario is in the event the deorbit burn engines are unable to fire, necessitating a return to station.

Since this "scrubbed" mission will be near the station (within 5 nautical miles), this rendezvous is a fairly simple problem. The problem is called a terminal phase rendezvous. To accomplish the rendezvous, two velocity changes will be required. The first is called the Terminal Phase Insertion (TPI). This velocity change places EGRESS on a trajectory that leads back to the station. The second maneuver is called the Braking Maneuver and is used to stop EGRESS once it reaches Space Station *Freedom*. This rendezvous maneuver is shown in Figure 6.12. The Terminal Phase Insertion velocity change is at Point A, and the braking maneuver is at Point B. The coordinate system is centered on the Space Station and is moving at the Space Station's local circular velocity.

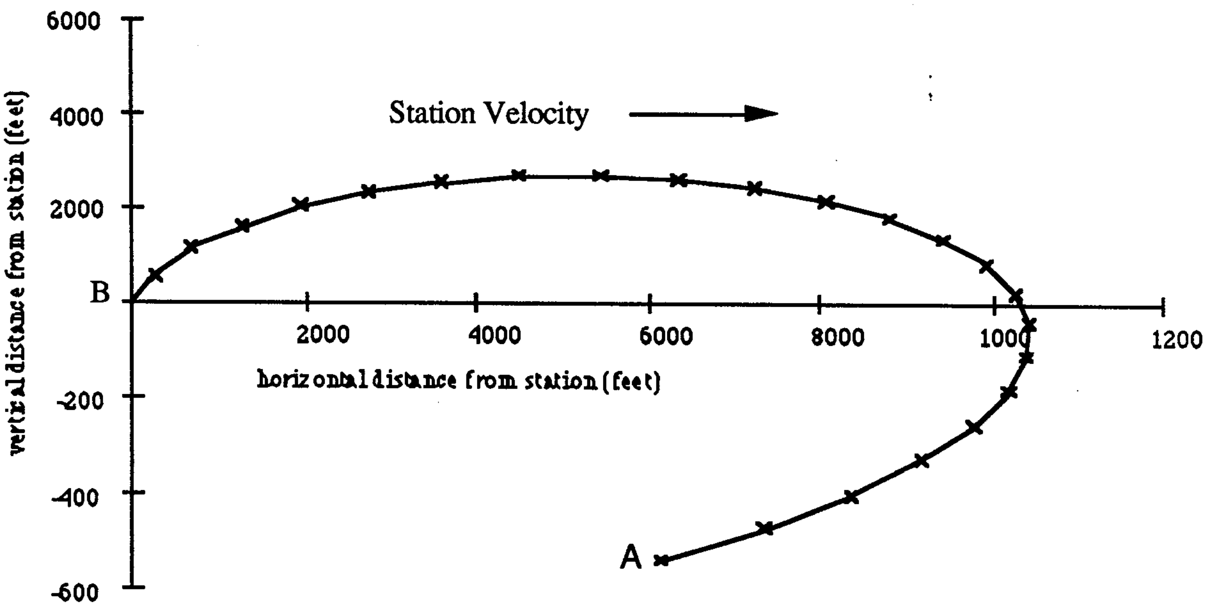

Figure 6.12 - Rendezvous Maneuver

Equations 6.3 to 6.8 describe the velocities needed to rendezvous with the station. The first equation, ΔV_1, describes the initial velocity change needed to alter ERGESS' course before the deorbit burn begins.

$$\overline{\Delta V_1} = [\dot{x}_d(0) - \dot{x}(0)]\,\bar{i} + [\dot{y}_d(0) - \dot{y}(0)]\,\bar{j} \tag{6-3}$$

$$\dot{x}_d(0) = \frac{14\, y(0)[1 - \cos\omega T] - [6\, y(0)\,\omega T - x(0)]\sin\omega T}{T\left[3\sin\omega T - \frac{8}{\omega T}(1 - \cos\omega T)\right]} \tag{6-4}$$

$$\dot{y}_d(0) = \frac{-\,y(0)\,[3\,\omega\,T\cos\omega\,T - 4\sin\omega\,T] - 2\,x(0)\,[1 - \cos\omega\,T]}{T\left[3\sin\omega\,T - \frac{8}{\omega\,T}(1 - \cos\omega\,T)\right]} \qquad (6\text{-}5)$$

EGRESS will move towards the station and will then need a braking velocity, ΔV_1, to slow down.

$$\overline{\Delta V_2} = [-\,\dot{x}(T)]\,\bar{i} + [-\,\dot{y}(T)]\,\bar{j} \qquad (6\text{-}6)$$

$$\begin{aligned}\dot{x}(T) = {} & [-\,3\,\dot{x}_d(0) - 6\,\omega\,y(0)] + [-\,2\,\dot{y}_d(0)]\sin\omega\,T \\ & + [4\,\dot{x}_d(0) + 6\,\omega\,y(0)]\cos\omega\,T\end{aligned} \qquad (6\text{-}7)$$

$$\dot{y}(T) = [2\,\dot{x}_d(0) + 3\,\omega\,y(0)]\sin\omega\,T + [\dot{y}_d(0)]\cos\omega\,T \qquad (6\text{-}8)$$

The rendezvous data for a sample mission (Space Station altitude of 200 nm) has been calculated. Assuming that EGRESS is approximately one nautical mile ahead and below the Space Station, the Terminal Phase Insertion velocity change is equal to 7.8 ft/s. This velocity change places EGRESS on a trajectory that will intersect the Space Station 46 minutes after the TPI. When EGRESS is near the station it will use a braking velocity change of 6.9 ft/s so that it is at rest relative to the Space Station. The actual docking procedure will utilize the cold gas thrusters of EGRESS.

Although this example is for the sample altitude of 200 nm, the required velocity changes for variations in the Space Station's altitude are minimal. The total velocity change (both TPI and braking) at 200 nm is 14.7 ft/s. At the Space Station's lowest altitude of 140 nm, this velocity change is 15 ft/s. The extreme altitude of the station at 270 nm requires a change of 14.4 ft/s. Depending on the altitude of the station the required velocity change for the rendezvous varies only 4% from the highest required velocity change to the lowest.

6.5 Stationkeeping Capability

Stationkeeping is the process of maintaining a vehicle at a certain relative position to a given point; EGRESS will have this capability. Possessing the ability to stationkeep at a given distance from Space Station *Freedom*, will enable the EGRESS pilot to maintain a safe distance from the station in a scenario in which EGRESS is unable to deorbit immediately after separation. A possible scenario requiring this stationkeeping capability would be a catastrophic failure of *Freedom* requiring evacuation before the station is in the proper position to begin the maneuvers to return to earth.

There are two common methods for stationkeeping which are shown in Figure 6.13. The first method is stationkeeping at a point on *Freedom* 's velocity vector, called V-Bar stationkeeping. This method places EGRESS on the same orbital altitude as *Freedom* ; however, the vehicle will be located either forward (+V-Bar stationkeeping) or aft (-V-Bar stationkeeping) of the Space Station. The benefit of this type of stationkeeping is that the relative velocity between EGRESS and *Freedom* is zero since both are traveling at the same velocity on the same circular orbit.

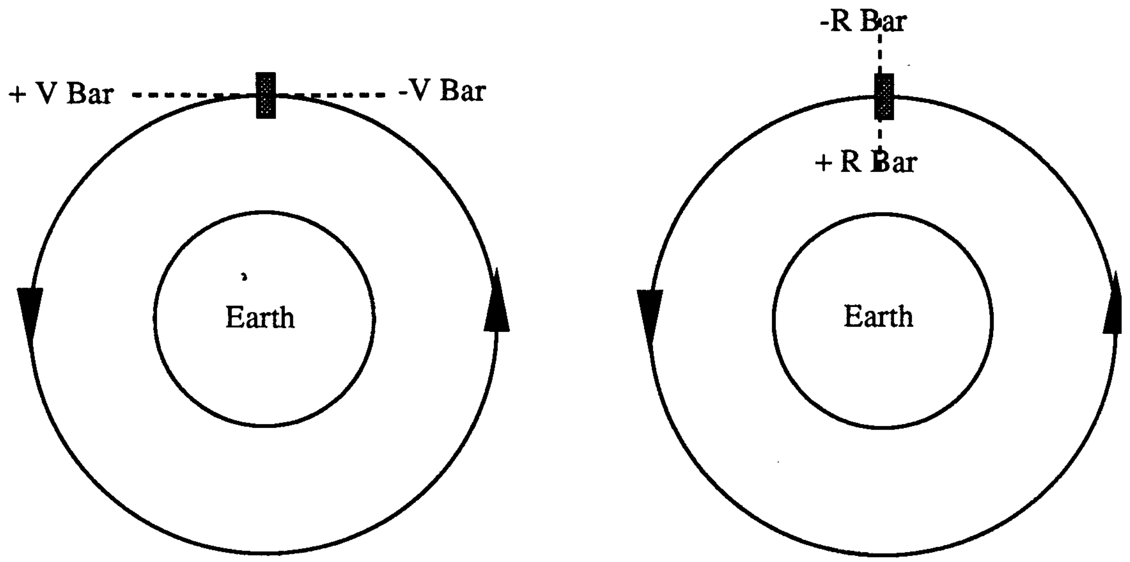

Figure 6.13 Two Common Methods of Stationkeeping

The other possible option is stationkeeping at a point on *Freedom* 's radial vector from earth, commonly referred to as R-Bar stationkeeping. This type of stationkeeping can occur either above or below the Space Station. This is not a stable configuration, since EGRESS would be located at a different orbital altitude than the Space Station and would not travel at the same rate as the Space Station. For example, if EGRESS was located at a -R-Bar position (above the Space Station), it would travel at a slower speed than the station and begin to lag. Although this lag is fairly small, over a period of hours this lagging will become significant.

EGRESS will utilize a +V-Bar stationkeeping position ahead of the Space Station. In the event of a scrubbed mission, EGRESS would perform the normal separation maneuver. This places EGRESS on the trajectory shown in Figure 6.14. Position A is where the separation maneuver begins. When EGRESS reaches point B, it is at a position 4.5 miles ahead of the Space Station's velocity vector. At this point EGRESS will perform a braking maneuver that will stop the vehicle so it will stationkeep at a stable position on the same circular orbit as the Space Station. The total change in velocity for the braking maneuver is approximately 3 ft/s. These numbers do not change appreciably for varying Space Station altitudes.

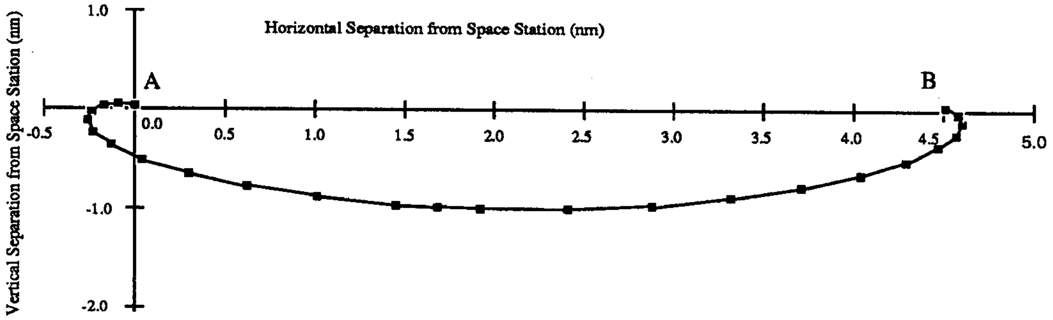

Figure 6.14 Stationkeeping Maneuver

6.6 Evacuation of Space Station

In the event that the entire Space Station crew need to be evacuated, mission plans for the use of both EGRESS vehicles have been determined. A mission scenario has been developed based on the following criteria:

- Proximity operations might be risky since the two vehicles are docked 35 ft apart on the station. To reduce the risk of collision, vehicle departures must occur at least 5 minutes apart.
- If the two vehicles remained 5 minutes apart throughout the mission, the crew must be aware of the potential of a faulty deorbit burn. The deorbit burn engine on the first EGRESS might burn too long, slowing the craft down enough that it might collide with the second EGRESS.
- The two vehicles must remain far enough apart during reentry to reduce the potential for collision at the high reentry velocities.

Because of the danger involved with maneuvering two EGRESS vehicles close to each other, the vehicles will use successive orbital passes - and stationkeep when necessary - in order to return to earth. Both EGRESS vehicles must reach the same landing site, and with this in mind, two cases arise.

The first case to consider arises when the Space Station is positioned such that two successive orbits will allow both EGRESS vehicles to reach the same landing site. This will lead to a relatively simple mission in that both EGRESS vehicles will leave the station within five minutes of each other. The first vehicle will maneuver into position to station-keep while the second will begin its deorbit burn and continue to earth just as it would for the sample mission. When the first EGRESS reaches the appropriate point in orbit, it will perform a maneuver similar to the phase two separation and will then follow the sample mission scenario. Both vehicles will complete their missions by landing at the same site within approximately 91 minutes of each other.

The second case that must be considered arises when the Space Station is positioned such that the time available to prepare and use both EGRESS vehicles will not allow both vehicles to reach the same landing site. For example, Hawaii can be reached on orbits 9 through 14. The mission requires the use of two successive orbits; therefore, the first EGRESS must leave the station before the station reaches the beginning of orbit 13. Assuming that the EGRESS crew needs at least two hours (approximately one-and-a-half orbits) to prepare for departure, the decision to leave the station must be made before the station reaches the half-way point of orbit 11. If the decision to use the two EGRESS vehicles is made at any point after orbit 11 1/2, the vehicles must plan to land elsewhere.

If such a situation should arise, both EGRESS vehicles will leave the station and both will station-keep. Since the EGRESS vehicles will leave five minutes apart, a safe distance of 600 ft will be achieved and maintained throughout the station-keeping maneuver. Once in the appropriate orbit, the first EGRESS will maneuver into its deorbit burn position and continue its mission while the second EGRESS will continue to station-keep. On the next orbit, however, the second vehicle will begin its maneuvers to reach the appropriate landing site. As in the first case, both EGRESS vehicles will complete their missions by landing at the same site within 91 minutes of each other.

Chapter 7

Atmospheric Flight

7.0 Summary

The Atmospheric Flight Group of Project EGRESS was responsible for the flight of the EGRESS from 400,000 feet until the unfurling of the parachutes at 23,000 feet. The efforts of the Atmospheric Group were directed towards four main areas: trajectory analysis, development of a thermal protection system, determination of the aerodynamic flow field, and an aerodynamic stability analysis. This section contains a review of the Atmospheric Group's efforts.

One of the concerns of the Atmospheric Flight Group was the determination of the trajectory of EGRESS as it descends through the atmosphere. Concerns in this area include flight crew g-forces, evaluation of possible landing sites, or reentry footprint, for a given reentry window, and heat transfer considerations. To aid in our effort here, a computer program was developed to determine the trajectory of the EGRESS given the vehicle's mass, lift to drag ratio, ballistic coefficient, and bank angle. In addition to the trajectory, velocity and acceleration profiles are generated.

The EGRESS vehicle must be protected from the intense heat generated as the vehicle's kinetic energy is imparted to the atmosphere. The Atmospheric Flight Group was concerned with the rate of heat transfer to the vehicle as well as the maximum temperature experienced during reentry. Several types of heat shields to protect the EGRESS from the heat generated were also investigated, and in the end, the Atmospheric Flight Group decided on a ceramic thermal protection system for the EGRESS.

Additional concerns include calculation of the aerodynamic flow field about the EGRESS vehicle and the aerodynamic forces exerted by that field on the vehicle. Knowledge of the aerodynamic forces on the vehicle is important in the trajectory analysis as well as the attitude control and aerodynamic stability of the vehicle.

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7.1 Initial Design Considerations

One of the first concerns addressed by Project EGRESS was to determine the type of reentry vehicle–ballistic, winged, or moderately lifting. Project EGRESS eventually decided to go with a moderately lifting vehicle with a lift to drag ratio of 0.8.

A main consideration was the reentry footprint of the vehicle. The distance between orbital tracks for the Space Station Freedom will be 650 nautical miles, and Project EGRESS decided that the vehicle should have the capability of reaching any recovery site between two adjacent orbital tracks. A plot of the ground area attainable for various hypersonic lift to drag ratios shows that a cross range of 500 nautical miles requires a lift to drag ratio of 0.8 [7-1]. A trajectory analysis computer code developed by the Atmospheric Flight Group also supported this conclusion.

Another important factor was the crew g-force limitations stated in the RFP. The entry acceleration on crew members is limited to 4 g's in the +X direction, 1 g in the +Y direction, and 0.5 g's in the +Z direction. The trajectory analysis program mentioned above illustrated that a minimum lift to drag of 0.5 is required to meet the g-force requirements prescribed in the RFP.

Thus, the two major limiting factors in the decision were footprint considerations and crew g-force limitations, both of which call for a lifting configuration. However, several operational aspects played a role in the decision to go with a moderately lifting configuration.

A highly lifting vehicle would need to be a winged vehicle. However, because the RFP requires that the ACRV be deployable via the shuttle, a winged configuration was ruled out due to vehicle size limitations. A winged vehicle would not fit in the cargo bay. Furthermore a winged vehicle would require aerodynamic control surfaces for maneuvering. Control surfaces would increase the complexity of the EGRESS vehicle, as well as make the vehicle more difficult to fly, and thus require more pilot training. Since the EGRESS should have minimal impact on the the operation of Space Station *Freedom,* simplicity in operation was an important design consideration. Thus, a truly winged configuration was ruled out.

Crew g-forces experienced during reentry provided an absolute lower bound to the lift to drag ratio for the EGRESS, while vehicle size and complexity provided an upper bound. With these considerations in mind, Project EGRESS selected a moderately lifting configuration for the vehicle. This configuration would meet the g-force requirements prescribed by the RFP and would meet the footprint requirement prescribed by Project EGRESS, while minimizing complexity in the design and the operation of the vehicle.

7.2 Trajectory Analysis

An analysis of the flight trajectory of a reentry craft is essential to understanding the demand that atmospheric reentry puts on the craft. Analysis of the flight path of the EGRESS vehicle during reentry and atmospheric flight effort was aided by the development of a computer model to determine the vehicle's trajectory in addition to velocity, acceleration and heat transfer profiles. This analysis provided crucial insight to the flight of the craft as it was subject to the demands of the atmosphere.

After defining a simple flight computer algorithm, the g-loading, heating, and cross range capability of the trajectory was determined by the trajectory model.

7.2.1 Computational Model

Development of the computational model involved three main phases. After isolating the variables needed for the analysis, a Cartesian coordinate system was selected to represent the model. A system of six differential equations was generated which models the vehicle's trajectory as it descends through the atmosphere. Finally, the set of six equations was then integrated from separation to splashdown, using two different models of atmospheric temperature and density for comparison.

7.2.1.1 Inputs

The flight characteristics of the vehicle were defined by

c_d	Coefficient of Drag
m	Mass of vehicle
A	Wetted Surface Area
L/D	Lift to Drag ratio

Furthermore, the flight path was dependent upon

α	Initial reentry angle, at 400,000 ft
H_{ssf}	Altitude where the deorbit burn occurs, assumed to be the same as the orbiting altitude of Space Station *Freedom.*

EGRESS is guided through the atmosphere using a simple reaction control system similar to that used on the Apollo reentry capsule. Reaction control jets are utilized to rotate EGRESS around its velocity vector. As the craft rotates, the lift vector, which is always perpendicular to the velocity vector, is rotated about the velocity vector to steer the craft. The angle of orientation of the lift vector is defined by

θ	Angle of roll around velocity vector, which varies throughout the flight of the EGRESS.

7.2.1.2 Coordinate Axes

The Cartesian coordinate axes system used in this analysis was defined with the origin at the center of the earth, x-axis passing through 0° longitude, the y-axis through 90°E longitude, and the z-axis through the North Pole. A Cartesian system was chosen for this analysis since forces can be resolved into Cartesian components with little difficulty. Furthermore, each coordinate direction can be dealt with symmetrically.

The alternatives, circular and spherical coordinates, at first seem more natural to model planetary reentry, as the radius and gravity vectors are more easily defined in these coordinate systems. However, this advantage is offset by the complexity of representing the other directions. The cross product, for example, is computationally simpler in Cartesian coordinates, as each component is dealt with symmetrically, unlike the cylindrical and spherical systems.

7.2.1.3 System of Equations

The system of equations used in the analysis is simplified by the use of the following assumptions

a) spherical earth with origin of Cartesian coordinate axes at center
b) constant L/D, c_d and m during atmospheric flight.

