

SYSTEMS ANALYSIS OF AN ION-PROPELLED ORBITAL TRANSFER VEHICLE

by

Richard Wyatt Brewster Jr.

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APPROVED:

Ben S Blanchard

Benjamin S. Blanchard, Chairman

A. K. Jakubowski

Antoni K. Jakubowski

Frederick H. Lutze

Frederick H. Lutze

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Committee Chairman: Benjamin S. Blanchard
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(ABSTRACT)

A systems engineering approach was used to produce a preliminary design configuration for an ion-propelled orbital transfer vehicle system.

The four components of the system are: ground software, ground hardware, the orbital transfer vehicle and the space shuttle. The orbital transfer vehicle uses electrostatic propulsion to transfer payload satellites from a low earth orbit, to any other desired orbit.

The system maintenance concept, and a conceptual design are derived from the statement of need and the system operational requirements. The resulting design, maintainability, reliability and support requirements are discussed.

A discussion of the feasibility of an ion propelled orbital transfer vehicle is included.

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1. INTRODUCTION

The objective of this paper is to give a concept definition and systems analysis study of an ion-propelled orbital transfer vehicle (OTV). A systems engineering approach¹ is used to produce a preliminary system configuration that can then be compared against other configurations that are capable of fulfilling the same need. The comparison against all other alternatives is not included. This is not a detailed technical design of an ion-propelled orbital transfer vehicle, but an overall view of the orbital transfer vehicle system that uses an ion-propelled vehicle. An overall system configuration is presented with some preliminary design to arrive at values that can be used in determining design feasibility.

An orbital transfer vehicle is a vehicle whose sole purpose is to transport other satellites from an initial orbit to a final orbit. The orbital transfer vehicle is attached to a payload satellite by the shuttle crew and released. After a safe separation distance is achieved,

1. Blanchard, Benjamin S., and Fabrycky, Wolter J., Systems Engineering and Analysis (New Jersey: Prentice-Hall Inc., 1981), p.

the OTV engines are turned on and the vehicle slowly tugs the payload satellite from a low earth orbit to a final orbit. When the final orbit is achieved, the OTV releases the payload satellite and returns to low earth orbit, where it will rendezvous with the shuttle to repeat the process. The OTV will operate continuously throughout its mission life. On each rendezvous with the shuttle, the OTV is refueled and serviced. Because of the very low thrust supplied by the ion engines, the transfer of orbits takes up to four weeks. The return trip takes about four days because there is no payload satellite and the vehicle is moving toward, not away from the earth.

A problem statement is given that identifies the need for an orbital transfer vehicle. The system operational requirements and maintenance concepts are given next. A functional analysis that defines the major functions required by the orbital transfer vehicle system is followed by a system configuration design. The system configuration design is derived from the system operational requirements and functional analysis. The subsystem breakdown takes the functions defined by the functional analysis and assigns them to specific vehicle subsystems. After the configuration is defined, system reliability, maintainability and system support require-

ments are given. A life cycle cost discussion is followed by conclusions about the feasibility of using ion-propulsion for orbital transfer vehicles.

2. STATEMENT OF NEED

As the space program moves into the era of permanent presence in space, the need for tools and equipment that operate in space will grow. One of the first and most basic pieces of equipment that is needed by men in space is an orbital transfer vehicle. A vehicle that operates continuously in space for long periods of time, that transports materials, equipment, and men from low orbit to any other orbit will be a basic necessity for man's march into space. An immediate need for this type of vehicle is to transport satellites from low earth orbit to any other earth orbit. Figure 1 shows the OTV baseline mission.

The cost of launching a satellite with a motor attached for the orbital transfer phase of its mission could be reduced by launching an orbital transfer vehicle and using it to transport a wide number of payloads. The OTV could be launched and refueled by the shuttle. The cost of launching weight into space is one of the most expensive aspects of satellite cost. If the amount of weight launched into space is reduced by the weight of the rocket motor, then more weight can go into the satellite itself. Therefore, companies can put more equipment on each satellite, or launch at a reduced weight and