The system of equations is expressed in the six independent variables (x, y, z, v_x, v_y, v_z) by

$$\begin{aligned} \dot{v}_x &= (\mathbf{a}_{drag} + \mathbf{a}_{lift} + \mathbf{a}_{gravity}) \cdot \mathbf{i} \\ \dot{v}_y &= (\mathbf{a}_{drag} + \mathbf{a}_{lift} + \mathbf{a}_{gravity}) \cdot \mathbf{j} \\ \dot{v}_z &= (\mathbf{a}_{drag} + \mathbf{a}_{lift} + \mathbf{a}_{gravity}) \cdot \mathbf{k} \\ \dot{x} &= v_x \\ \dot{y} &= v_y \\ \dot{z} &= v_z \end{aligned} \tag{7-1}$$

Directions for these accelerations were defined in terms of the

Radius vector	$\mathbf{r} = x\mathbf{i} + y\mathbf{j} + z\mathbf{k}$,	(7-2)
Velocity vector	$\mathbf{v} = v_x\mathbf{i} + v_y\mathbf{j} + v_z\mathbf{k}$,	(7-3)
Side direction	$\mathbf{s} = \mathbf{r} \times \mathbf{v}$,	(7-4)
and Up direction	$\mathbf{u} = \mathbf{v} \times \mathbf{s}$.	(7-5)

The acceleration is found by summing the gravitational and aerodynamic accelerations.

$$\mathbf{a}_{drag} = -\rho\, A\, V2\, \frac{c_d A}{m}\, \mathbf{v} \tag{7-6}$$

$$\mathbf{a}_{lift} = \frac{L}{D}\, \rho\, A\, V2\, \frac{c_d A}{m}\, (\mathbf{u} \cos\theta + \mathbf{s} \sin\theta) \tag{7-7}$$

$$\mathbf{a}_{gravity} = -\, g_0 \left(\frac{r}{r_0}\right)^2 \mathbf{r} \tag{7-8}$$

Where $g_0 = 9.806$ m/s^2 and $r_0 = 6{,}375{,}000$ meters.

The components of these accelerations along the **i**, **j**, and **k** directions were summed to get the appropriate acceleration component. For example, in the x-direction

$$\begin{aligned} a_x \;=\; & \frac{L}{D}\rho\, A\, V2\, \frac{c_d A}{m}\, (\mathbf{u}\cdot\mathbf{i} \cos\theta + \mathbf{s}\cdot\mathbf{i} \sin\theta) \\ & -\rho\, A\, V2\, \frac{c_d A}{m}\, \mathbf{v}\cdot\mathbf{i} \;-\; g_0 \left(\frac{r}{r_0}\right)^2 \mathbf{r}\cdot\mathbf{i} \end{aligned} \tag{7-9a}$$

$$\begin{aligned} =\; & \rho\, A\, V2\, \frac{c_d A}{m}\, \frac{L}{D} \Big((v_y s_z - v_z s_y) \cos\theta + (y v_z - z v_y) \sin\theta \Big) \\ & -\rho\, A\, V2\, \frac{c_d A}{m}\, v_x \;-\; g_0 \left(\frac{r}{r_0}\right)^2 x \end{aligned} \tag{7-9b}$$

$$a_x = \rho A V2 \frac{c_d A}{m} \left\{ \frac{L}{D} \left[(v_y(xv_y - yv_x) - v_z(yv_z - zv_y))\cos\theta + (yv_z - zv_y)\sin\theta \right] - v_x \right\} - g_0 \left(\frac{r}{r_0}\right)^2 x \qquad (7\text{-}9c)$$

Accelerations in other directions are computed similarly.

7.2.1.4 Atmospheric Model

Knowledge of the atmospheric density, which varies considerably with altitude, was required to determine the lift and drag forces acting on the vehicle. An atmospheric temperature model was also required for reentry heating calculations.

The modelled temperature [7-2] is shown in Figs. 7.3. The pressure as function of altitude was determined by integrating

$$\frac{dp}{p} = - \frac{g_0}{RT} dh \qquad (7\text{-}10)$$

The density may then be determined from the equation of state for an ideal gas.

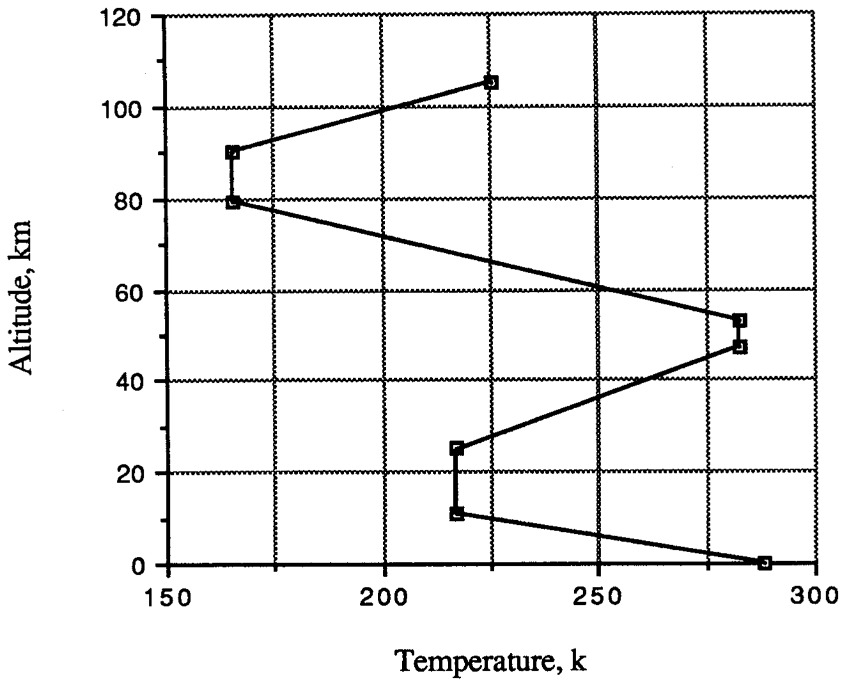

Figure 7.3 - Atmospheric Temperature Model

The standard exponential atmosphere model was also used for comparison. This model is defined by

$$\rho = \rho_0 \, e^{-h/h_0} \tag{7-11}$$

where $\rho_0 = 1.225$ kg/m^3 and $h_0 = 7162$ m. Although the density of the exponential model differs by as much as 10% from the previous model, a comparison of the final results show a difference of no more than 1% in flight time and down range distance.

7.2.1.5 Integration

The set of non-linear atmospheric dynamics equations were solved numerically to determine trajectories. The model, consisting of a set of 6 coupled differential equations in Cartesian coordinates, were solved using ODEPACK [7-3]. The equations were integrated from initial conditions until splashdown with an accuracy of 10^{-2} m in position and 10^{-5} m/s in velocity for each time step

$$\text{Splashdown if } x^2 + y^2 + z^2 \le r_0 = 6{,}375{,}000 \text{ m.} \tag{7-12}$$

Initial conditions are traditionally given at an altitude of 400,000 ft (122,000 m). Although atmospheric effects are first significant at about 255,000 ft (78,000 m), trajectory analysis begins at a higher altitude to provide consistent atmospheric effects as a craft passes 255,000 ft.

7.2.2 Three-Parameter Flight Path

The flight algorithm of EGRESS is defined by only three parameters. The EGRESS vehicle enters the atmosphere at some roll angle θ_1. It remains at this roll angle until it is below an altitude H_{rot}, at which the EGRESS slowly rotates to a roll angle θ_2. Figure 7.4 illustrates this definition.

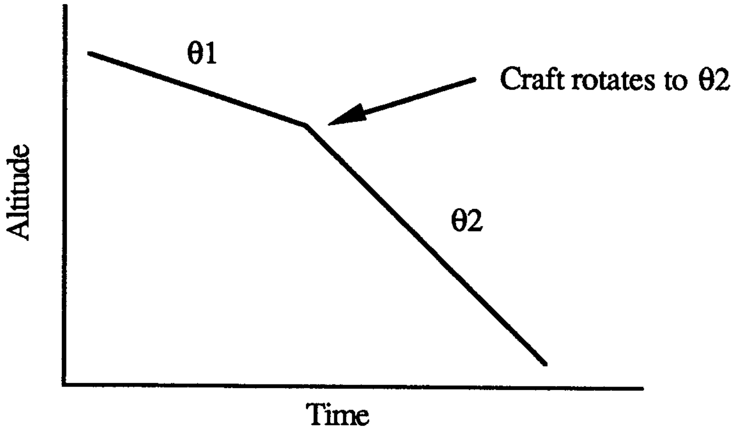

Figure 7.4 - Definition of Three Parameter Flight Path

This flight algorithm primarily serves a demonstration purpose. With three variables, the algorithm defines a landing point on the earth in two spatial coordinates. The third variable in the algorithm allows variation in time, and the potential to correct for changes in atmospheric conditions or errors in the deorbit burn, thus demonstrating a guidance capability.

Although the three-parameter flight algorithm is here used as an artificial algorithm for demonstration purposes, it also could serve a practical purpose. This algorithm would simplify the operation of EGRESS. While an equilibrium glide would require continuous roll adjustment, this flight path requires only one change of roll angle.

In order to minimize the impact of EGRESS on the crew schedules of Space Station *Freedom*, crew training for EGRESS had to be minimized. In the unlikely event of a failure of the flight computer, a crew member would have to pilot the craft. With the three-parameter flight path, the pilot would have to keep the roll angle constant at predetermined values, which could be accomplished with a minimum of crew training. On the other hand, it would not be as simple to fly the craft along an equilibrium glide trajectory, as constant adjustments of the roll angle are required.

7.2.3 Results

After numerical integration of the Eqns. 7-1, the flight path of the EGRESS may be determined. Fig 7.5 illustrates the side view of an example flight trajectory involving a 60° bank until 250,000 ft, and a 30° bank thereafter. This example trajectory also provides a cross range, orthogonal to the down range, of 460 nautical miles.

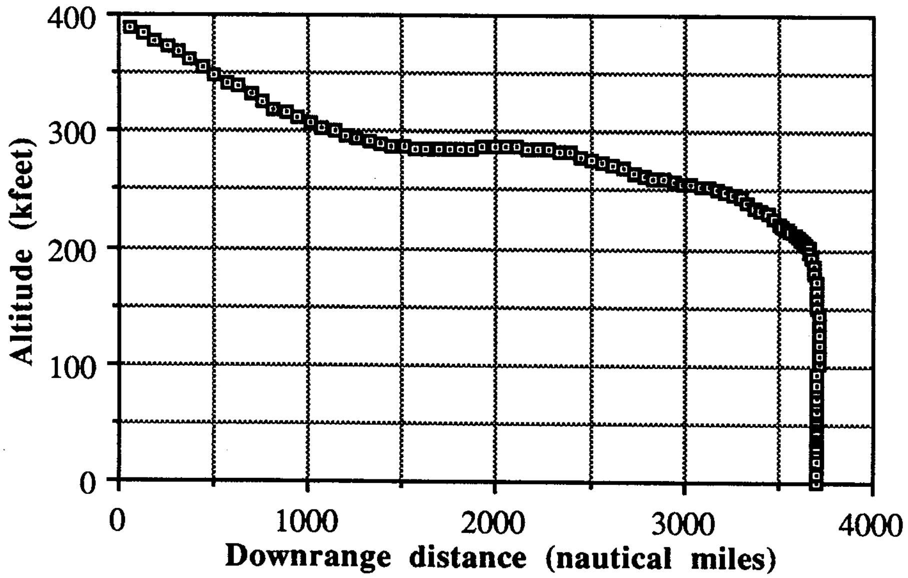

Figure 7.5 - Example Flight Trajectory with a 60° bank above 250,000 ft and a 30° bank below 250,000 ft.

Flight time to splashdown is also determined by the integration of Eqns. 7-1. For the three-parameter flight path, flight times vary from a minimum of 1200 seconds to a maximum of 2100 seconds. The example flight path shown in Fig 7.5 has a flight time of 1770 seconds (29.5 min) from 400,000 ft. to splashdown.

A velocity profile was also determined during the integration. The sonic speed for air may be determined from the standard density and temperature values used in the analysis [7-4], and a Mach number profile may also be generated. As Fig. 7.6 shows, most of the reentry flight occurs in the hypersonic regime (M>5), and thus, a simple Newtonian model of the flow field may be used to determine the aerodynamic characteristics of EGRESS. (See Section 7.4)

7.2.3.1 G-loading

Since the EGRESS will be in free fall during the reentry, the EGRESS crew will not feel the gravitational acceleration and will feel only the aerodynamic forces acting on the craft. The acceleration felt by the crew may then be determined from equation 7-9c without the gravitational term. The resulting 'g-force' felt by the crew is then determined by dividing the aerodynamic acceleration by $g_0 = 9.806$ m/s^2. Fig. 7.7 shows the g-loading for the example flight path given in Fig 7.5. For this example, maximum g-loading experienced by the crew is 2.3 g's.

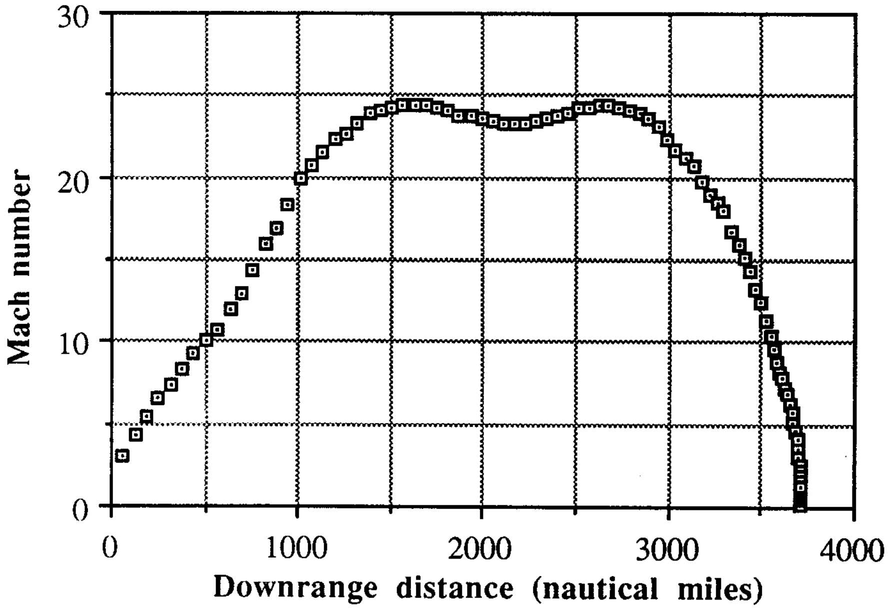

Figure 7.6 - Mach Number During Flight, showing that M>5 for most of the flight.

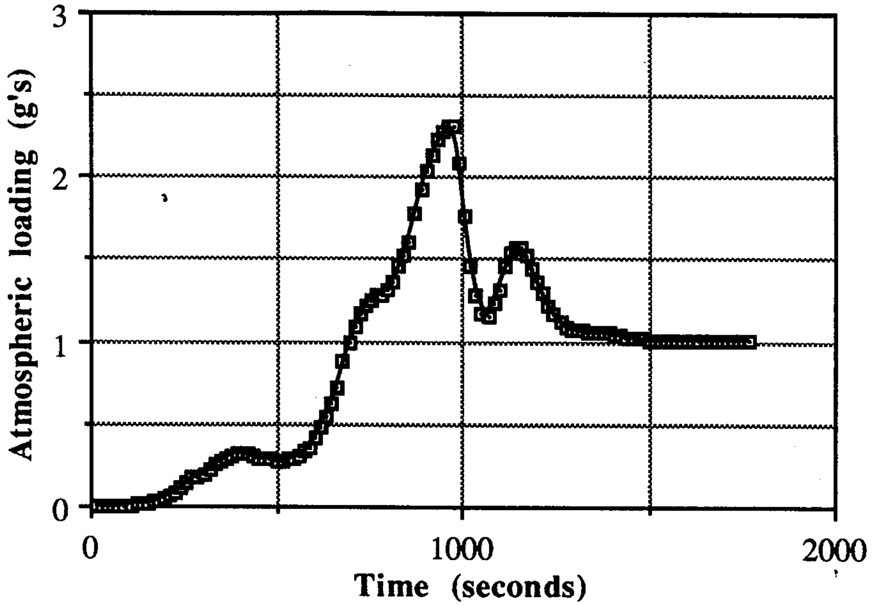

Figure 7.7 - G-loading for Example Flight Path.

The direction of the g-loading is determined by the L/D ratio. Since the lift is always assumed to be acting through the top of the craft, no side accelerations are felt. Furthermore, since the EGRESS is assumed to have a constant L/D = 0.8, atmospheric forces always act at a constant angle relative to freestream. Thus the direction of the force is always constant, and crew seats can be located so the g-loading can be most easily tolerated by the crew.

7.2.3.2 Heating Rates

The heating rate was computed from

$$Q = K\sqrt{\rho}\,V^3 \tag{7-13}$$

where

$$K = 1 - \frac{H_{wall}}{H_0} \tag{7-14}$$

For this analysis, K=.6 was assumed [7-5].

The nose heating rate for the example flight path is shown in Fig 7.8. Maximum heating for this example is 17.0 W/cm^2 (15.0 BTU/ft^{2}s).

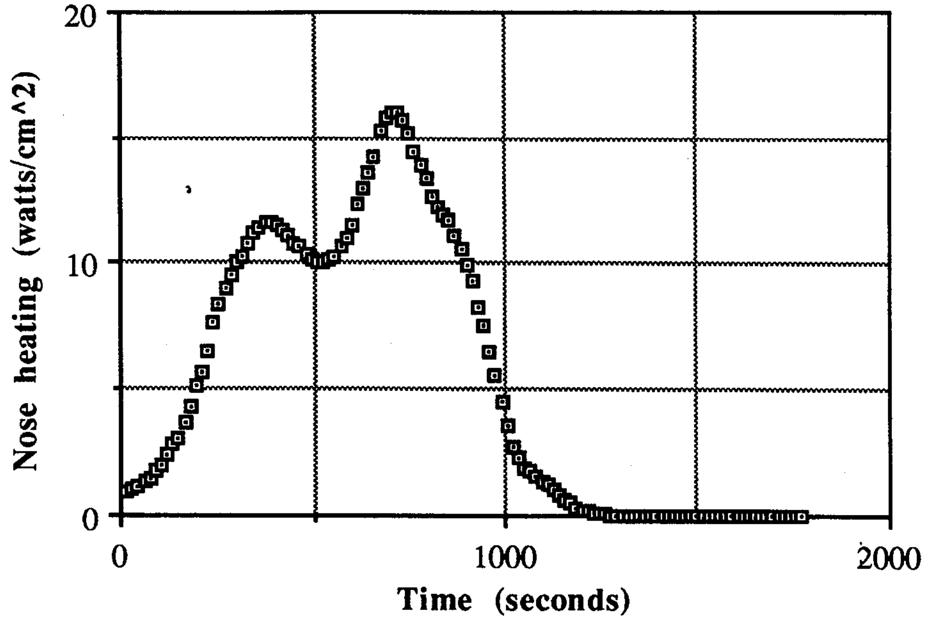

Figure 7.8 - Nose Heating for Example Flight Path

7.2.3.3 Footprint

From the g-force and heating rate calculations, a footprint of possible landing sites with the three-parameter flight path can be generated. These landing sites are limited by the atmospheric g-loading tolerable by the crew, and the maximum heating rate allowable by the thermal protection system. The RFP states that an injured crew member can tolerate no more than 4 g's during reentry (see Section 3.4.3.1). Furthermore, for the available thermal protection system (see Section 7.3), the maximum allowable heating rate is 55 W/cm^2 (50 BTU/ft^2s).

Subject to limitations of 4 g's and maximum heating of 55 W/cm^2, Fig 7.9 shows all possible landing sites to the left of the orbital track achievable by the three-parameter flight path, with all possible θ_1's and θ_2's, and varying H_{rot} between 190,000 ft and 250,000 ft for H_{ssf} of 200 nautical miles. A mirror image of the footprint would exist for points to the right of the orbital track. As the figure shows, a cross range of 500 nautical miles is possible for a vehicle with L/D=0.8, while down range may vary from 2,200 to 7,000 nautical miles from the location of the EGRESS when it passes 400,000 ft.

The footprint demonstrates the guidance capabilities of the EGRESS vehicle. There exists a flight path defined by three parameters which lands at each point within the footprint. Since these this landing location exists on a 2-dimensional spatial footprint, the three parameters define both a location and a landing time, the additional variable providing a mechanism of correcting for pilot error.

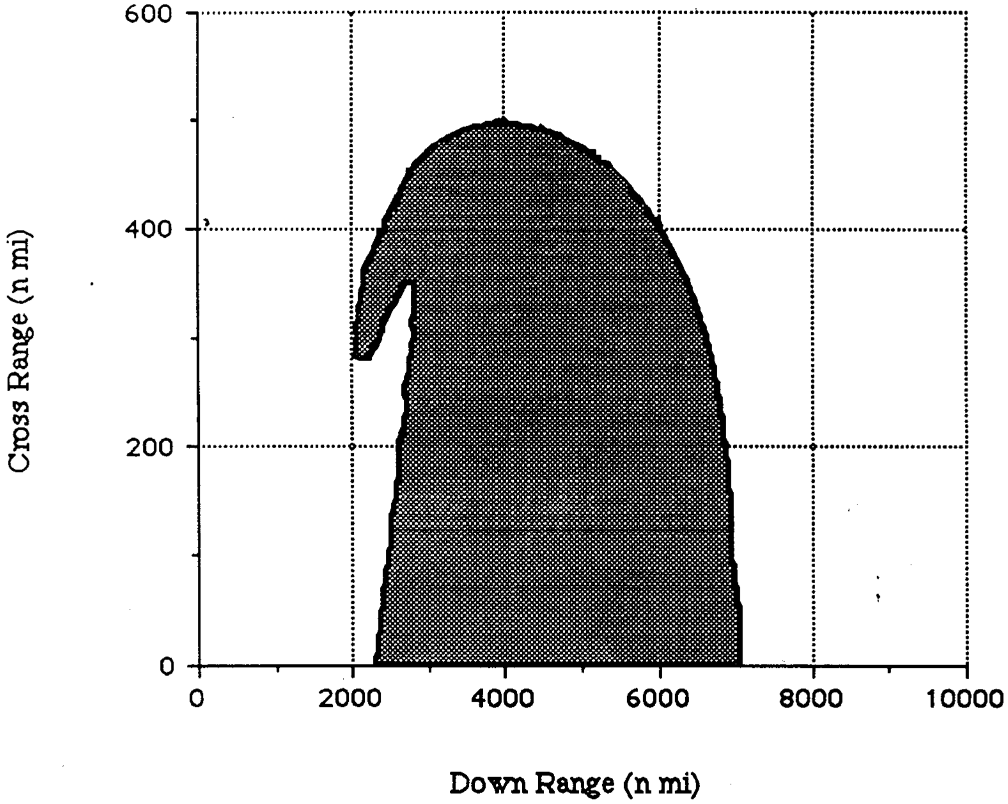

Fig 7.9 - Footprint of possible landing sites subject to a g-loading of 4 g's heating limitations

Although the three-parameter algorithm provides some flexibility in landing times, changing the time of separation from the Space Station provides a much greater freedom. After initial separation, the time to perform all further orbital and atmospheric maneuvers is determined solely by the flight algorithm. Thus, placing the separation earlier or later does not affect the shape or location of the footprint , but it does shift the location of the footprint on the earth. Since the Space Station orbits at approximately 4 nautical miles per second, a two minute (120 second) delay in separation provides the equivalent of 500 nautical miles of down range. The cross range capability is far more critical.

With the large cross range of this footprint, the entire ground track may be covered. The distance between successive orbits along the equator is 1300 nm. Since the orbits are inclined at an angle of 28.5°, the orthogonal distance between ground tracks is 1300 x sin 28.5°, or 620 nm at the equator (Fig 7.10). The ability to land anywhere within the ground track in 24 hours requires a cross range capability of at least half the orthogonal distance at the equator, or 310 nm. Since the EGRESS is capable of a 500 nm. cross range, any point between 28.5°N latitude and 28.5°S latitude may be reached in a 24 hour period.

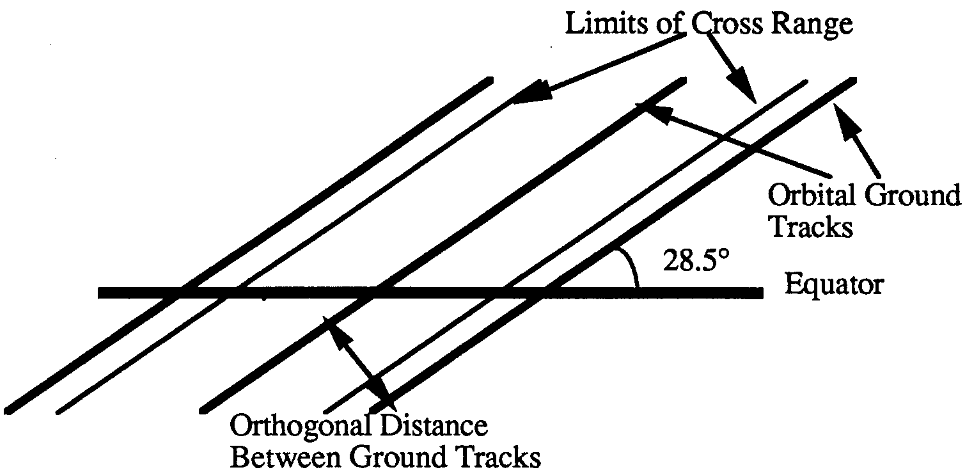

Figure 7.10 - Cross Range Capabilities

In order to have the potential to land at a given site on two successive orbital tracks, the cross range must equal or exceed the orthogonal spacing. This does not happen at the equator; however, orbital tracks are nearer at higher latitudes. For higher latitudes, the orthogonal distance between successive orbital tracks may be approximately determined from comparison with orthogonal distances between great circles

$$D_{orthogonal} = D_{equator} \times \sqrt{1-\left(\frac{°latitude}{°inclination}\right)^2} \qquad (7\text{-}15)$$

Equation 7-15 shows that, for a 28.5° inclination where $D_{equator}$ = 620 nautical miles, the orthogonal distance equals a cross range of 500 nm. at 17.1° N latitude. Thus, EGRESS will be able to land at any location above 17.1°N or below 17.1°S on two successive orbits. All three primary landing sites are above 17.1°N latitude.

7.3 Thermal Protection System

The EGRESS must be protected from the intense heat generated during reentry as the vehicle's kinetic energy is imparted to the atmosphere. A shock forms in front of the EGRESS as a result of molecular collisions between the air molecules reflected from the surface of the body and the incident air molecules. Many of the incident molecules are prevented from striking the EGRESS and thus, heat transfer by convection is reduced. In order to generate a strong bow shock, the bottom of the EGRESS will be blunt, and the EGRESS will have roughly a 40 degree angle of attack during the reentry trajectory.

Much of the heat generated during reentry is diverted away from the EGRESS by the bow shock discussed above. However, a significant amount of heat transfer does occur, and a thermal protection system is needed to shelter the EGRESS and its occupants. The ideal Thermal Protection System (TPS) would be lightweight, low cost, have a high-temperature capability and be able to withstand a long-term space environment.

Of the three systems considered–metallic, ablative, and ceramic–a ceramic thermal protection system proved to be the most ideal. Specifically, a TPS consisting of a high-temperature reusable surface insulator, HRSI, and an advanced flexible reusable surface insulator, AFRSI was chosen.

The HRSI is currently being used on the space shuttle orbiters in the underbelly and nose area. The HRSI is produced in the form of tiles composed of 99.6% pure silica fibers. These tiles are coated with thin, black borosilicate glass to obtain the proper high-temperature emittance value. The HRSI tiles are capable of withstanding a one-use exposure up to 3100 degrees F, weigh 22 lb/cu ft, and cost between $8000 and $9000 per square foot.

The AFRSI is currently in use protecting the cargo bay doors of the space shuttle orbiters. The AFRSI is a needled, silica-based Nomex felt blanket coated with a thin silicone elastomeric film. It has one use capability up to 2100 degrees F, weighs 6 lb/cu ft, and costs $3000 per square foot.

Both the HRSI tiles and the AFRSI blanket are impervious to ultraviolet radiation and atomic oxygen. Thus, the ceramic TPS is lightweight, has a high-temperature capability and can withstand the long-term space environment. However, because of the high cost, two other types of thermal protection systems were examined; metallic and ablative.

A metallic TPS would consist of a metal skin thick enough to absorb heat while remaining structurally sound. Unfortunately, the only metals that can survive temperatures up to 3000 degrees F are incredibly heavy - the proposed metallic TPS weighed more than the weight allotted to the entire vehicle. Thus, due solely to weight consideration, a metallic TPS was eliminated.

An ablative system would consist of a material similar to fiberglass. This material under intense heat chars, melts and vaporizes - ablates. The ablative process absorbs heat and the vaporized material tends to block heat flow from the shock layer to the body. However, the ablative material is composed of certain organic compounds which degrade in the presence of ultraviolet radiation and atomic oxygen. A teflon coating over the ablative shield was considered but rejected when it was determined that the coating would not be able to protect against degradation over a period of several years in orbit.

The TPS of the EGRESS will consist of HRSI tiles covering the underbelly and nose area of the craft with an AFRSI blanket covering the remaining areas. This type of ceramic TPS is lightweight, has a high-temperature capability, will not degrade in orbit, and would be reusable if not damaged on impact with the ocean.

7.4 Aerodynamic Analysis

An important aspect of the design of the EGRESS vehicle was its flow field analysis. The hypersonic regime was considered the most important area for flow analysis, since most of the flight occurs in this regime, as illustrated in Figure 7.6. A modified Newtonian flow model was used to simply and accurately determine the vehicle's flight characteristics. This analysis allowed us to develop a body shape and size which would generate the lift to drag ratio necessary to meet the g-force and cross range requirements discussed earlier. Furthermore, the center of gravity was located as a result of this analysis, in addition to an initial assessment of the vehicle's static stability.

From this analysis, the maximum lift to drag ratio was determined to be 0.8, for which the drag coefficient would be 1.2. Furthermore the EGRESS was determined to be statically stable in the yaw, pitch, and roll.

7.4.1 Newtonian Flow Theory

Hypersonic flow analysis can fortunately be simply analyzed using a Newtonian model. Newtonian flow theory is valid for hypersonic flows where the random molecular velocity of the air molecules is much smaller than the free stream velocity, and thus, the random motion is ignored.

$$\frac{V}{a} >> 1 \quad , \qquad (7\text{-}16)$$

Furthermore, a gas particle, when striking a surface, is assumed to lose its normal component of momentum, while its tangential component of momentum is unaffected. A relatively simple formula may be derived which defines the pressure coefficient on the vehicle surface as a function of the angle between the free stream velocity and the surface.

$$C_p = 2\left(\frac{V\,\hat{n}}{|V|}\right)^2 = 2\sin^2\delta \qquad (7\text{-}17)$$

A more complex modified Newtonian model defines the pressure coefficient as a function of the angle between the free stream velocity and the ratio of specific heats.

$$C_p = \frac{2}{\gamma M_\infty^2}\left\{\left[\frac{(\gamma+1)^2 M_\infty^2}{4\gamma M_\infty^2 - 2(\gamma-1)}\right]^{\frac{\gamma}{\gamma-1}}\left[\frac{1-\gamma+2\gamma M_\infty^2}{\gamma+1}\right] - 1\right\}\sin^2\delta \qquad (7\text{-}18)$$

At high Mach numbers,this relation can be reduced to the following expression.

$$C_p = 1.839\sin^2\delta \qquad (7\text{-}19)$$

The total force F on a surface of area A can be then be calculated from the pressure coefficient. This force is directed perpendicular to the plane of the area affected.

$$F = \tfrac{1}{2}\rho V^2 C_p A \qquad (7\text{-}20)$$

The above relationships demonstrate that the forces acting on an object in hypersonic flight are solely dependent on the shape of the vehicle impacted by the free stream, as the unexposed aft portion of the vehicle is assumed to be in a vacuum. Therefore, solving the total flow field around the vehicle is not necessary.

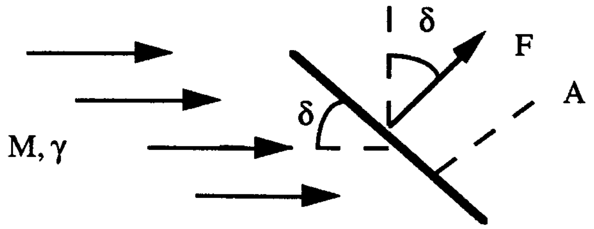

Figure 7.11 - Definition of Newtonian flow parameters

7.4.2 Newtonian Flow Computer Program

To aid in our flow field study, a computer program was developed to model the Newtonian flow field about an arbitrary three dimensional body. The pressure coefficient was calculated over the surface and integrated to determine the total forces and moments on EGRESS during its flight.

To numerically describe the shape of the EGRESS, thousands of points were located over the body surface, and their positions stored in Cartesian coordinates. Vectors joining triangles of body points were then calculated. The local surface normal vector was determined by taking the cross product of two triangle side vectors. The triangle surface area could then be taken from the magnitude of this cross product. The centroid of each triangle was then located, and a second vector derived to provide the position of the triangle centroid with respect to the coordinate system origin.

After the normal vectors, areas, and positions of the triangles composing the body shape had been calculated, the aerodynamic force acting on each triangle was determined. The pressure coefficient for a given triangle was found from the dot product of the local normal vector and the free stream velocity vector–any angle of attack or sideslip angle could be chosen. From this coefficient and the triangle area, the magnitude aerodynamic force acting on a body triangle was determined. The direction of the aerodynamic force would then be in the direction of the local surface normal.

Recalling that no force aerodynamic force acts on triangles on the upper surface which are not directly exposed to the free stream, the local force vectors were summed over the lower surface, and the total aerodynamic force on the vehicle determined. Furthermore, the local force vectors were assumed to act through the centroid of their respective triangle, and the aerodynamic moments determined.

The total force vector was then decomposed into components perpendicular to the free stream velocity vector–the lift–and parallel to the free stream velocity vector–the drag. The hypersonic lift and drag coefficients were then calculated. The center of pressure was also determined knowing the aerodynamic moments. The center of gravity could then be located from knowledge of the center of pressure.

By taking different runs with varying angles of attack and sideslip angle, roll, pitch, and yaw stability were studied. By observing whether moments induced by a change in flow velocity acted to counteract that change (i.e., bring the craft back to its previous equilibrium position), one could evaluate the stability of the craft.

7.4.3 Flow Analysis Program Results

The flow analysis program was ran with an approximate body shape. The output was analyzed to determine whether a L/D of 0.8 could be attained. If this minimum L/D could not be attained, the vehicle was modified to meet this criterion. Several iterations were completed before an acceptable vehicle shape was discovered. Our final body shape had the following L/D characteristics for given angles of attack:

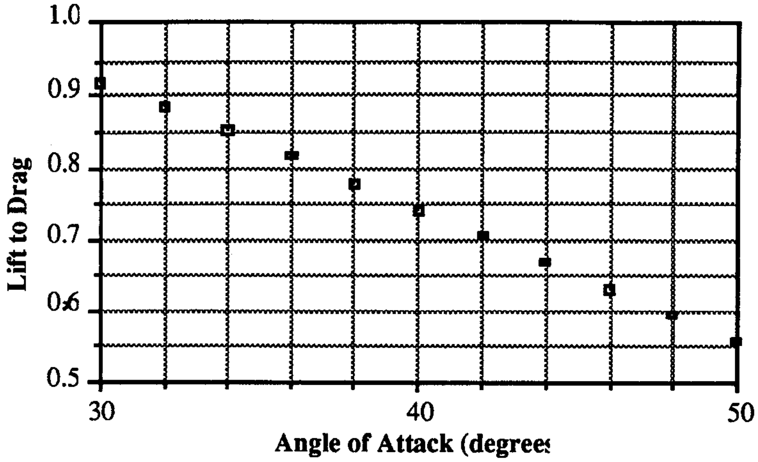

Figure 7.12 - Lift to drag versus angle of attack

Obviously, angles of attack of greater than roughly 40 degrees would not provide acceptable lift to drag ratios. Also, angles of attack of less than 35 degrees would allow too much flow to reach the upper surface of the vehicle. Thus, an center of gravity had to be chosen that would provide an acceptable angle of attack, and hence, lift to drag. The newtonian flow program also allowed the center of pressure to be determined, thus providing an accurate picture of the lines of force of the atmospheric drag and lift.

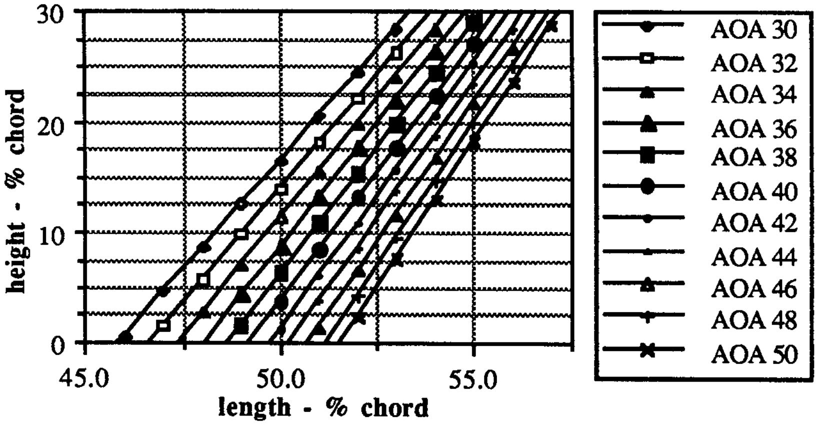

Figure 7.13 - Lines of force for varying angle of attack

Obviously, this demonstrates the range of possible locations for the center of gravity of the vehicle. So long as the center of gravity is placed along the lines of the 36, 38, or 40 degrees angle-of-attack lines, the lift to drag of the vehicle will be acceptable. In addition to this, it demonstrates by this graph that the pitch stability of the vehicle is favorable; if the vehicle pitches to an unfavorable angle of attack, the center of pressure moves to correct the disturbance.

Analyses of yaw and roll stability were also completed. Here it was successfully demonstrated that the vehicle is statically stable. This means that disturbances in yaw and roll resulted in forces that acted to counteract the disturbances. The only restriction to this is that the center of gravity must be located below the 20% chord point of the vehicle. This equates to approximately the 50% height location.

Chapter 8

Landing and Recovery

8.0 Summary

The Landing and Recovery group was responsible for the mission during the final portion of descent, splashdown, crew removal and transportation to health care facility, and spacecraft retrieval. First, the Landing and Recovery group needed to decide whether the EGRESS vehicle would land on water or on land. After this initial decision, the rest of Landing and Recovery's responsibilities involved finding appropriate landing sites, designing a deceleration system to lessen the landing impact, and determining the recovery forces and procedures at each of the landing sites.

After researching the advantages and disadvantages of a land or water based landing, our group decided that EGRESS would land on water. Most of Space Station *Freedom's* ground track is over water. Also, a land lander is more complex than a water landing vehicle, and requires more pilot training and more pilot control during reentry. Finally, the advantages of a land landing vehicle could be negated by careful design and operational techniques of a water landing craft. A water landing became the logical answer.

The EGRESS vehicle uses a conventional deceleration system of two drogue chutes and three flat circular parachutes that are deployed by means of three smaller pilot chutes. A ram-air system was not selected since it has not been sufficiently researched for weights comparable to that of the EGRESS vehicle. An attenuation system that would provide increased deceleration right before impact is not needed since the conventional chutes can slow the craft to an impact deceleration within the specifications of the RFP. For this reason, retrorockets or an air-bag system that would be deployed on impact through the bottom of the craft will not be needed.

To determine the specific locations of the landing sites, available recovery forces and health care facilities had to be researched, and the ground track had to be analyzed. The limiting factor in the recovery forces proved to be the availability of a heavy lift helicopter capable of lifting 10,000 lbs., the weight of EGRESS. The U.S. Navy has such helicopters at only some of its bases. In addition to the constraints of the recovery forces, the ground track itself posed problems. Only a small portion of the ground track goes over the United States or coastal areas with nearby U.S. military bases. In the RFP, Design Reference Mission 2 calls for the craft to leave with relatively short notice; it is desirable to have the craft be able to land at a primary landing site from any of its orbits. With these criteria in mind, Pearl Harbor (Hawaii), Okinawa (Japan), and Kennedy Space Center (Florida) were chosen as the primary landing sites, and Guam was chosen as a secondary site.

To provide for Design Reference Mission 3, return of an injured crew member, Landing and Recovery determined that the crew should be removed and transported to a health care facility (HCF) as quickly as possible. For this reason, the Coast Guard was chosen to remove the crew, when available, and the Navy was chosen to recover the EGRESS craft. The Navy would also retrieve the crew if the Coast Guard is unavailable.

Since an EGRESS vehicle would be used in an emergency situation, the specific landing procedures must be outlined. These outlines must include provisions for landing at night and landing in poor weather. Research showed that EGRESS can land at night with minimal changes to daylight procedure, while extremely poor weather would force a landing at another site. In the event that the only available landing sites have poor weather, a modified recovery procedure would be used in which the entire EGRESS would be lifted out of the water and transported to a HCF, with the crew inside. This procedure would avoid the possibility of the craft being swamped once the hatch is opened.

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8.1 Land vs. Water Landing

This section of the report describes why a water landing was chosen over a land landing. Many factors were considered; among the most important were the ground track, accessibility of sites, and landing accelerations.

The ground track of Space Station *Freedom* is mostly over water. In order to have a landing other than a splashdown, a high lift to drag vehicle, similar to the space shuttle, would be needed to allow the craft to move outside the ground track the distance needed to attempt a touchdown on land. A low or medium lift to drag vehicle like EGRESS has some cross range abilities, but not enough to increase possible land landing sites. A water landing allowed more reentry windows than a land landing, due to the fact that there are many more available landing sites in water than there are sites for putting the craft down on land.

New landing sites for a land touchdown would have to be built in remote areas to eliminate the possibility of destruction to human surroundings. This once again limits the number of possible landing zones to put the craft down on land. It would be easier to clear a splashdown zone of boats in short notice than it would be to remove people from a similar zone on land.

A water landing also reduces pilot workload. The less precise landing requirements of the craft translate into less navigational and computational equipment needed aboard EGRESS. The reduction in these systems alleviates much of the initial training and update training while on board the space station. Fewer tasks are required of the pilot during reentry and touchdown to the earth's surface.