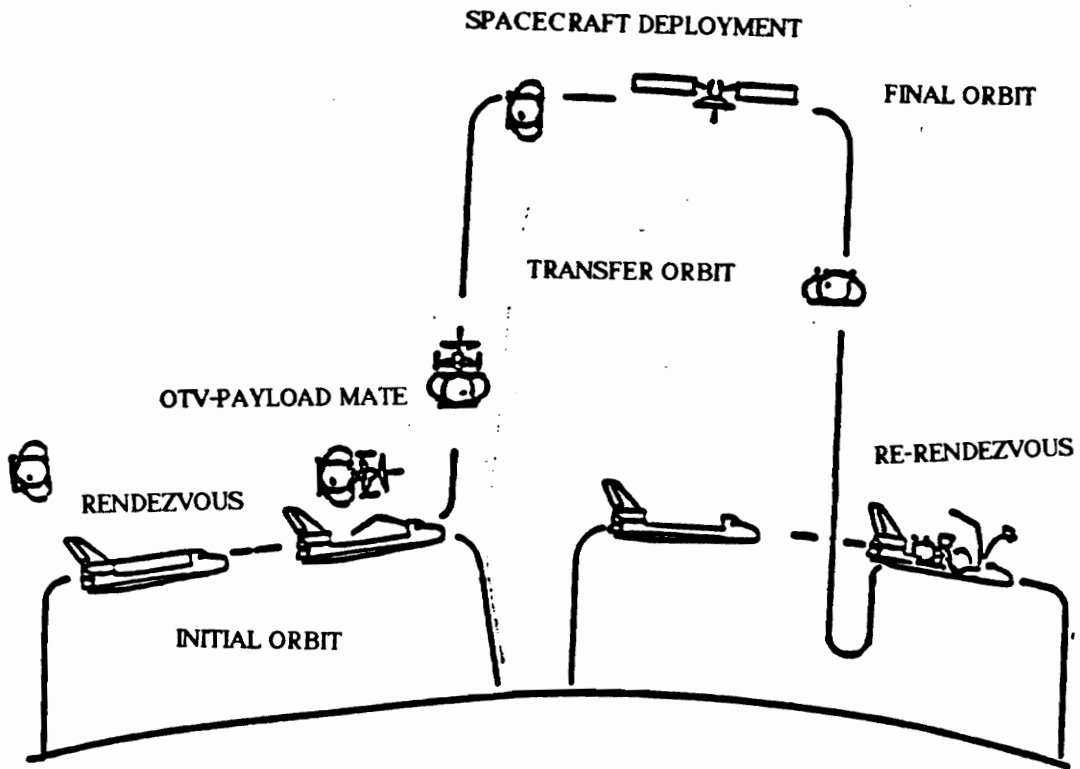


FIGURE 1. MISSION DEFINITION

cost. Any reduction in launch weight is a worthwhile investment. Launching cost is about seventeen hundred dollars per pound² of payload, so the need is obvious.

An orbital transfer vehicle would be used by SDI to transport it's many satellites from shuttle orbit to their final operational orbits. Communication satellites would use this orbital transfer vehicle to go from low shuttle orbit to geosynchronous orbit. Because this vehicle would be available to transport the vehicles from initial to final orbits, these satellites don't need to supply their own means of orbital transfer. This makes the payload satellites lighter, less complex, and cheaper to launch. When the space station is complete, these orbital transfer vehicles could also be used to retrieve on-orbit satellites and bring them back to the space station for servicing.

2. Nasa, Orbital Vehicle Concept Definition and Systems Analysis Study, N88-20339. July 1987. p. 15.

3. SYSTEM OPERATIONAL REQUIREMENTS

In order to design a system that will fulfill the statement of need, system operational requirements need to be defined. The requirements addressed here are mission definition, performance parameters, operational deployment, operational life cycle, utilization requirements, and system effectiveness factors.

The mission definition of the OTV is to transfer payloads from a low earth orbit, to any earth orbit, and then return to low earth orbit and rendezvous with a space platform or shuttle, so the process can be repeated.

The performance factors are reliability, longevity, size, weight, and accuracy. The most critical system performance parameter is reliability. The system must operate the entire mission life without failure. Longevity is also important because the longer the system lasts, the more economical it is. The size of the OTV is constrained by the size of the shuttle bay, which is fifteen feet by sixty feet. As weight increases, the benefits decrease, so weight is always a limiting factor. Accuracy is very important, because the more precise the injection into final orbit, the less weight the payload has to spend on correction and housekeeping. The time needed for orbit transfer is not an issue here.

This system uses a single OTV that is deployed into low earth orbit, but once the OTV is developed, any number (as required) can be used. There would be ground hardware and software support required, receiving facilities, personnel, and computer support.

Life cycle estimation is ten years³, with vehicle and software design and development taking five years (from design to final construction), and a mission life of five years. The life cycle increases with the number of OTV's.