The advantages of a land touchdown were nullified in the final design. One of the major concerns was the impact accelerations on an injured crew member. A shuttle-like landing would have less impact accelerations than a splashdown landing. This concern was addressed when a deceleration system was chosen to allow the craft to splashdown with impact accelerations below the maximums given in the RFP. The concern of the craft's hatch facing into the water rather than facing into the air was alleviated with the implementation of a craft righting device, that would deploy upon impact. There also were thoughts that removing the crew would be difficult in water, but studies of the crew removal of the Apollo missions gave evidence that removal on the water can be done effectively.

The last reason for having a land touchdown would be the close proximity to a health care facility (HCF). A splashdown 10 to 12 nautical miles from shore requires only a 10 minute flight in a helicopter to reach the HCF. While it may be possible to land slightly closer to a HCF on land, a 10 minute helicopter flight for a splashdown is well under the one hour limit given by the RFP. Since a splashdown is superior to a land touchdown in all other aspects, the added 2 or 3 minutes time delay was negligible.

8.2 Deceleration System

Without any deceleration system, a reentry craft would impact sea level at a speed of 200-300 miles per hour. At this speed, even a healthy crew member would be seriously injured and most likely killed. Thus, a system was required to slow EGRESS' descent velocity. Since EGRESS will carry an injured crew member, a deceleration system had to be designed to reduce this speed to below 20 miles per hour. The deceleration system for EGRESS is heavily based upon the Apollo command module descent system.

The craft is initially decelerated by two flat circular, twenty foot diameter, nylon drogue parachutes which are fired from mortars at approximately 23,000 feet. Each drogue is deployed in two stages and is suspended approximately 65 feet above the craft. EGRESS descends on the drogues until 10,000 feet where these chutes are released, then the pilot extraction parachutes for the mains are fired from mortars. Each of the three flat circular, nylon pilots is 14 feet diameter and extends 50 feet above the main parachutes. The pilot chutes pull the three main chutes out of the vehicle and into the airflow for deployment. Each of the three flat circular, nylon main chutes is 110 feet in diameter, weighs 224 lbs., and is approximately five cubic feet in volume when packed. The main parachutes deploy in three stages which allows full deployment at 7,500 feet. EGRESS descends on the mains until splashdown. The mains are then severed from their attachment points.

Since the conventional system is not controllable, an alternative ram-air "parafoil" was considered. The ram-air system is similar in nature to the parachutes that most skydivers presently use. The ram-air system was composed of a single 20 foot diameter drogue and one fifty foot diameter flat circular parachute for primary deceleration. Once the descent velocity is reduced appreciably, the 4,500 square foot (39 foot chord, 116 foot span) parafoil would be deployed in three stages. The system also contained a single one hundred foot diameter flat circular reserve chute in the event of a failure of one of the other primary chutes. Each system was evaluated in eleven different categories.

Five of the categories showed neither system had an advantage over the other--weight, volume, reusability, cost, and deployment accelerations. First, calculations were made to determine the size (storage volume required) and weight of each system as shown in Figure 8.1. The sizes and weights of the two systems were found to be quite similar. Reusability of each system was also studied. All canopy material for both systems would be synthetic in nature, and therefore would have the same relative lifespan and be unaffected by salt water exposure upon landing [8-1]. The ram-air system would have slightly higher costs; the canopy material and assembly costs would be about the same, but the ram-air would cost more due to its control systems. Then, after studying the deployment accelerations, we concluded that both systems can be designed to have very similar relative accelerations upon parachute deployment.

	Conventional System	Ram-Air Parafoil
Canopy Weight	3.0 oz/yd^2	3.0 oz/yd^2
Canopy Density	44 lb/ft^3	44 lb/ft^3
Total Weight	800 lbs	920 lbs
Packing Volume	16 ft^3	20 ft^3

Figure 8.1 - Deceleration System Dimensions and Weights

The categories of controllability and impact attenuation made the ram-air system the heavy favorite. The high glide characteristics are a strong selling point of any ram-air system. With a L/D of three or greater and the ability to penetrate sixty mile per hour winds, a parafoil is an extremely attractive deceleration system. Also, the flaring capability of the system is a built-in impact attenuation system that gives the capability for an essentially zero velocity impact. The conventional system, as specified, has no method of control and no impact system. The vehicle will drift with the wind to a point possibly miles from the desired landing, and if the impact loads are too high for the crew's safety, a separate attenuation system must be included that will add to the weight and volume required and system complexity. Both are very strong points in favor of the ram-air system; however, controllability became less important when it was decided to design for a water landing. Also, the conventional system can be designed so that a separate impact attenuation system is not needed.

The last four categories of reliability, redundancy, complexity, and deployment swayed the decision towards a conventional deceleration system. The most important aspect of any system is its reliability; the lives of the astronauts are at stake, and any system that leaves doubt as to their safety should be rejected. The ram-air system has been under serious development for only ten or fifteen years. Tests have been completed for payloads of 10,000 pounds, but there is no such system in use, and this testing was for unmanned payloads. In contrast, conventional parachutes have been used for more than fifty years with heavy payloads and with reentry bodies since the beginning of the space age. In the history of the United States space program, there has never been an astronaut death attributed to a parachute system failure. Just as important as reliability is a system's redundancy; the more redundant a system is, the less chance of a catastrophic failure. If the ram-air system's parafoil fails, it requires a system to sever the chute and deploy a conventional flat circular reserve chute with no flaring capability. However, the conventional system with three main chutes is inherently redundant. If one main chute fails, the descent velocity of the craft increases by only four mile per hour. System complexity also reduces reliability for a ram-air system. With its control mechanisms, electronics, and sensing systems, the ram-air is a complex deceleration system. However, the conventional system requires only a launching mechanism (altitude sensors for deployment decision and pyrotechnic launchers to deploy the chutes) which would necessarily be a part of the ram-air system as well. Finally, the chute deployment mechanics favored of a conventional system. Conventional parachute deployment is understood fairly well, but only personal sized ram-air chutes have been studied in depth. A parafoil is rectangular and therefore does not deploy symmetrically about its center as a conventional chute does; the actual opening dynamics of parafoils are poorly understood and are tested mostly through trial and error. With only two of the categories favoring a parafoil and four favoring a conventional system, as shown in Figure 8.2, Landing and Recovery decided to use the conventional deceleration system as shown in the deployment sequence represented in Figure 8.3.

	Conventional System	Ram-Air Parafoil
Weight	=	=
Volume	=	=
Reusability	=	=
Cost	=	=
Deployment Accelerations	=	=
Controllability	-	+
Impact Attenuation	-	+
Reliability	+	-
Redundancy	+	-
Complexity	+	-
Deployment Ease	+	-

Figure 8.2 - Deceleration System Comparison

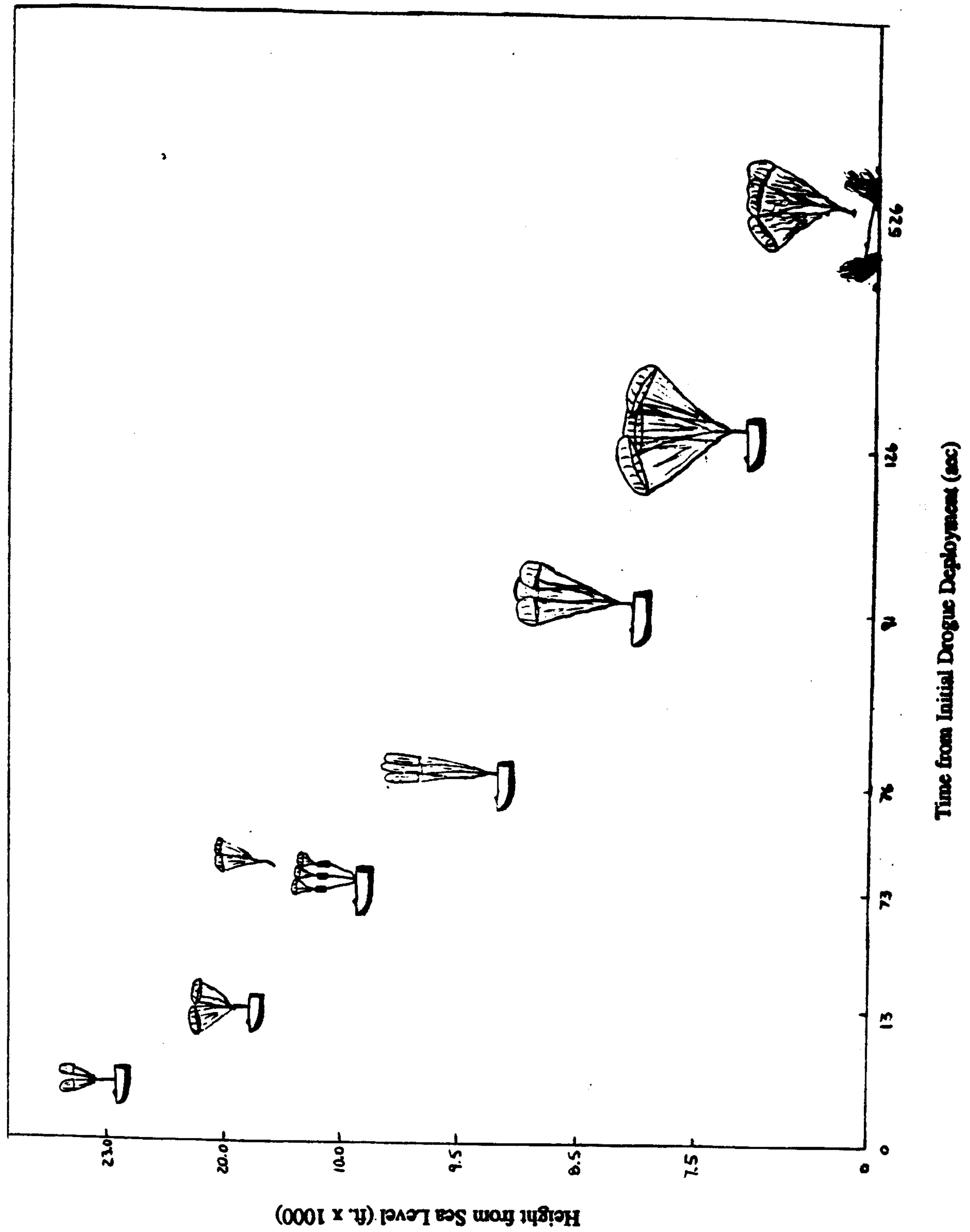

Figure 8.2 - Parachute Deployment Sequence

Figure 8.3 - Parachute Deployment Sequence

Of secondary concern involving the deceleration of the craft was the possible need for a separate impact attenuation system. With injured crew aboard, it was believed that a parachute system may not meet the minimum impact deceleration constraints. For this reason, two systems were analyzed for impact attenuation: retro-rockets and air bags.

The retro-rockets were an exciting option, but failed to meet requirements of ease of deployment and minimum impact on the space station work schedule--the solid fuel propellants, due to aging, would have to be replaced every two to three years while EGRESS was attached to the station. Retro-rockets would also add weight and cost to the system. An air bag system promised to provide a comfortable impact with good reliability. However, since their only current application is in automobiles, extensive field testing would be required before placement on the vehicle could be allowed. In addition to the given reasons for each system, the idea of an impact system was rejected when calculations indicated that the given conventional deceleration system would provide a safe 3-g impact without reducing the descent velocity to the point of excessive drift. Eliminating the need for a separate impact system also saves on vehicle cost, complexity, and weight and volume constraints.

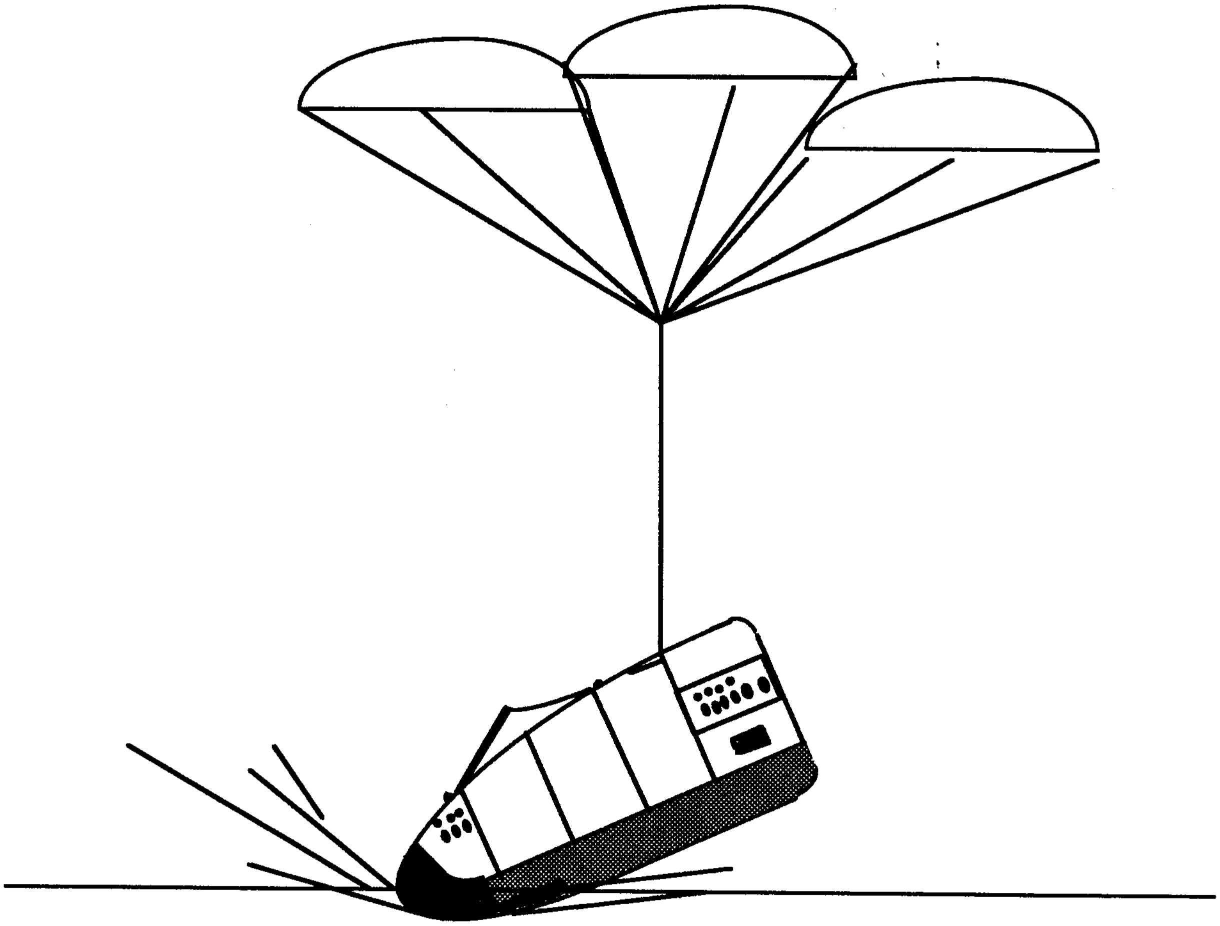

Figure 8.4 - EGRESS Splashdown

Once we selected the conventional system, we used a program that analyzed the descent of the vehicle on a given parachute system. From this program, we determined that the aforementioned system would provide an impact speed of 20 feet per second. Using a simple model for the water impact, we determined the impact loading would be approximately three g's. Consequently, the group decided to attach the chutes to the vehicle so that it would hang at an angle of ten degrees under the horizontal, and in this way the RFP acceleration requirements could be met without the addition of an impact attenuation system. The vehicle landing angle was determined from the reentry angle for which the seats were designed.

Each of the drogue and main chutes will be attached separately to the craft by a steel arm linked to a universal joint to minimize torsional stresses. The center of attachment for both sets of chutes to give the necessary hang angle is chosen based on the vehicle's center of gravity. After deployment of the main chutes the center of gravity will move forward, and in order to maintain the same vehicle's hang angle, the center of attachment of the main chutes should also move forward. unfortunately, due to space limitations, the attachment centers may be nearly coincident; this simply means that the vehicle will hang at a larger angle than planned during main descent and impact. However, provided the hang angle is less than 60 degrees, the impact accelerations experienced by the occupants will not exceed the limits imposed by the RFP. Figure 8.4 shows how the EGRESS vehicle will hang before splashdown. Note that the parachutes and their suspension lines are not drawn to scale. The top view of the parachute compartment layout is shown in Figure 8.5.

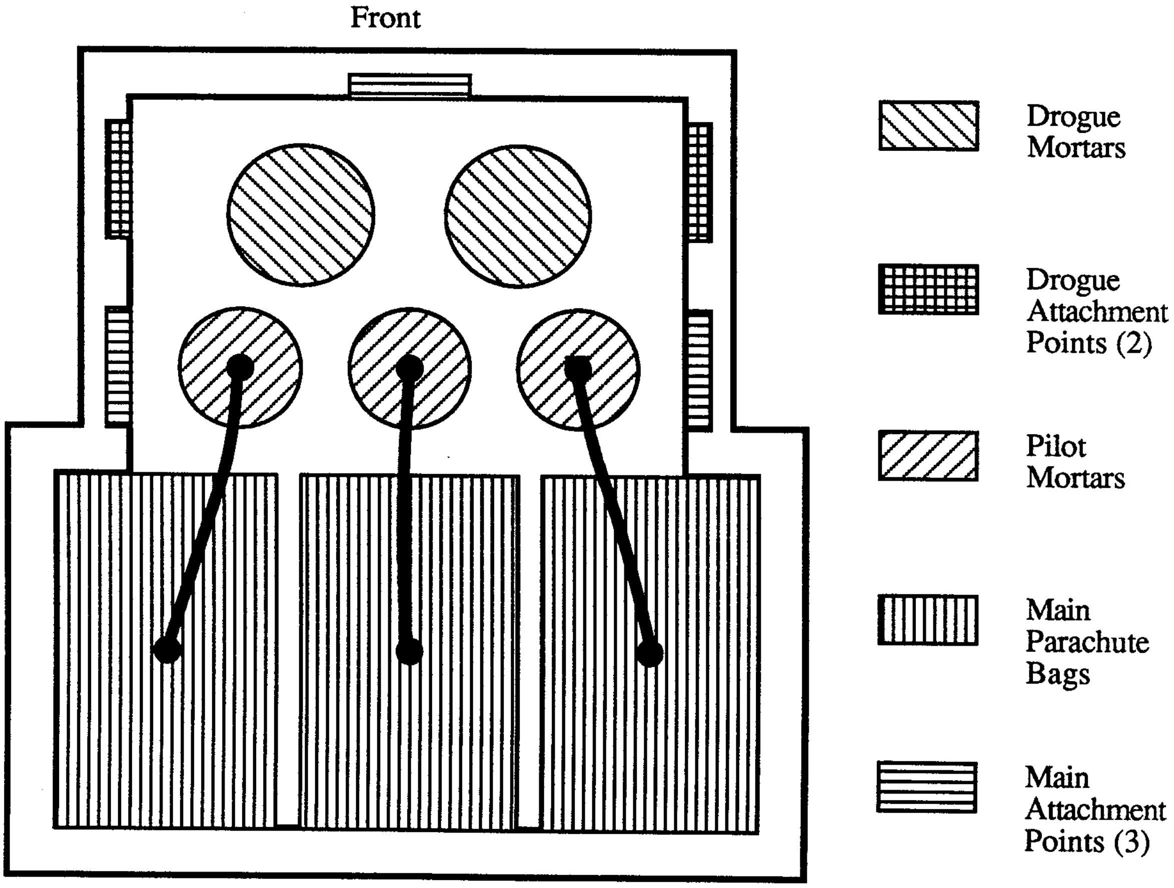

Figure 8.5 - Parachute Compartment Layout, Front View

The deployment sequence accelerations are as follows: the drogue parachutes give a maximum g-loading of 1.64, and upon drogue deployment that the vehicle swings to a twenty-five degree downward position. The maximum acceleration of 4.79 g's occurs when the main parachutes are deployed to the fifty percent reefed position. In the event that EGRESS descends on two main chutes, the maximum impact g-loading is 3.7 g's.

8.3 Landing Sites

Since EGRESS will be used for emergencies, it is necessary to choose possible landing sites and the recovery forces well in advance. These landing sites must be located on the space station's ground track because EGRESS has limited cross range abilities and will be based on the space station. Also, each landing site must have sufficient forces available to recover the crew and the spacecraft which weighs 10,000 lbs. Necessary recovery forces were determined to be United States military bases and/or United States Coast Guard stations. A further necessity was that the heavy-lift helicopter for vehicle recovery must be located on the base at the landing site at the time of the splashdown. Finally, each landing site needs to have a nearby health care facility. Based on this criteria, the following landing sites, located on Figure 8.7, with the health care facilities shown in Figure 8.6 were chosen:

Primary Sites
- Pearl Harbor, Hawaii
- Okinawa, Japan
- Kennedy Space Center, Florida

Secondary Site
- Guam

More secondary sites were researched; however, they were discarded because they did not contribute more landing flexibility from different orbital positions, nor did they have nearby resources for recovery forces, or meet the communication requirements. The Marshall Islands fall on a repetitive ground track with Okinawa and therefore offer no added benefits as a prospective site. Fraser Island was eliminated due to lack of recovery forces. Dakar was without a heavy-lift vehicle within the specifications. San Diego does not fall within the cross-range of the ground track and also posed weather complications. Diego Garcia is located in the Indian Ocean and thus did not meet our communication needs. Manila in the Philippines did not have sufficient health care facilities nearby.

Landing site	HCF
Pearl Harbor	Pearl Harbor Naval Hospital
Okinawa	Kadena Naval Hospital
KSC	Patrick Air Force Hospital
Guam	Anderson Air Force Hospital

Figure 8.6 - Health Care Facilities at Landing Sites

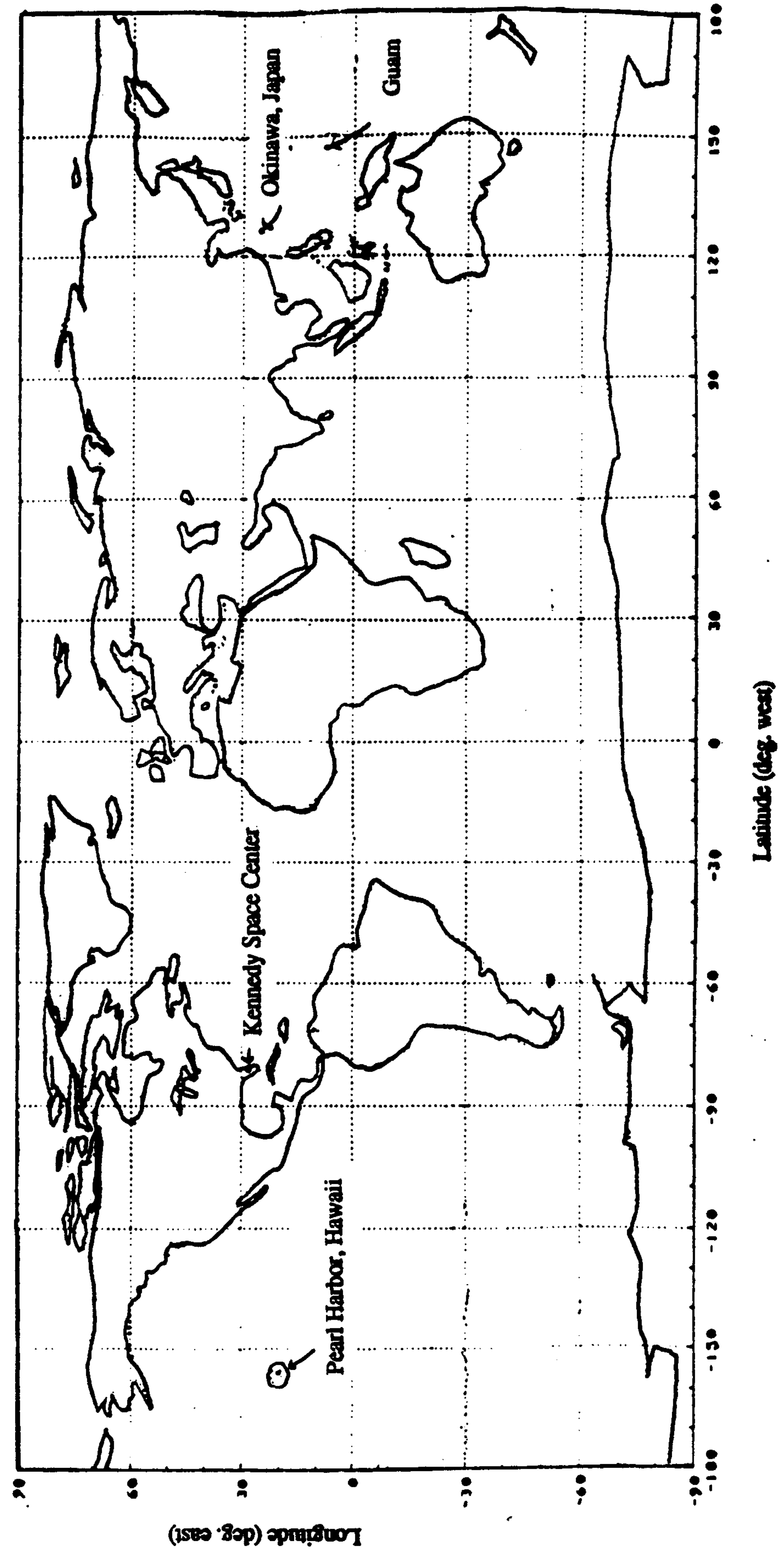

Figure 8.7 - Landing Site Map

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8.4 Recovery

To complete the mission after splashdown, the crew must be retrieved, the injured crew member taken to a health care facility, and the craft must be removed from the water. To accomplish this portion of the mission, recovery forces and the procedure they will follow were determined for each landing site.

8.4.1 Forces

Since EGRESS will be used to transport injured or ill crew members, it is desirable to remove the incapacitated crew member, along with the others, and transport them to a nearby health care facility before the EGRESS is lifted out of the water. For this reason, two different rescue vehicles will be used; a fast search and rescue helicopter (SAR) and a heavy lift helicopter. The Coast Guard was chosen for crew recovery, when available, because of their experience and availability, and the Navy will be used for vehicle recovery. The Navy will also be used for crew recovery if the Coast Guard is unavailable. The final transportation of the vehicle to Kennedy Space Center will occur by loading the EGRESS vehicle into a cargo transport plane (such as a C-141B cargo transport) which will fly directly to Kennedy. Figure 8.8 shows the helicopters [8-2] available for use at each of the landing sites:

Recovery Site	Hawaii	Okinawa	KSC
Crew Transport	HH-65A (Dolphin)	Huey (Bell UH-1H)	HH-65A
Vehicle Transport	CH-53E (Super Stallion)	CH-53E	CH-53E
Final Transport	C-141B	C-141B	C-141B

Figure 8.8 - Recovery Forces at Primary Landing Sites

Patrick Air Force Base, located at Cape Canaveral, does not have CH-53E helicopters stationed there. To solve the problem of vehicle recovery, the Navy base at Jacksonville, North Carolina will have to be notified, so that a Super Stallion can be flown down to Patrick AFB to recover EGRESS. Ideally, Jacksonville should be notified 2.5 hours in advance so that a helicopter will arrive on location when EGRESS lands. Although the vehicle needs to be removed from the water as quickly as possible to avoid exposure damage, in an emergency when a Super Stallion does not have enough advance notice, the EGRESS vehicle can float with its hatch resealed until recovery forces arrive.

Landing at the secondary site of Guam will require flying a Super Stallion from Hawaii or Okinawa. In addition, crew recovery will depend on a Navy Huey helicopter since the Coast Guard does not have an air station on Guam.

8.4.2 Daytime and Nighttime Landings

Rescue over water was once considered a problem due to the need for a set horizon for a helicopter to hover. This problem is alleviated by the Doppler coupler which creates an imaginary horizon upon which to fix. These couplers are found on all rescue helicopters used by the United States Coast Guard and the United States Navy. In addition, recovery of the crew and vehicle requires trained rescue air crewmen (formally known as frogmen); these also are common elements of all search and rescue teams.

During night recovery, the horizon will be provided by the coupler again. Locating the EGRESS vehicle will be accomplished with the aid of GPS which will provide the precise location to the dispatcher of the helicopter. In the event that GPS fails, EGRESS is equipped with a radio beacon which can be tracked by any search and rescue vehicle. Once the rescue helicopters are at the recovery site, spotting will be accomplished with a red strobe light, located on the craft above and below hatch, so that night vision can be preserved. During the rescue procedure, spotlights standard to all rescue helicopters, will aid the rescue air crewmen in their duties. Although daytime rescues are easier and less time consuming, nighttime rescues are possible.

8.4.3 Calm vs. Bad Weather Procedures

If an EGRESS vehicle is used, the weather and time of day at the primary landing sites will have an effect on the site choice and landing procedures. Landing and Recovery determined that the hatch will have approximately 5-6 ft. of dry-deck above the water, waves should not exceed a height of 6 ft. for normal procedure. It is possible that the only landing sites available to EGRESS at the time of the decision to leave *Freedom* will have bad weather. In this case, an alternate procedure for rough water landing will be used. The calm weather and rough weather landing procedures are outlined below.

Calm Weather Landing

- Mission control contacts recovery forces when the decision to use EGRESS is made
- Mission control contacts recovery forces a second time after deorbit burn
- At 23,000 ft., the beacon will turn on automatically as the main chutes deploy, and radio will provide EGRESS vehicle voice contact with rescue station
- Dolphin helicopter leaves base 8 minutes after parachutes deploy
- Splashdown 10 nautical miles from shore
- Crew turns on daytime/nighttime visible light
- Crew makes contact with Coast Guard Dolphin which is on its way
- Dolphin assumes hover position within 3 minutes of splashdown
- Rescue air crewmen dive into water near EGRESS
- Hatch is opened
- Stretcher removal
  - Hoist mechanism is attached to stretcher
  - Pilot and medical technician detach stretcher
  - Cord attached to stretcher to aid air crewmen in pulling out stretcher
  - Rescue air crewmen pull out stretcher with pilot and medical technician assisting from inside
- As stretcher is lifted up, other EGRESS crew members exit craft
- After all EGRESS crew is on Dolphin, hatch is resealed
- Dolphin pilot contacts super stallion which then leaves for splashdown site
- Air rescue crewmen are then lifted and Dolphin heads for hospital
- Super stallion arrives and rescue air crewmen dive into water
- Hoist is hooked onto EGRESS
- Air rescue crewmen are lifted up by means of a hoist off the side of the helicopter
- EGRESS lifted up out of water
- EGRESS taken to nearby military base where it will wait for cargo transport (such as a C-141B) to KSC, its final destination

Rough Weather Landing

- EGRESS crew informed of decision for bad weather procedure after deorbit burn
- Beacon turns on at 23,000 ft.
- Crew contacts Coast Guard for confirmation
- Crew contacts Super Stallion helicopter which is on the way
- Super Stallion assumes hover and rescue air crewmen dive into water
- Rescue air crewmen attach hoist to craft
- Rescue air crewmen are lifted into the helicopter
- EGRESS vehicle is lifted up out of the water and flown directly to the hospital
- At health care facility, injured crewman on chair is lifted out of craft
- Remaining EGRESS crew exit craft
- Hatch resealed
- Super Stallion picks up EGRESS and transports it to Navy base to await transport to KSC

8.4.4 Recovery of the Parachutes

During the rescue phase of the mission, it is suggested the recovery forces have an observation ship that will supervise the operation. This ship will also be responsible for the recovery of the chutes. The chute capture will take place after the EGRESS vehicle is removed from the landing site. Each main parachute will have a floatation device incorporated into them, so that the chutes will be reusable instead of sinking wastefully into the water.

8.5 Self-Righting Procedure

When the EGRESS splashes down, a self-righting system will automatically deploy to right the vehicle. The uprighting system will use air bags to change the center of buoyancy, causing the craft to right itself. A manual backup switch is available in the event that the automatic system fails. The self-righting system will provide additional dynamic stability to the EGRESS in heavy seas beyond the static stability of EGRESS. The center of buoyancy of the vehicle was positioned to provide a natural stability to the EGRESS.

To determine the center of buoyancy, a computer program form the Naval Architecture Department at The University of Michigan was used. Inputs are the center of gravity, the weight of the vehicle, and points along the circumference of the vehicle. From this information, the program calculates the center of buoyancy and the location of the water line on the craft as it sits in the water. Figure 8.10 shows the water line of the EGRESS vehicle, and Figure 8.9 shows the data from this computation.

To understand the results of the calculations, certain measurements must be defined. The draft is the height measured from the bottom of the craft upward to the water line. The trim is the difference between the forward and aft drafts. It should be noted that forward refers to the front of the craft, and aft refers to the back. The center of buoyancy is measured upward from the bottom of the craft and backward from the midship position which is located at 1.829 meters from the front of the craft.

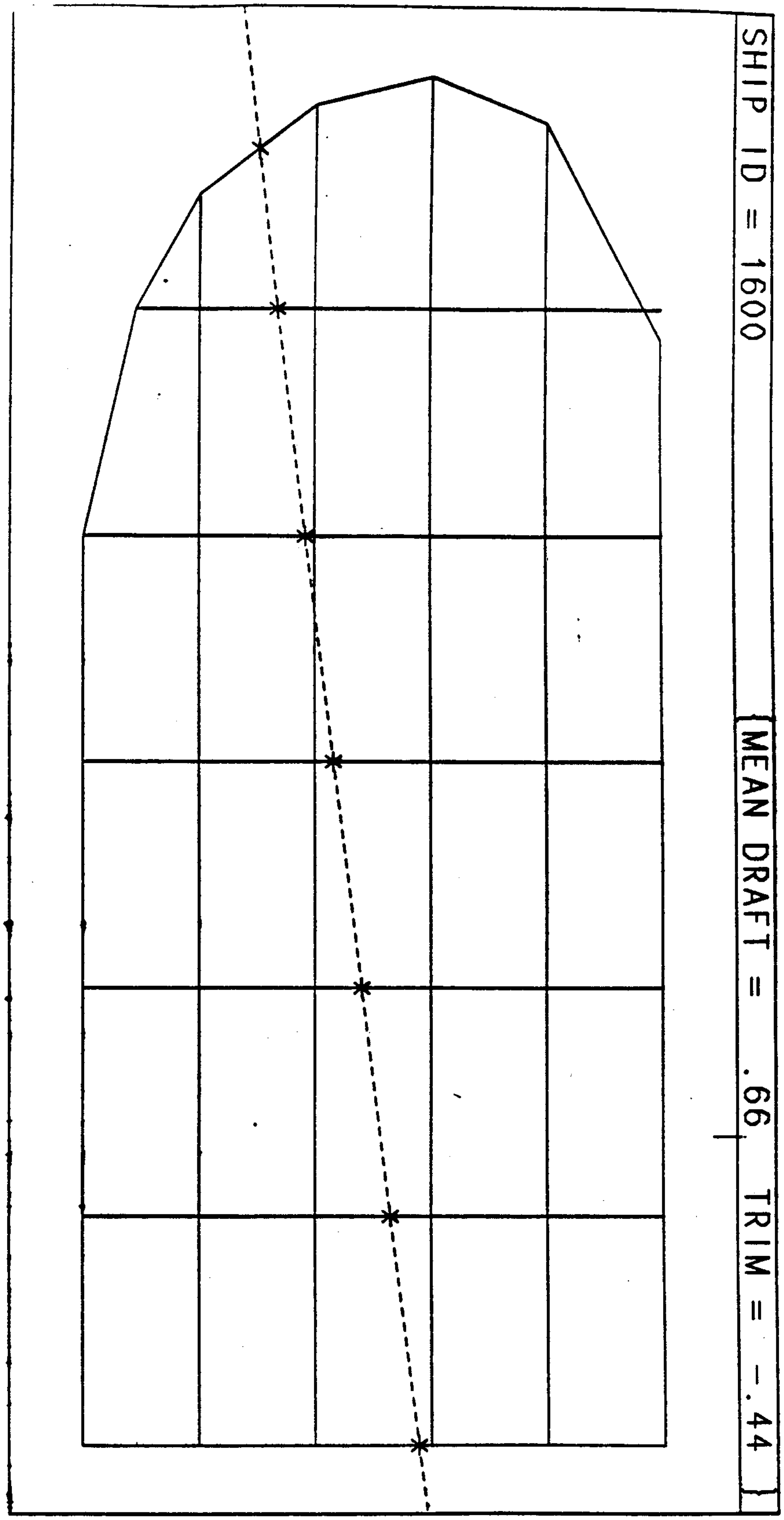

Figure 8.9 - Location of the Water Line on EGRESS

Forward Draft	0.436 m
Aft Draft	0.881 m
Trim	-0.445 m
Wetted area	6.962 m
Mean Draft	0.659 m
Longitudinal Center of Buoyancy	0.609 m
Vertical Center of Buoyancy	0.406 m

Figure 8.10 - EGRESS Static Stability Data

8.6 Total Evacuation Recovery

In the event of a complete space station evacuation, Design Reference Mission 2, recovery forces must be able to accommodate 8 people and 2 EGRESS vehicles. Each primary landing site has sufficient forces for this type of recovery. If the landing takes place at Kennedy, the transported Super Stallion will have to recover the vehicles in two trips. It is also possible to transport 2 Super Stallions to Kennedy to assure that a Super Stallion is available immediately upon impact.

The recovery procedures will not change. In this scenario, the second EGRESS vehicle will descend one orbit later than the first vehicle which will provide 1 1/2 hours between the two splashdowns. This time span will be enough to recover the first EGRESS vehicle before the second one splashes down.

Chapter 9

Logistics and Support

9.0 Summary

The Logistics and Support group had a wide range of responsibilities in Project EGRESS. The group was responsible for many of the interfaces between the EGRESS spacecraft and the Space Station, as well as the NSTS. These interfaces included the launch system interface, storage and maintenance of the vehicle, determination of the number of vehicles needed, and the placement of these vehicles on Space Station *Freedom* (SSF). Other issues addressed included impacts of EGRESS on the Space Station and its crew, such as crew training, docking/berthing, and maintenance checkups and schedules. The last area of responsibility included ground operations in which storage of the EGRESS ground fleet was determined and options for replacing the EGRESS vehicles on ground once the vehicles have been used.

The primary launch system for the EGRESS craft was specified by the RFP to be the NSTS, which placed certain requirements on dimensions and possible outer configurations for placement in the payload bay. If the space shuttle were unavailable, a back up system in the form of an expendable booster was also considered. The Martin-Marietta Titan III was the most cost effective alternative and met all the necessary specifications.

To minimize the effects of contaminants in the environment aboard the vehicle, as well as other primary sources of failure in equipment [9-1], the vehicle will be placed in a dormant state while on-orbit with its hatch closed. Remote controlled diagnostic tests will be run periodically to detect any failure in the systems and results will be sent to ground control for analysis. Extensive maintenance check-ups will be performed semi-annually for a complete inspection of all the components aboard EGRESS.

In order to determine the number of vehicles that would be needed both in-orbit and on ground, certain requirements were considered, such as crew evacuation capability and support from the ground fleet. Space Station will have two vehicles, while four vehicles on the ground would provide both support and redundancy with back-up craft, as well as the capability to easily update certain systems in the spacecraft on the ground. The two vehicles aboard SSF will be placed at nodes 1 and 2 of the Space Station, resulting in ease of departure from the station and minimum interference to the Space Station operations.

Since the EGRESS vehicle will be docked on Space Station *Freedom*, it will impact the station and crew in many ways including docking/berthing, crew training and station drills. The procedure for docking the EGRESS vehicle will be handled completely by remote manipulator arms of the Space Station . The vehicle will be extracted from the shuttle cargo bay by the Space Station's Remote Manipulator System (RMS) which will place the vehicle in its proper location on the station. To minimize the impact of crew training, all initial training will be performed on ground, including pilot training, maintenance and checkout procedures, and also training for basic repairs of the EGRESS vehicle systems.

The last area of responsibility for the Logistics and Support Group was ground operations. Ground operations are needed to support the craft while on-orbit. Areas of ground operations include storage on ground, mission control, and post recovery operations. Since there will be four on-ground spares for the EGRESS vehicle, an EGRESS operations center was suggested to house the ground fleet as well as any spare parts and official documentation pertaining to the EGRESS project. In the event an EGRESS vehicle is used and a replacement needs to be sent in its place, the issue of replacing the ground spare was also considered. Extensive research showed that the most cost effective alternative for replacement for the ground spare would be the construction of a new EGRESS vehicle which would reuse of any properly functioning subsystems from the used vehicle.

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9.1 Launch Systems Interface

The EGRESS vehicle will need some means of transport from ground to the Space Station. The RFP requires that the primary method of transport be the NSTS [9-3], therefore the vehicle must meet certain specifications to fit inside the shuttle cargo bay including size and weight. An alternate launch system in the form of an expendable booster was also considered in the case that the shuttle is unavailable.

9.1.1 Space Shuttle

In order to minimize external configurations on the EGRESS vehicle, the vehicle will be mounted in the shuttle cargo bay in a cradle-like device in accordance with NSTS specifications (see Section 2.4). The vehicle, in its cradle, will be placed at the aft cargo joists, as seen in Fig. 9.1. This will place the center of gravity of the entire payload in the proper position for a launch, in accordance with NSTS cargo requirements [9-5].

After being processed for launch at the vertical processing facility at Kennedy Space Center, the EGRESS vehicle will be inserted into the payload bay when the shuttle is in the vertical position. Due to the NASA cargo requirements, large amounts of fuel for extended periods aboard the shuttle are considered dangerous. Vertical insertion of the EGRESS vehicle is therefore preferred since insertion is done much closer to launch time thereby reducing risk. The fuel of EGRESS is the same as the fuel of the OMV, which will also be launched by the shuttle.