The engine operates for up to six weeks at a time, up to eight missions per year, and up to forty missions in it's lifetime⁴. The ground station contacts the vehicle and retrieves data and loads new commands. The ground station will use computers on the ground to analyze downlinked data, and to generate command loads to be uplinked to the vehicle. The OTV will rendezvous with the shuttle once per mission to pick up a new payload.

3. Life cycle estimation is an engineering design goal.

4. Blanchard, Benjamin S., and Fabrycky, Wolter J., Systems Engineering and Analysis (New Jersey: Prentice-Hall Inc., 1981), p.

The most important effectiveness factor is failure rate. The entire system must run continuously for five years without OTV failure. Another important effectiveness factor is the skill of the people who construct and operate the OTV. Highly trained and highly skilled personnel are required to operate this system.

4. SYSTEM MAINTENANCE CONCEPT

System maintenance can be broken down into four areas, ground hardware, ground software, the OTV and the space shuttle. Maintenance actions themselves can be broken down into three levels⁵, organizational intermediate and producer maintenance. Organizational maintenance is done on site by operating personnel. Intermediate maintenance is done by mobile crews that travel to the work site. Depot/producer maintenance is performed by the manufacturer at the manufacturer's home site.

OTV maintenance changes throughout the life of the system. Before construction, there is no OTV maintenance, during construction, the construction equipment, construction facility and testing equipment all need highly skilled maintenance. After construction up to orbital injection, the OTV will need to be maintained in an environmental controlled facility and monitored with special test equipment. This also requires special maintenance equipment and personnel. On orbit, the OTV will need maintenance by astronauts on the shuttle. This maintenance will include exchanging fuel pods, servicing

5. *ibid.*, p. 242

the OTV, replacement of damaged equipment with spares, and servicing the propulsion system. The OTV must fit within the maintenance concept of the shuttle. The maintenance of the OTV must meet with all of the NASA requirements for safety. There can be no activities that endanger the shuttle or it's crew, such as radioactive outgasing of the nuclear reactor, or exposing the shuttle to dangerous levels of radiation. The OTV will be returned to earth at the conclusion of it's mission and refurbished so it can start another five year tour of duty.

The OTV system must be compatible with the shuttle maintenance system. Any spare parts the OTV will need that are supplied by the shuttle, will have to meet all of NASA's safety requirements. There is some equipment that will be used by the shuttle in connection with the OTV system that may require maintenance by the shuttle ground crew (i.e.- the equipment the shuttle would use to attach payloads to the OTV).

Ground maintenance consists of ground hardware and ground software maintenance. Since the OTV will use existing ground stations, the additional maintenance due to OTV contacts will be small, and is an extension of existing procedures. The computers and other equipment needed by the OTV support personnel will also have to be considered in the maintenance concept.

The ground software would be unique and need its own support group. The initial support would be large, but as the software was used, the amount of new errors would diminish. A small software group would be co-located with the ground station that is supporting the OTV. This provides quick response to software problems. The contractor that wrote the software could fix major software problems at their location and transfer solutions easily over the telephone. The ground station would need a small number of new people that would be dedicated to the OTV performance and monitoring. Figure 2 shows the top level system maintenance concept for the on-orbit OTV system.

SYSTEM COMPONENT	ORGANIZATIONAL MAINTENANCE	INTERMEDIATE MAINTENANCE	DEPOT/PRODUCER MAINTENANCE
ORBITAL TRANSFER VEHICLE	ON SITE SUBSYSTEM ANALYSIS	ON ORBIT SERVICING BY SPACE SHUTTLE	POSSIBLE RETURN BY SHUTTLE
GROUND SOFTWARE	ON SITE DEBUGGING	NONE	DETAILED CODE CHANGES CODE REWRITES
GROUND HARDWARE	ALREADY DEFINED	ALREADY DEFINED	ALREADY DEFINED
SPACE SHUTTLE	ALREADY DEFINED	ALREADY DEFINED	ALREADY DEFINED

FIGURE 2. SYSTEM MAINTENANCE CONCEPT

5. FUNCTIONAL ANALYSIS

The orbital transfer vehicle is just part of a larger system that is required to support it. The ground support requires software, computers, data storage facilities, communication equipment, and highly skilled personnel. The OTV is launched by the space shuttle and all of the support that goes with it. The payloads are built by many different contractors, but all of them must follow some compatibility design so the payload can be attached to the OTV. Finally, the actual construction of the OTV requires a complete design phase from conceptual design through system retirement.