Another reason for using vertical insertion is that it can be done when the shuttle is on the launch pad; thus the vehicle could be sent to the Space Station with a shorter lead time than would be possible with horizontal insertion. For instance, if a shuttle were on the launch pad and ready to go and it became necessary to send a replacement vehicle to the Space Station, the payload aboard the shuttle could be taken out and EGRESS could be vertically installed. If the vehicle was designed such that it had to be inserted horizontally into the payload bay, insertion would have to be done before the shuttle is attached to its external tank and solid rocket boosters which would mean a considerable delay before launch. In any case, vertical change-out must be completed no less than 49 hours before NSTS lift-off to ensure on-time lift-off [9-4].

The cost of launching the EGRESS vehicle on the NSTS is determined by considerations of the weight and the length of the vehicle. The impact that the vehicle or length has on price is determined by load factors. These factors are determined as follows [9-6]:

$$\text{Weight Load Factor} = \text{Weight of Vehicle} / 65{,}000 \text{ lbs.} \tag{9-1}$$

$$\text{Length Load Factor} = \text{Length of Vehicle} / 720 \text{ in.} \tag{9-2}$$

The large load factor is then divided by 0.75 to determine the cost factor. This cost factor is multiplied by \$74 million, the cost for a dedicated shuttle flight (FY 1988 dollars).

$$\text{Cost} = (\text{Load Factor} / 0.75) * \$74 \text{ million} \tag{9-3}$$

The weight of the total vehicle assembly, including airlock, is 13,300 pounds. The total length of the assembly is 291 inches. Thus, the weight load factor is 0.205 and the length load factor is 0.404. Since the length load factor is higher, it determines the cost which is \$39.9 million for the complete EGRESS system.

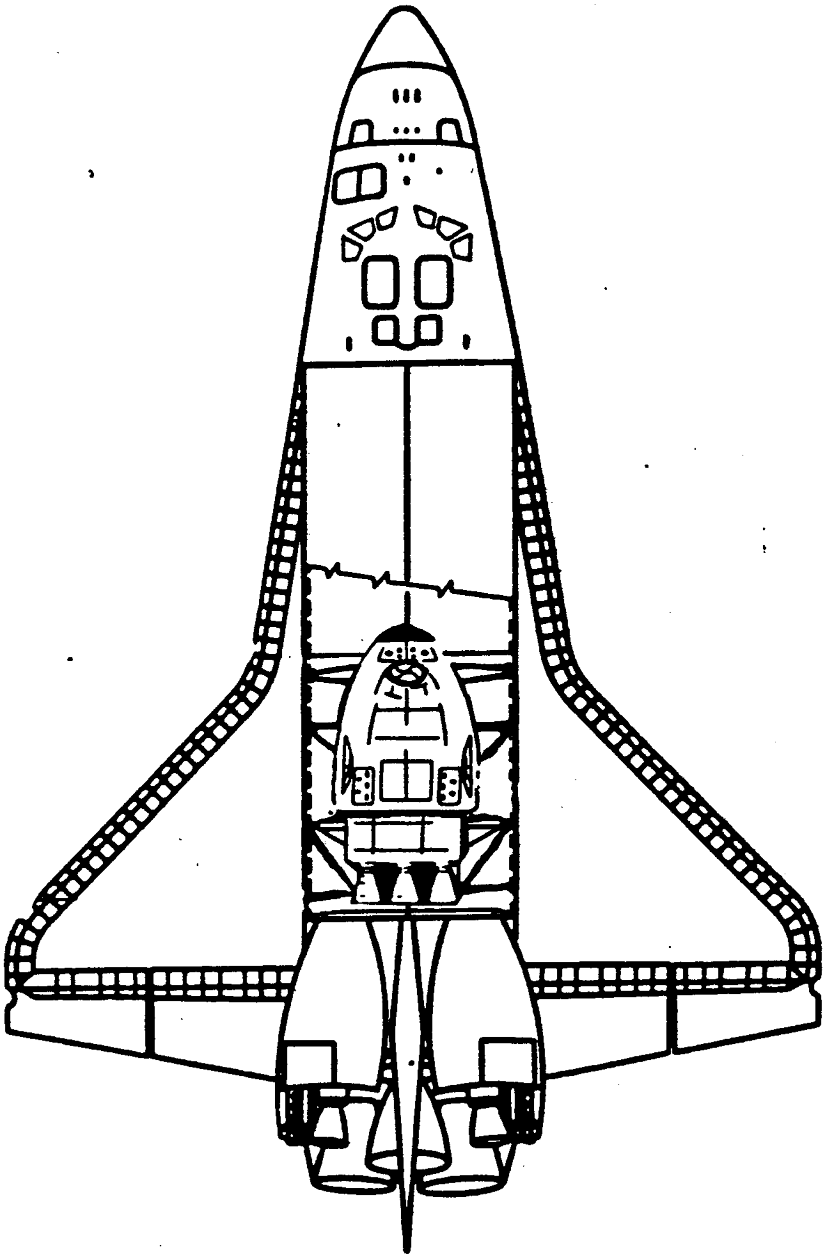

Figure 9.1 - Placement of the Project EGRESS Vehicle in the Space Shuttle Cargo Bay

9.1.2 Alternate Launch Vehicle

Although the NSTS is the primary launch system for the EGRESS vehicle, an alternate launch system was also considered in the event the shuttle is unavailable. Certain requirements had to be met by the expendable launch vehicle (ELV), such as payload weight to LEO, core diameter and the RFP request of only current available boosters [9-3]. Since the entire EGRESS configuration has been designed to have a width of 9 ft. and weigh over 10,000 lbs., the choices for an alternate launch vehicle were limited to the Martin-Marietta TITAN family of rocket boosters. The TITAN III and TITAN IV rockets were both found to meet the requirements for the alternate launch vehicle as shown below [9-7, 9-8]. Both vehicles meet payload as well as core diameter requirements.

TITAN III	**TITAN IV**
• 31,900 lbs. to LEO	• 40,000 lbs. to LEO
• 10 ft. core diameter	• 10 ft. core diameter
• Full scale future production	• Full scale future production
• $95+ million per launch	• $212+ million per launch
• KSC launch capability	• KSC launch capability

Both vehicles are capable and currently available; however, the lower cost estimates of the TITAN III rocket made it preferable as a back-up launch system for the EGRESS spacecraft, which can be seen in Fig 9.2.

9.2 On Station Procedures

Since EGRESS will have a lifespan of 30 years [9-3], proper storage and maintenance is crucial in order to assure its reliability and long-term operability. Each of the systems on board the EGRESS vehicle will need to be designed to survive for an extended period of time under orbital conditions and the environment must also be kept free from excessive moisture and contaminants that could degrade the performance and reliability of the systems on EGRESS.

9.2.1 On Station Storage

In order to ensure the reliability of the EGRESS vehicle, possible sources of problems in equipment must be minimized. The primary causes of equipment failure can be categorized as follows [9-1] :

- Human intervention: Frequent operation and testing of equipment greatly increases the probability of failure of a system.

- Environmental influences: Moisture, heat and corrosive elements are primary causes of failure induced by the environment. Connectors, switches, and other components involving mechanical contact for operation are most commonly effected.

- Undetected design or manufacturing defects.

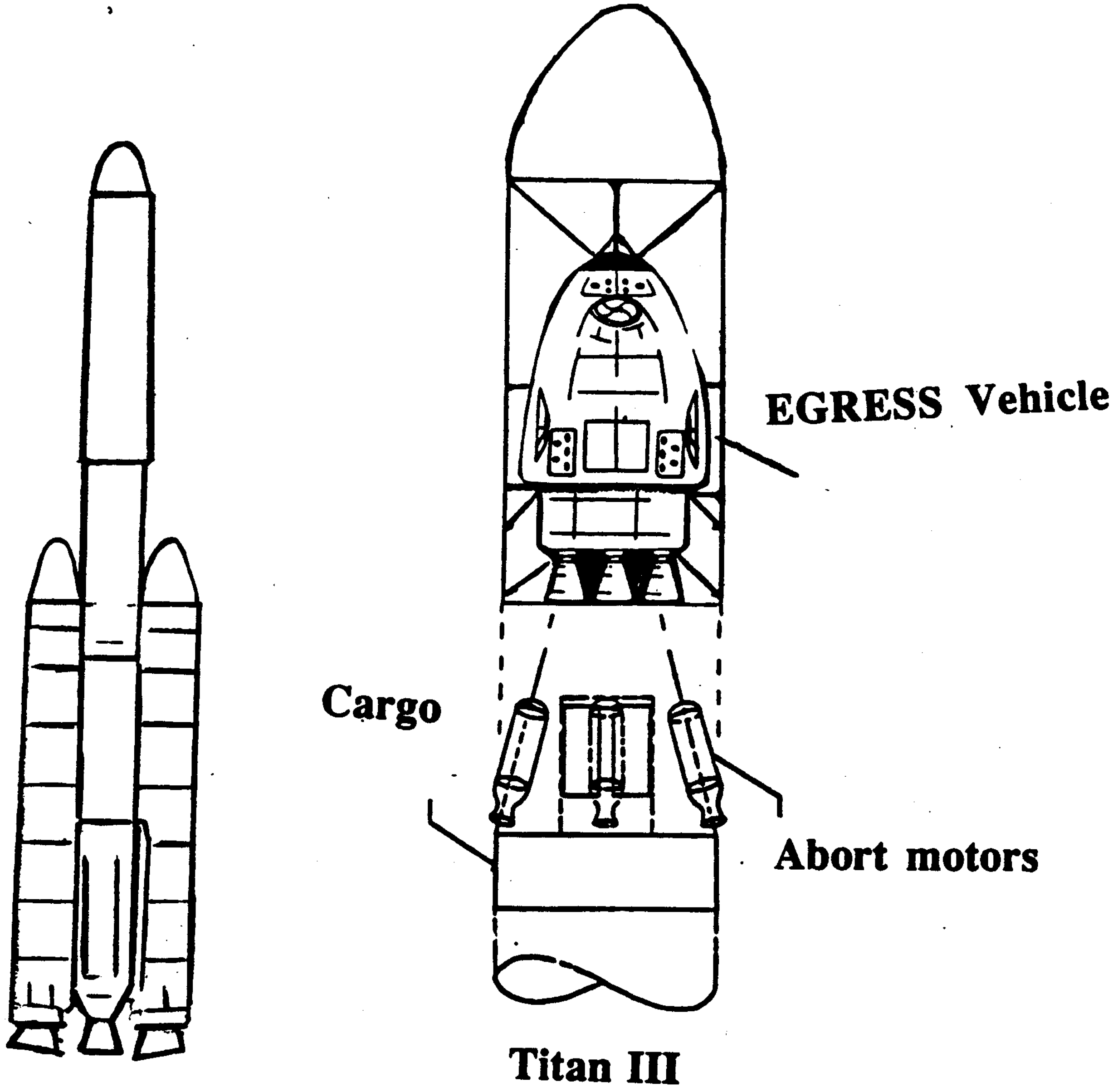

Figure 9.2 - Project EGRESS Alternate Launch Vehicle : Martin-Marietta Titan III

Although manufacturing and design defects can not be prevented, the other causes of failure can be minimized by keeping the environment free of contaminants and reducing operation and testing to a minimum. To ensure these conditions, EGRESS will be placed in a dormant state on the Space Station with the hatch closed at all times.

The environment inside the EGRESS vehicle will be maintained passively while in a dormant state. The cabin will be pressurized to the same level as the SSF allowing for rapid entry into the vehicle when needed. To minimize the effects of moisture and other contaminants on the avionics systems, the systems will be placed in moisture resistant containers which can be opened for maintenance access and which will have a built in moisture- absorptive chamber to dehydrate the system after EGRESS is returned to its dormant state. Desiccant packages will also be placed in the crew compartment to control the amount of moisture in the cabin area. These may be replaced each time the vehicle returns to its dormant state.

9.2.2 Maintenance

Maintenance of the EGRESS spacecraft is necessary to ensure it remains fully operational at all times. Since manpower aboard the Space Station will be at a premium, regular maintenance must require minimal crew involvement. Maintenance aboard the EGRESS vehicle can be grouped into three main categories: On-orbit maintenance, routine ground maintenance cycle, and information management.

9.2.2.1 On-Orbit Maintenance

In order to minimize the impact of regular maintenance of the EGRESS vehicle on the Space Station and its crew, remote controlled diagnostic tests will be run on all major components of EGRESS once each month to detect faults or failures in the systems. Activation of the remote testing will be controlled by Space Station personnel. Systems that can not be activated except for actual use, such as RCS jets, will be provided with passive indicators to show operational status, such as pressure gauges on gas tanks. A separate rechargeable battery supply will be used to power the system and will be located outside the spacecraft in the adjoining airlock. The battery supply will be recharged when the SSF is running below maximum power. Every six months extensive maintenance tests, including a visual inspection, will be performed by the Space Station crew members on the EGRESS vehicle in order to assure that all systems are operating properly. Personnel will enter the vehicle and check all systems manually, going through normal procedures that would bring the vehicle to operational status. These procedures will be discussed in sec. 9.2.3.

In the event a fault is detected, corrective maintenance will need to be performed. If the problem is not complex and the necessary equipment is available, a Space Station crew member will fix the problem; otherwise, fly-in personnel and equipment on routine shuttle flights will be used .

9.2.2.2 Routine Ground Maintenance Cycle

To assess the long term on-orbit stay capability of the EGRESS vehicle and its subsystems, a periodic ground maintenance cycle is necessary. The first period of the ground maintenance cycle will be two years. Evaluation of the EGRESS vehicle will include assessment of long-term exposure of the thermal protection system (TPS) to the space environment, as well as the effects of long-term stay in LEO on the other vehicle components. The EGRESS vehicle will return home aboard the NSTS following a replacement with a ground spare. Routine ground maintenance will also include replacement of any limited life consumables (such as batteries), updating hardware to conform to any design changes or improvements, and repairs to any degraded components. The fuel tanks for the engines, as well as the attitude control thrusters and lines, will be checked for bleed-off and leakage, and testing and verification for flight reuse will also be performed. After evaluation and possible refurbishment of the vehicle and its subsystems, the vehicle will be placed in storage at KSC along with the other EGRESS ground fleet. After the vehicle has been evaluated, and if trend analysis indicates that the vehicle is capable of a longer stay on orbit, the time between ground evaluations will be extended to four years.

9.2.2.3 Information Management

Storage and updating of procedures and information will also be needed to support the maintenance of the EGRESS vehicle. Maintenance procedures and manuals, which include a configuration drawing of the vehicle and location of the main subsystems, will be kept and updated after every maintenance check. Schedules, parts history and any system upgrades will also be logged.

9.2.3 Check-out Procedure

During operational start-up, it will be necessary to perform a checkout procedure to verify that the subsystems of the vehicle are operational. This procedure will entail entering the EGRESS vehicle and testing and verification of all systems to insure that they are working properly. Before entering the vehicle, the environment will be checked to insure that it has the proper composition, temperature and pressure. After entering the vehicle, a completed systems check will be performed by members of the Space Station crew. The checkout will included the following:

- Establishing communications with the ground and station to make sure communication systems are functioning properly.
- Power check to make sure that the batteries are at full charge.
- Computer diagnostics program will be run.
- Life support systems check.
- Propulsion check to make sure fuel is at pressure and and check possible fuel bleed off as well as conduct a pressure-test for fuel line integrity.
- Medical systems check to insure that equipment is operational.
- Instrumentation check to see if instruments and displays are functioning properly.

This checkout procedure will also be used for the 6 month maintenance cycle and will include check of medical supplies and consumables. After the checkout is completed, the hatch will be closed and the EGRESS vehicle will be returned to its dormant state.

9.3 Number and Placement of Vehicles on Station *Freedom*

In order to determine the number of vehicles and the placement of these on Space Station *Freedom*, certain factors must be taken into consideration, such as the number of crew members on the Space Station and the size of the support fleet on the ground. The total fleet must be able to support any mission requirements aboard the station and provide back-up vehicles when needed. Placement of the vehicles on the station must meet the following criteria

- single axis of departure from the Space Station
- no impact on Space Station operations
- using only those ports which are not already occupied by other systems

9.3.1 Number of Vehicles

In order to determine how many vehicles need to be initially produced, several aspects need to be considered, including the number of vehicles to be on the Space Station as well as the number of extra vehicles needed on ground to support those on the station.

9.3.1.1 Number of Vehicles on the Space Station

The RFP requires for a minimum of two vehicles aboard the Space Station [9-3]. In addition, the vehicles placed on SSF must be capable of evacuating the entire crew in case of a station-wide emergency. The RFP states that the total crew of the station is eight people [9-3]. Lastly, the normal crew for a medical emergency will be three people : a pilot, a medical technician, and the seriously ill or injured crew member.

The final decision was to place two vehicles on the Space Station with each vehicle having the capability of transporting up to five crew members. In case of a total crew evacuation, four people could be placed in each vehicle, or three in one and five in the other. Two vehicles would also provide the capability for a total crew evacuation after a medical emergency mission has used one vehicle while leaving five crew aboard the Space Station.

Another driving factor for having only two vehicles is that there are only a limited number of available docking ports on SSF. This fact will be covered in greater detail in sec. 9.3.2.

9.3.1.2 Number of Vehicles on the Ground

In addition to the vehicles placed on the Space Station, there must be a certain number of vehicles on the ground to immediately replace or augment the vehicles on SSF should the need arise. At least two vehicles are needed on the ground to support the two on-orbit; this would allow the use of one of the vehicles from the Space Station which would be replaced with one vehicle from the ground, leaving another in the ground fleet to support those on-orbit.

The ground fleet was expanded to four in order to improve our capability to serve the Space Station in a number of ways. First, if both vehicles on the Space Station are used they could be replaced immediately by two from the ground and still leave two additional vehicles to support those at the station. Secondly, with four vehicles in the ground fleet, certain systems could be updated on two of the vehicles while keeping two other vehicles ready for launch if needed, providing the capacity to update critical systems without compromising a potential mission of the EGRESS.

While the four ground vehicles may cost more than two vehicles initially, the total cost was deemed to be lower as initial production costs are lower than restarting or retooling production lines at a later time. Producing more than four vehicles was considered to be impractical and uneconomical, since there is no way to determine, at this time, how many times the EGRESS vehicle will be used over the life of the station.

9.3.2 Placement of Vehicles on the Space Station

The first step in determining a location for the vehicles was the identification of ports on the Space Station which were already occupied. Fig. 9.3 shows the Space Station habitation modules and has the docking ports labeled 1 through 9. Ports 3 and 6 are reserved for NSTS docking, and port 8 is an alternate location for Freedom's logistics module. Ports 1, 2, 4 and 5 were considered less desirable due to their proximity to the shuttle docking locations. Vehicles placed on these ports might interfere with the loading and unloading of payloads from the shuttle's cargo bay. In addition, vehicles placed at these locations would interfere with the field of vision from the cupolas, which will be the workstations from which Freedom's remote manipulator system will be operated. Thus ports 7 and 9, on nodes 1 and 2, were chosen for EGRESS placement. The vehicles are shown in their proper locations in Fig. 9.4.

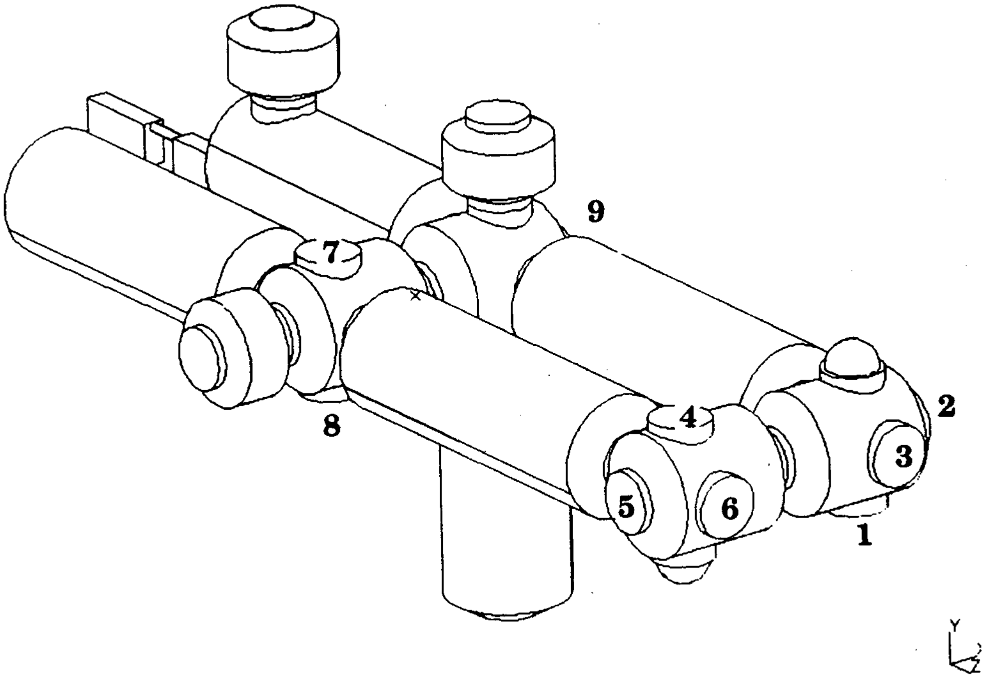

Figure 9.3 - Numbered Docking Ports on Space Station *Freedom*

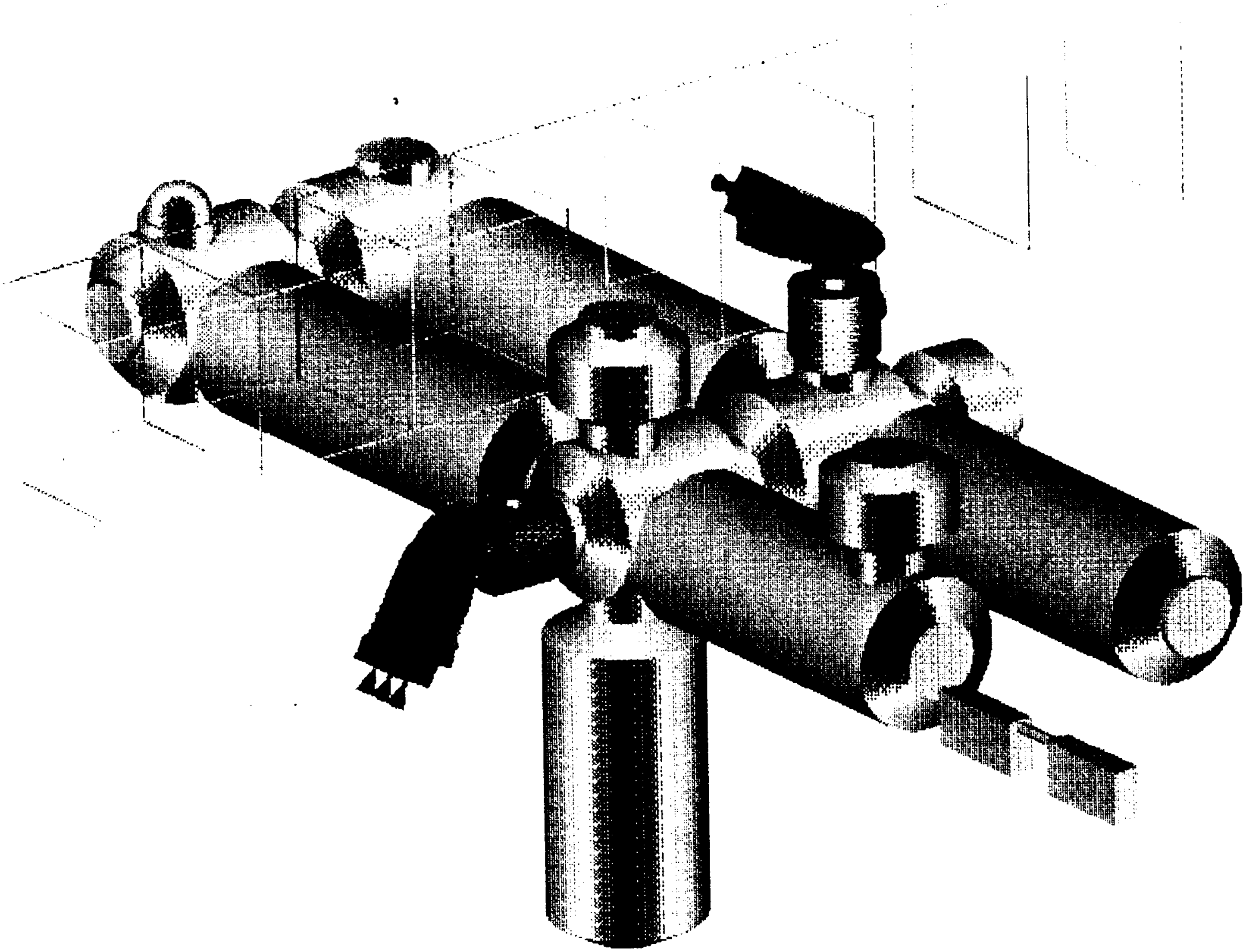

Figure 9.4 - Placement of Vehicles on *Freedom*

The problem with these two ports is that they face in two different directions, 90 degrees apart. Departure straight up from port 7 was considered the optimum departure trajectory, so a method was needed to allow the vehicle on port 9 to depart in the same direction without any maneuvering near the Space Station. The solution was to include a retractable docking ring as part of the EGRESS airlock design. (See Section 2.2) This will allow the vehicle to float free from the Space Station before it's cold gas thrusters are activated. Thus, the vehicle does not have to depart in the direction that port 9 is facing, as shown in Fig. 9.5

The EGRESS vehicle placement should not adversely affect the station's center of gravity, or its microgravity environment. The craft's central location on nodes one and two assures that the center of gravity will not be largely affected. The vehicles will also be placed on opposing halves of the station. This was originally to uphold the "safe haven" concept in which both sides would be accessible to a craft, but has the added advantage of loading the station symmetrically.

Preliminary studies indicate that any node placement configuration will not affect the microgravity environment due to stored momentum [9-7]. However, docking and berthing of either the EGRESS vehicle of the NSTS could have adverse effects on the microgravity environment and special caution should be taken when docking and berthing occurs, especially when performing any experiments aboard the Space Station.

9.4 Space Station Impacts

Since the EGRESS vehicle will be docked on the Space Station it will have several impacts on the station and crew. These impacts include docking and berthing, crew training and station drills as well as storage of any replacement items for the EGRESS vehicle. The goal was to minimize these impacts.

9.4.1 Docking Procedures

Under normal conditions, the Remote Manipulator System (RMS) on the Space Station will be used to extract EGRESS from the NSTS payload bay and attach it to the station, as depicted in Fig. 9.6. Alternately, it is possible to use the shuttle's manipulator arm to extract the vehicle from the shuttle, and then hand the vehicle to the station's arm which would then place the vehicle in it's final position on the station. However, the station arm is long enough to perform both the extraction and placement procedures so that no hand off procedure would be necessary. The use of the single RMS eliminates the need for complicated coordination of the arms as well as the need for two grappling fixtures on the EGRESS vehicle itself.

In the case of an aborted mission, there are two possible redocking scenarios. First, if there are still crew members on board *Freedom*, the Space Station's arm can perform the redocking in the same manner as original placement. If the total crew has been evacuated, and redocking is necessary, the vehicle's RCS jets will have to be used to maneuver the vehicle into position. This is not considered a normal situation, and will only be done if absolutely necessary; there are concerns that use of RCS jets so close to the Space Station could damage the Station.

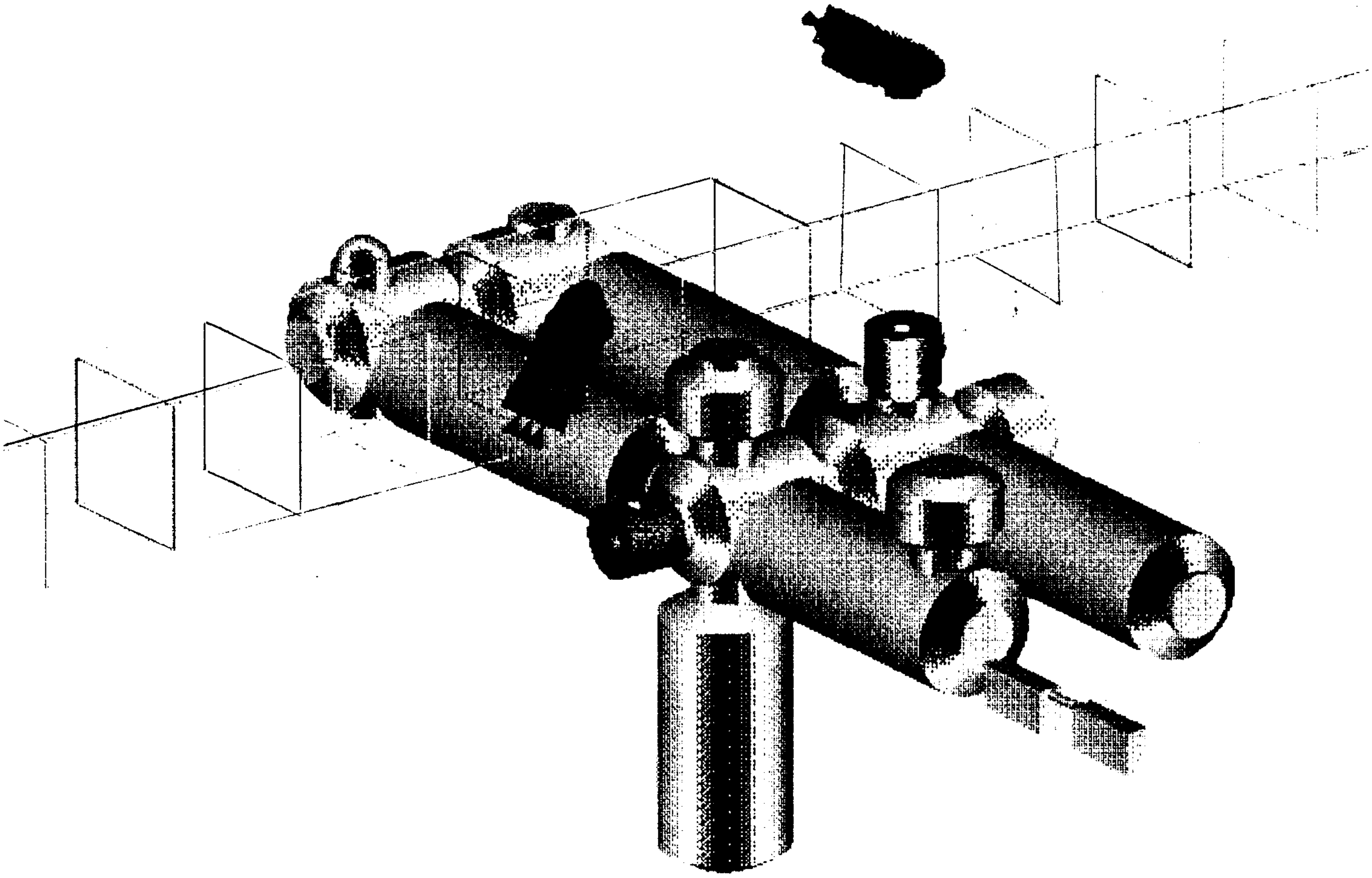

Figure 9.5 - Departure from Space Station *Freedom*

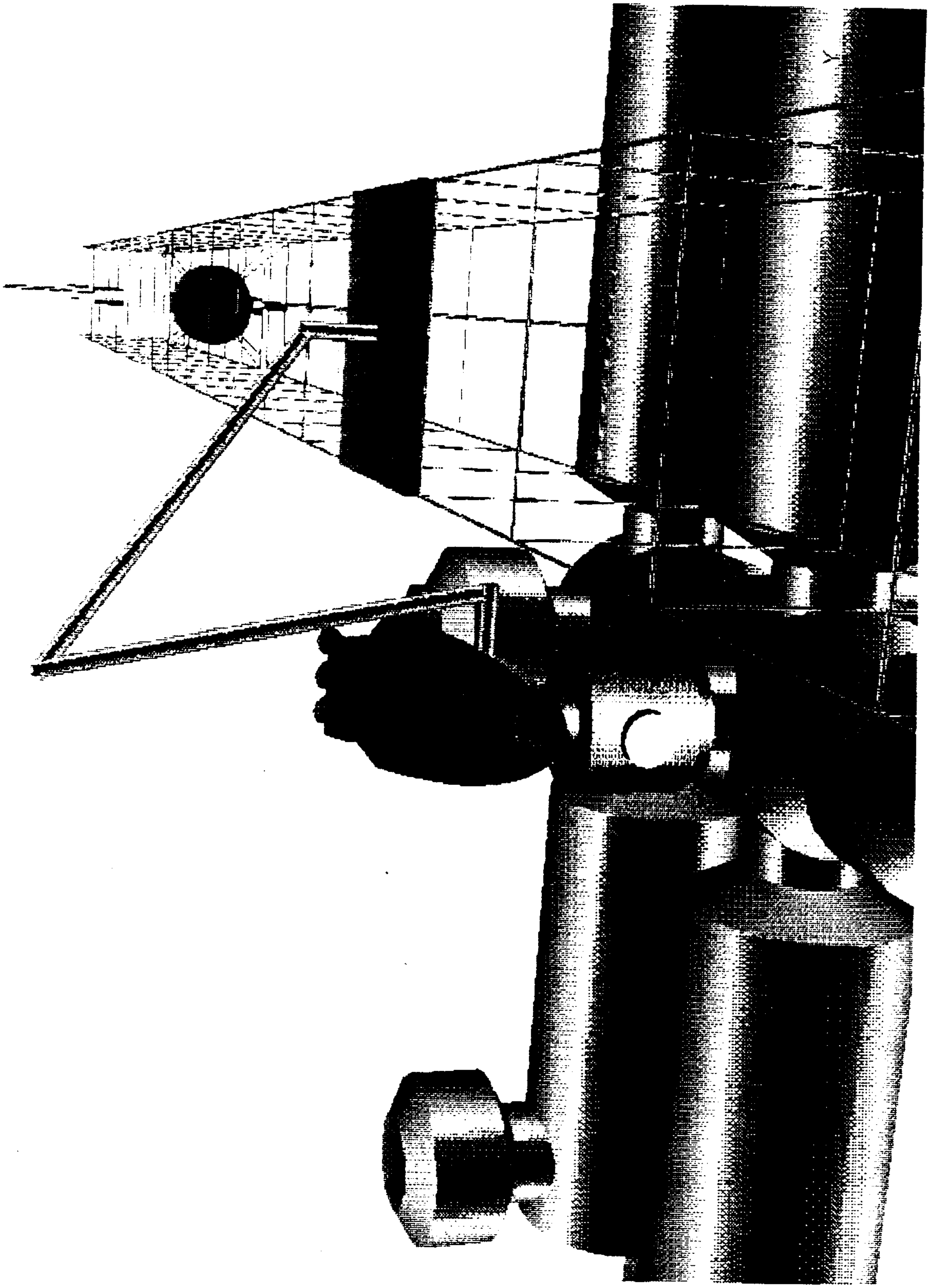

Figure 9.6 - Docking of the EGRESS Vehicle using *Freedom's* RMS

9.4.2 Crew Training

In order to minimize crew training aboard Space Station *Freedom*, all initial training will be performed on ground with a proposed mock-up of an EGRESS to familiarize the pilot and crew with the vehicle systems and its internal configuration. Training will include piloting and navigation as well as use of all other systems on board the EGRESS vehicle. Pilot training will also include the familiarization with the back-up manual system. Basic repairs of the vehicle's main systems, maintenance and checkout procedures will also be covered.

The Apollo training program was considered a model program since the EGRESS vehicle most resembles the Apollo craft in design than any other NASA spacecraft. The Apollo training program consisted of three main phases [9-9]:

- Basic systems familiarization and crew tasks
- Mission simulation
- Integrated simulation

In order to learn the EGRESS procedures, the Space Shuttle crew will undergo Apollo-type simulator training for the EGRESS in addition to normal training. Each phase of training consisted of 1 hour oral briefings and 3 hour simulator exercises. The total training time was 200 hours of simulator exercises and 60 hour of briefings. The simulators were used for entry, rendezvous, and docking practice and were also used to simulate emergency situations. Thus, an EGRESS simulator environment must be designed and constructed for this training.

Periodic on-orbit training will also be needed for the crew to a maintain basic knowledge of the operational procedures of the EGRESS vehicle. Subsequent pilot training will also be needed to insure proficiency in the manual back-up system and maintain pilot familiarity with the cockpit. A simulator for piloting the vehicle should be provided aboard *Freedom* . Manuals and configuration drawings of the vehicle will also need to be available on the station for maintenance checkout and in case simple repairs are needed.

9.4.3 Station Drills

Emergency drills for the EGRESS spacecraft will be necessary aboard Space Station *Freedom* to insure proficiency of the crew in case of a true emergency. The scenario for these drills should be the design reference mission for a complete Space Station evacuation, since a medical emergency would not involve every member of the station crew, and leaving due to NSTS interruption would not involve time constraints. By practicing for evacuation, elements from all three reference missions will be included, although medical staff will need to keep proficient in the procedure for a seriously ill or injured crew member.

To minimize the impact of station drills on the crew, drills should be conducted at intervals between two and four weeks [9-10]. This would allow for at least three drills during a 90 day period which will be the average on-orbit stay for the Space Station crew [9-3]. Crew aboard the station should be assigned a particular vehicle either based on their location of work or immediate proximity to the vehicle. This would prevent any confusion in the case of an actual emergency.

The drill would commence with the sounding of an alarm, after which all crew members would proceed to their designated craft. Instead of entering the vehicle, the crew would meet in front of the airlock leading to the craft, so as to not disturb its dormant state. The pilot should orally go over procedures involving entry, power-up and other responsibilities shared by the crew including basic departure procedures. A configuration drawing of the cabin compartment should also be available so that the crew may refamiliarize themselves with inner configuration of the craft. The drill will not last more than 15-20 minutes, to minimize impact on the Space Station.

9.4.4 Storage of Replacement Parts

In order to minimize the impact of storage of replacement parts for the EGRESS vehicle on the Space Station, spare parts will be kept to a minimum. Preliminary studies have shown that *Freedom* will store replacements for approximately 10% of the installed equipment, in mass and volume, aboard the station [9-11]. Storage of any critical spare items for the EGRESS vehicle will be kept in the logistics module or aboard the vehicle. Other replacement parts will be stored and tracked on the ground and will be sent up in the shuttle when needed.

9.5 Ground Operations

Ground operations will be required to support the EGRESS vehicle while on-orbit. Ground operations will include storage of the vehicles on ground, responsibilities of mission control, and also replacement of the ground fleet once an EGRESS vehicle has been used.

9.5.1 Storage of Vehicles on Ground

Due to the fact that there will be four vehicles stationed on the ground, and that the vehicles placed on the Space Station will need regular maintenance on the ground, it is suggested that an EGRESS operations center be built to house and store the vehicles and any spare parts that are needed. Such a building would also conduct all vehicle ground maintenance and provide a location to store all official documents and paperwork that will be devoted to Project EGRESS. In addition, if the EGRESS vehicle is ever used, such a building would provide a location for post-flight analysis of the vehicle so that performance data could be gathered for future vehicle improvements. Ideally, such a building would be located near the Vertical Processing Facility at Kennedy Space Center.

9.5.2 Mission Control

The RFP does not allow for special facilities to be built to serve as mission control for Project EGRESS [9-3]. As a result, ground control will be handled from the mission control center used for the Space Station. Similar the the shuttle mission control, EGRESS control will be handled by a staff of ground officers with the responsibility for the mission.

These will include, but not necessarily be limited to, the positions listed below All of these positions would be filled from either normal Space Station ground operations staff or any back-up personnel stationed at ground control.

- Flight Director,responsible for overall EGRESS mission and all decisions concerning safe expedient flight conduct.
- Spacecraft Communicator, will serve as the primary communicator between ground control and EGRESS crew.
- Flight Dynamics Officer, responsible for planning all maneuvers and monitoring trajectories along with the Guidance Officer.
- Guidance Officer, monitors all on-board navigation and on-board guidance computer software.
- Flight Surgeon, responsible for monitoring patient status along with instructing and assisting the on-board medical technician.
- Propulsion Systems Engineer, responsible for monitoring all propulsion functions during all phases of phases.
- Guidance, Navigation and Control Systems Engineer, responsible for monitoring all vehicle GNC systems, notifying Flight Director and crew of impending abort situations or guidance malfunctions.
- Electrical & Environmental Engineer, monitors all power levels and environmental systems during the flight.
- Instrumentation and Communication Systems Engineer, plans and monitors all in-flight communications and instrumentation configurations.

9.5.3 Replacing the Ground Fleet

In the event that an EGRESS spacecraft is used, a replacement vehicle will be sent to Space Station. This replacement will come from the ground fleet; thus, the issue of replacement for the ground fleet needs to be addressed. Three possible options exist for the replacement of EGRESS vehicle ground spare :

- Refurbishment of the used vehicle
- Construction of a new EGRESS vehicle from scratch.
- Cannibalization of the used craft in constructing the ground replacement.

According to a preliminary cost analysis for refurbishment an EGRESS vehicle [9-7], the cost for refurbishment is nearly 20 % lower that the cost of building a new vehicle; however, because the vehicle will have a water landing other considerations had to be taken into account. The NASA policy for a water landing vehicle is not to reuse the craft after landing [9-2]. NASA considered the reusability of the Gemini spacecraft but decided against it since the cost and time for the extensive testing and the manhours necessary to insure the craft's structural integrity and reliability after splashdown was deemed unreasonable.

Studies showed that the most cost effective alternative remaining would be to cannibalize all reusable systems in the used vehicle to build the new ground spare. Although most of the EGRESS spacecraft will not be salvageable, certain systems inside the vehicle could be reused. However, since the craft will sit low in the water, water may spill into the cabin compartment damaging many of the systems inside the cabin area. To minimize water entry the hatch can remain closed until the crew must exit the vehicle.

The main deorbit fuel-oxidizer propulsion pack will be jettisoned, retrieved in orbit, and possibly brought back to ground in the shuttle where it would be refurbished and reused. Attitude thrusters and separation burners will not be reusable due to salt water contamination. The displays and readouts may be damaged by the salt water contamination; however, the main computers, which contain the navigation, flight operations, communications as well as ECLSS, will be sealed from the pressurized interior of the vehicle and will thus be protected from possible water damage. The parachutes used in the landing will be reusable with only minimal cleaning required. Testing and verification will need to be performed on all reusable systems to insure no damage was sustained during landing. If the systems check out then they will be used in the construction of a new EGRESS vehicle.

Chapter 10

Conclusion

10.0 Summary

Project EGRESS has designed a craft that meets the requirements of Johnson Space Center's Request for Proposal. In addition to the design, it was important to analyze the development and production costs of the EGRESS, as well as identify fields where further research is necessary. This section details these two additional areas of concern.

EGRESS will cost under $30 million to design and produce a single vehicle. With a total of six vehicles built, including two to be stationed on the Space Station, total production and delivery costs will be $257 million.

Three primary areas have been identified as needing further research. First, since the EGRESS will spend at least 2 years in the space environment, the effects of long duration exposure on structural strength and life support systems must be determined. Second, procedures must be developed for retrieving the jettisonable propulsion pack after the deorbit burn. Third, the dynamic stability of the EGRESS within the supersonic flight regime must be addressed.

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10.1 Cost Analysis

Cost Analysis is often the most difficult portion of any research project. At the conclusion of Project EGRESS, the team began the process of cost analysis of the vehicle. What follows is a preliminary cost analysis for one EGRESS vehicle:

TOTAL COST OF ONE EGRESS		29.5
PROPULSION		5.7
ENGINES	2.5	
THRUSTERS	3.5	
PROPELLENT TANKS AND BLADDERS	0.1	
PROPELLANT	0.1	
THERMAL PROTECTION SYSTEM		1.0
HRSI	0.7	
AFRSI	0.3	
LIFE SUPPORT SYSTEMS		1.0
STORAGE AND REGULATION OF ATMOSHPERE TANKS	0.3	
MEDICAL EQUIPMENT	0.5	
GENERAL PROVISIONS	0.2	
INTERIOR CONFIGURATION		1.5
DECELERATION SYSTEM AND RECOVERY OF VEHILCE		4.3
POWER AND COMMUNICATIONS		12.0
VEHICLE STRUCTURE		4.0

Figure 10.1 - Cost Breakdown of One EGRESS Vehicle in Millions of Dollars Fiscal 1989

The Life Support Systems include the storage and regulation of the internal atmosphere of the EGRESS vehicle, medical equipment, and general provisions. To storage and regulate the oxygen and nitrogen EGRESS will be equipped with tanks, regulators, sensors, and scrubbers. The medical equipment on board EGRESS will include: a ventilator, defibrillator, medication, and Intravenous device. And the general provisions for the EGRESS vehicle include a water tank, food, a waste management system, and a survival kit. The cost of the Life Support Systems is as follows:

The interior configuration of the vehicle includes the cost of two command couches, two jump seats, the stretcher, controls and displays, and the miscellaneous costs of configuring the interior of a space vehicle. The total for the interior of the EGRESS vehicle will be approximately $1.5 million.

In addition to the cost of constructing an EGRESS vehicle, there is the cost of launching the vehicle aboard the NSTS (Space Shuttle), which is $39.9 million. The cost for delivering one EGRESS vehicle to Space Station *Freedom* will be approximately $69.4 million. To construct six vehicles and deliver two of the vehicle to *Freedom* will cost::

SIX VEHICLES	177.0
LAUNCH OF TWO EGRESS VEHICLES ABOARD NSTS	79.8
PROJECT EGRESS TOTAL COST	256.8

Figure 10.5 - Cost Breakdown of Project EGRESS in Millions of Dollars Fiscal 1989

The goal of a simple and reliable vehicle has implications on the cost of the vehicle. The use of existing hardware will eliminate the need for Research and Development (R&D) from Project EGRESS.

10.2 Further Research

Research must be done in three areas. Long duration exposure of materials and man to the space environment must be analyzed, the implications of a jettisonable propulsion pack must be determined, and flight stability of the craft must be proven.

EGRESS is planned to spend up to two years in the environment of outer space. Unlike the satellites that have spent long periods in earth orbit, the EGRESS is designed to transport people, and must have higher standards of performance. Unfortunately, the effects of long exposure to the unusual radiation and micrometeorite debris of space are not well known, and this is cause for further research. For the attitude control and deorbit burn systems, EGRESS will store fuel which may be affected by radiation. The Thermal Protection System may also degrade due to radiation and micrometeorite impacts, although the EGRESS TPS was chosen because it was impervious to atomic oxygen. The atomic oxygen and radiation may alter the structural properties of the materials from which EGRESS is constructed. Hopefully, with the recent retrieval of the experimental Long Duration Exposure Facility, many of these questions will be answered. Other questions, such as the physiological and psychological effects of space on humans, may not be answered until Space Station *Freedom* becomes the first long term American structure in space. Because of these uncertainties, the first EGRESS will be returned from the Space Station after two years in order to assess long duration exposure effects.

EGRESS was designed with a jettisonable propulsion pack. After completing a deorbit burn in return mission from the Space Station, the propulsion pack would separate from EGRESS and enter a safe orbit. The details of the safe orbit, and the means of assuring that the propulsion pack will get there, must be defined. The jettisonable system was developed to minimize total cost of the EGRESS, since the propulsion pack may be reused.

The fuel systems may be recharged on the Space Station with fuel launched aboard the Shuttle or an expandable launch vehicle, or the pack may be loaded into the Shuttle and returned to earth for recharging. Procedures for retrieval and refurbishment of the pack must be defined.

Since nearly all of the flight of EGRESS through the atmosphere occurs in the hypersonic (M>5) regime, the flight analysis concentrated on that area. Nevertheless, for a few minutes before splashdown the EGRESS will fly in the supersonic and subsonic regimes, and the flight characteristics of the vehicle in these regimes must be addressed. Of primary importance is determining the stability of the craft in those few minutes before splashdown. Although EGRESS is known to be stable in hypersonic flight, the issue of dynamic stability in supersonic and subsonic flight has not been fully addressed.

ACKNOWLEDGEMENTS

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Appendix A

Provisions and Equipment

A-1 Medical

A-2 Life Support

A-3 General

CATAGORY	ITEM	QTY	UNIT WEIGHT (LBS)	TOTAL WEIGHT (LBS)	DIMENSIONS			UNIT VOLUME (CU. FT.)	TOTAL VOLUME (CU. FT.)
					L (INCHES)	W	H		
A-1 MEDICAL									
EQUIPMENT	DEFIBRILLATOR	1	20.00	20.00	5.6	10.0	18.4	0.600	0.600
	AIR MIXER	1	2.00	2.00	4.0	3.0	2.0	0.014	0.014
	VENTILATOR	1	4.50	4.50	4.0	5.0	6.0	0.069	0.069
	VITAL STATS MONITOR	1	16.94	16.94	8.6	12.4	5.0	0.308	0.308
	IV DELIVERY DEVICE	1	14.00	14.00	10.0	8.0	5.0	0.231	0.231
	D OXYGEN TANK	1	9.50	9.50	16.0	4.0	DIA	0.116	0.116
	BLOOD PRESSURE CUFF	1	0.64	0.64	6.0	3.0	3.0	0.031	0.031
	STETHESCOPE	1	0.21	0.21	8.0	3.0	1.0	0.014	0.014
	AMBU BAG AND CONNECTORS	1	2.09	2.09	12.0	5.0	DIA	0.136	0.136
	VENTILATOR CIRCUIT	1	0.66	0.66	5.0	8.0	DIA	0.145	0.145
	PATIENT OXYGEN MASK	1	1.10	1.10	5.0	4.0	3.0	0.035	0.035
	MAST PANTS	1	4.00	4.00	9.5	10.0	6.0	0.330	0.330
	VELCRO STORAGE POCKETS	10	0.20	2.00	6.0	3.0	6.0	0.063	0.625
	STORAGE BAG (FILLED)	1	1.00	1.00	24.0	12.0	12.0	2.000	2.000
	DRUG PACK BAG (FILLED)	1	0.50	0.50	14.0	8.0	4.0	0.259	0.259
SUPPLIES	LITER BAGS OF L.R. SOL.	2	2.30	4.60	10.0	3.0	2.0	0.071	0.141
	* IV CATHETERS, 21 GAUGE	4	0.01	0.03	4.0	3.0	1.0	0.002	0.007
	* NONVENTED I.V. SETS	2	0.08	0.15	6.0	2.5	1.5	0.007	0.013
	* NEEDLES, 18 GAUGE	10	0.00	0.03	3.0	3.5	0.8	0.000	0.005
	* SYRINGES, 10 CC	5	0.02	0.11	6.0	2.5	DIA	0.003	0.017
	* SYRINGES, 3 CC	5	0.01	0.04	5.0	1.5	DIA	0.001	0.005
	* STERILE 4X4 GAUZE	10	0.01	0.13	6.0	6.0	2.0	0.004	0.042
	* ALCOHOL PREP PADS	21	0.00	0.07	6.0	2.0	0.5	0.000	0.003
	TAPE, 2 INCHES	2	0.22	0.44	2.0	2.5	DIA	0.006	0.011
	TAPE, 1 INCH	2	0.11	0.22	1.0	2.5	DIA	0.003	0.006
	* STERILE GLOVES, SIZE 7.5	6	0.07	0.44	5.0	5.0	2.0	0.005	0.029
	* POVIDONE-IODINE SWABS	10	0.01	0.14	6.0	2.3	2.0	0.002	0.016
	* DISPOSABLE THERMOMETERS	5	0.01	0.07	5.5	0.5	DIA	0.000	0.001
	+ ORAL INTUBATION SET	1	0.70	0.70	7.0	9.0	3.5	0.128	0.128

* Dimensions reflect total volume

\+ Mass and/or volume estimated

CATAGORY	ITEM	QTY	UNIT	TOTAL	DIMENSIONS			UNIT	TOTAL
			WEIGHT	WEIGHT	L	W	H	VOLUME	VOLUME
			(LBS)	(LBS)	(INCHES)			(CU. FT.)	(CU. FT.)
+	CIRCOTHYROTOMY SET	1	0.90	0.90	9.0	11.0	3.5	0.201	0.201
	ACE BANDAGES	2	0.11	0.22	6.0	3.0	DIA	0.025	0.049
	TOURNIQUET	2	0.11	0.22	8.0	3.0	1.0	0.014	0.028
*	HEPARIN LOCKS	2	0.00	0.01	2.0	1.0	0.8	0.000	0.001
+	NASOSTAT	1	0.44	0.44	6.0	1.0	0.5	0.002	0.002
*	BANDAIDS, SMALL	10	0.00	0.02	4.0	1.3	0.3	0.000	0.001
*	BANDAIDS, LARGE	10	0.00	0.04	3.0	3.0	1.3	0.001	0.007
*	SUCTION CATHETERS	12	0.04	0.49	20.0	3.0	DIA	0.007	0.082
*	ABSORBANT PADS	5	0.05	0.26	12.0	9.0	1.0	0.013	0.063
+	TUBEX INJECTOR	1	0.04	0.04	5.0	0.8	DIA	0.001	0.001
MEDICATION									
ORAL	DRAMAMINE	1	0.11	0.11	3.0	1.3	DIA	0.002	0.002
	ASPIRIN	1	0.11	0.11	3.0	1.3	DIA	0.002	0.002
	NITROGLYCERIN, 0.4 MG	1	0.11	0.11	3.0	1.3	DIA	0.002	0.002
	DIGOXIN, 0.25 MG	1	0.11	0.11	3.0	1.3	DIA	0.002	0.002
	DEXEDRINE, 5 MG	1	0.11	0.11	3.0	1.3	DIA	0.002	0.002
	LOMOTIL TABLETS	1	0.11	0.11	3.0	1.3	DIA	0.002	0.002
	TYLENOL	1	0.11	0.11	3.0	1.3	DIA	0.002	0.002
	CODEINE, 15 MG	1	0.11	0.11	3.0	1.3	DIA	0.002	0.002
	SCOP/DEX CAPS, 0.4MG/5MG	1	0.11	0.11	3.0	1.3	DIA	0.002	0.002
	BENADRYL, 25 MG	1	0.11	0.11	3.0	1.3	DIA	0.002	0.002
	ACTIFED TABLETS	1	0.11	0.11	3.0	1.3	DIA	0.002	0.002
	HALCION, .25 MG	1	0.11	0.11	3.0	1.3	DIA	0.002	0.002
INJECTABLE	EPINEPHRINE 1:1000	1	0.18	0.18	3.0	1.3	DIA	0.002	0.002
	BENADRYL 50 MG/ML	1	0.18	0.18	3.0	1.3	DIA	0.002	0.002
	ISOPROTERENOL 1:5000	1	0.18	0.18	3.0	1.3	DIA	0.002	0.002
	ATROPINE 0.4 MG/ML	4	0.01	0.04	1.5	0.5	DIA	0.000	0.001
	LIDOCAINE 40 MG/ML	1	0.18	0.18	3.0	1.3	DIA	0.002	0.002
	XYLOCAINE 2% WITH EPI.	1	0.18	0.18	3.0	1.3	DIA	0.002	0.002

* Dimensions reflect total volume

\+ Mass and/or volume estimated

CATAGORY	ITEM	QTY	UNIT	TOTAL	DIMENSIONS			UNIT	TOTAL
			WEIGHT	WEIGHT	L	W	H	VOLUME	VOLUME
			(LBS)	(LBS)	(INCHES)			(CU. FT.)	(CU. FT.)
	MORPHINE SO4 10MG/ML	4	0.01	0.04	1.5	0.5	DIA	0.000	0.001
	DECADRON 4 MG/ML	1	0.18	0.18	3.0	1.3	DIA	0.002	0.002
	COMPAZINE 5 MG/ML	1	0.18	0.18	3.0	1.3	DIA	0.002	0.002
TOTAL MEDICAL		182		91.59					5.813
A-2 LIFE SUPPORT									
ATMOSPHERE	OXYGEN TANK	1	55.26	55.26	35.0	7.0	DIA	0.780	0.780
	NITROGEN TANK	1	53.64	53.64	36.0	7.3	DIA	0.868	0.868
	EMERGENCY OXYGEN TANK	1	12.23	12.23	24.0	4.8	DIA	0.260	0.260
	REGULATORS	5	6.00	30.00	7.0	7.0	7.0	0.198	0.990
+	VALVES, SENSORS, LINES, ETC.	1	10.00	10.00	12.0	6.0	6.0	0.250	0.250
	PRESSURE RELIEF VALVES	4	1.00	4.00	3.0	2.0	DIA	0.005	0.022
+	ATMOSPHERE VENT	1	1.50	1.50	3.0	4.0	4.0	0.028	0.028
+	CABIN FAN	1	7.00	7.00	8.0	8.0	6.0	0.222	0.222
+	AIR PUMPS	2	6.00	12.00	3.0	5.0	DIA	0.034	0.068
	EMERGENCY FACE MASKS	5	1.10	5.50	5.0	4.0	3.0	0.035	0.175
CO2	PRIMARY LiOH CANISTERS	2	6.60	13.20	19.5	14.0	DIA	0.221	0.442
	SECONDARY LiOH CANISTERS	2	6.60	13.20	10.0	7.0	DIA	0.100	0.200
	CARBON DIOXIDE SENSORS	3	0.29	0.87	3.0	1.0	DIA	0.001	0.004
HUMIDITY	RELATIVE HUMIDITY SENSORS	3	0.29	0.87	3.0	1.0	DIA	0.001	0.004
	EMERGENCY WATER REMOVAL	1	29.26	29.26	12.0	6.0	6.0	0.250	0.250
	PATIENT WATER REMOVAL	1	36.52	36.52	12.0	6.0	6.0	0.250	0.250
									0.000
TEMP +	INSTRUMENT COLD PLATE	1	20.00	20.00	36.0	18.0	2.0	0.750	0.750
+	ATMOSPHERE HX	1	20.00	20.00	12.0	12.0	10.0	0.833	0.833
+	CABIN COOLANT, LINES, TANK	1	20.00	20.00	16.0	4.0	DIA	0.116	0.116
+	CABIN THERMOSTAT	1	1.00	1.00	4.0	2.0	1.0	0.005	0.005
+	HEAT RADIATOR	1	50.00	50.00	38.0	40.0	2.0	1.759	1.759

* Dimensions reflect total volume + Mass and/or volume estimated

CATAGORY	ITEM	QTY	UNIT	TOTAL	DIMENSIONS			UNIT	TOTAL
			WEIGHT	WEIGHT	L	W	H	VOLUME	VOLUME
			(LBS)	(LBS)	(INCHES)			(CU. FT.)	(CU. FT.)
+	COOLANT PUMP	1	6.00	6.00	4.0	6.0	DIA	0.065	0.065
+	CABIN AIR HEATER	1	4.00	4.00	6.0	4.0	2.0	0.028	0.028
	TEMPERATURE SENSORS	1	0.29	0.29	3.0	1.0	DIA	0.001	0.001
									0.000
WATER	POTABLE WATER & TANK	1	50.00	50.00	24.0	16.0	12.0	2.667	2.667
	POTABLE WATER SPOUT	1	0.07	0.07	11.0	2.0	0.5	0.006	0.006
	WATER DELIVERY TUBE - 10 FT.	1	0.26	0.26	13.0	7.5	0.5	0.028	0.028
+	POTABLE WATER HAND PUMP	1	2.00	2.00	4.0	5.0	3.0	0.035	0.035
									0.000
WASTE +	FECAL BAGS	10	0.02	0.22	6.0	3.0	3.0	0.031	0.313
+	URINE BAGS	10	0.02	0.22	6.0	3.0	3.0	0.031	0.313
+	SUCTION DEVICE & TUBING	1	12.00	12.00	12.0	6.0	4.0	0.167	0.167
+	DRY WASTE CONTAINER	1	6.00	6.00	14.0	12.0	12.0	1.167	1.167
+	WET WASTE TANK	1	6.00	6.00	17.0	10.0	DIA	0.773	0.773
	SANITARY WIPES	20	0.00	0.06	6.0	2.0	0.5	0.000	0.003
	SUCTION TUBING - 10 FT.	1	0.26	0.26	13.0	7.5	0.5	0.028	0.028
	SUCTION TUBING TIP	1	0.07	0.07	11.0	2.0	0.5	0.006	0.006
TOTAL LIFE SUPPORT		91		483.51					13.876
A-3 GENERAL									
GENERAL	FLARE GUN WITH FLARES	1	4.00	4.00	7.0	7.0	1.5	0.043	0.043
	FLASHLIGHT	2	1.50	3.00	9.0	2.5	DIA	0.026	0.051
	BLANKETS	5	3.75	18.75	18.0	14.0	3.5	0.510	2.552
+	LIFE RAFT	1	25.00	25.00	25.0	6.0	DIA	0.409	0.409
+	LIFE VESTS	5	1.00	5.00	20.0	10.0	6.0	0.694	3.472
	PRESSURIZED PENS	2	0.03	0.07	6.0	0.3	DIA	0.000	0.000
	CLIPBOARDS	2	0.58	1.17	8.5	12.0	0.3	0.018	0.035
	FIRE EXTINGUISHERS	2	2.50	5.00	10.0	3.5	DIA	0.056	0.111
CREW SYSTEMS	STRETCHER - COUCH	1	35.00	35.00	60.0	18.0	3.0	1.875	1.875

* Dimensions reflect total volume + Mass and/or volume estimated

CATAGORY	ITEM	QTY	UNIT WEIGHT (LBS)	TOTAL WEIGHT (LBS)	DIMENSIONS L (INCHES)	W	H	UNIT VOLUME (CU. FT.)	TOTAL VOLUME (CU. FT.)
+	PILOT/MED TECH SEAT	2	32.00	64.00	60.0	18.0	3.0	1.875	3.750
+	JUMP SEATS	2	30.00	60.00	50.0	18.0	2.0	1.042	2.083
+	EECLS CONTROL PANEL	1	15.00	15.00	24.0	24.0	8.0	2.667	2.667
+	MAIN FLIGHT CONTROL PANEL	1	20.00	20.00	24.0	24.0	8.0	2.667	2.667
+	SIDE PILOT CONTROL PANEL	1	15.00	15.00	24.0	12.0	8.0	1.333	1.333
+	RADIOS	2	10.00	20.00	12.0	12.0	8.0	0.667	1.333
	NUCLEAR PARTICLE DETECTOR	1	3.00	3.00	3.0	4.0	1.0	0.007	0.007
+	LIGHTS	3	0.25	0.75	3.0	SPHERE		0.008	0.025
FOOD	M & M PACKETS	10	0.11	1.10	5.0	2.0	0.5	0.003	0.029
	BREAKFAST FOOD BARS	5	0.15	0.77	1.5	2.0	0.8	0.001	0.007
+	APPLE SAUCE PACKS	5	0.22	1.10	3.0	3.0	2.0	0.010	0.052
TOTAL GENERAL		54		297.70					22.502
TOTAL: EGRESS VEHICLE		327		872.80					42.19

* Dimensions reflect total volume

\+ Mass and/or volume estimated