Functional flow diagrams⁶ for the entire system are used for the functional analysis. Figure 3 shows the top level functional diagram for the OTV system. Each major function of the system is broken out and listed separately. Figure 4 shows the first level breakdown of the construction phase of the OTV system. The satellite and ground software designs are conducted simultaneously.

A suitable ground station for the OTV would have to be located. Since NASA may operate the OTV, their facilities in Houston and Florida may be used. This

6. *ibid.*, p. 258

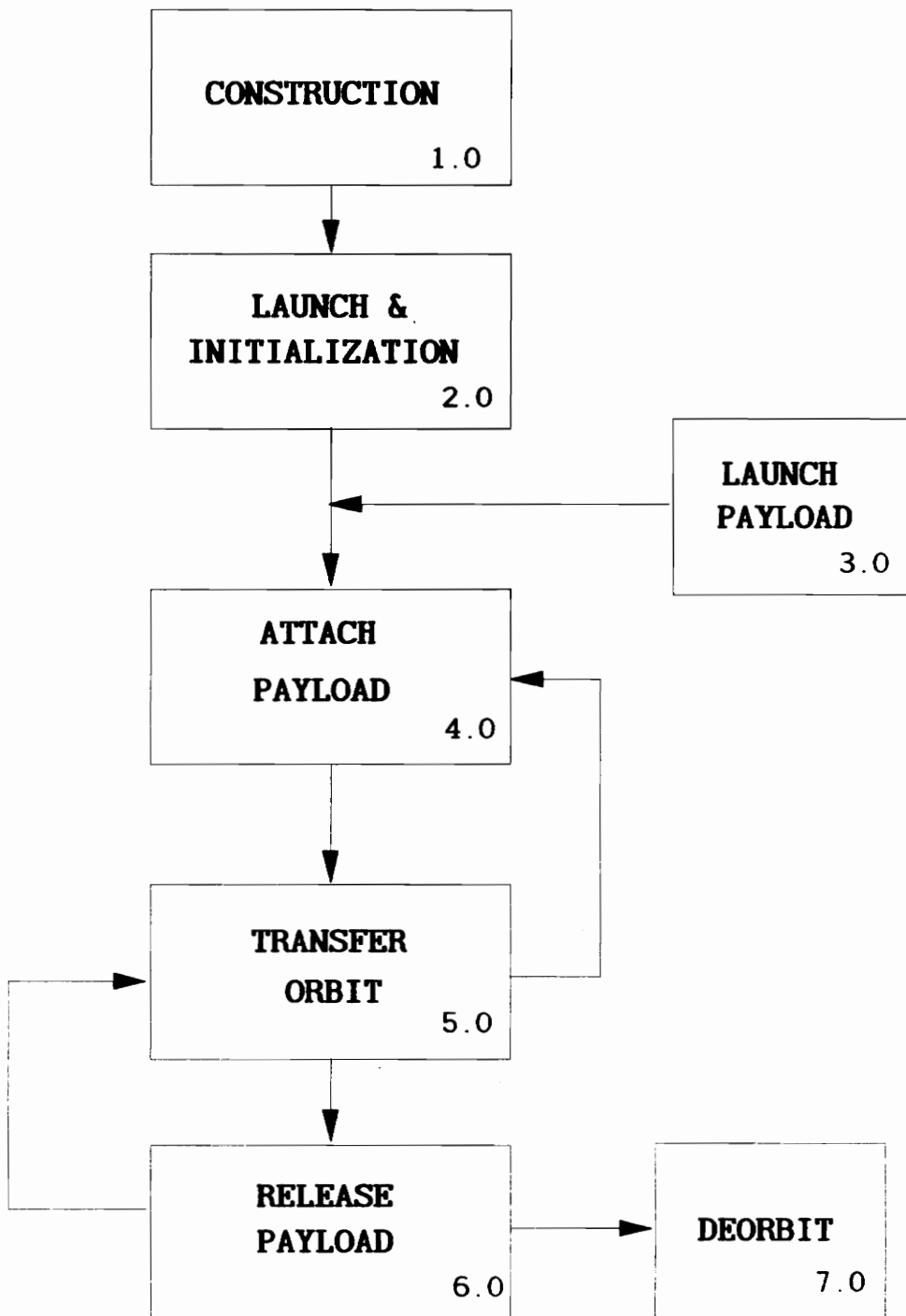


FIGURE 3 OTV FUNCTION BLOCK DIAGRAM

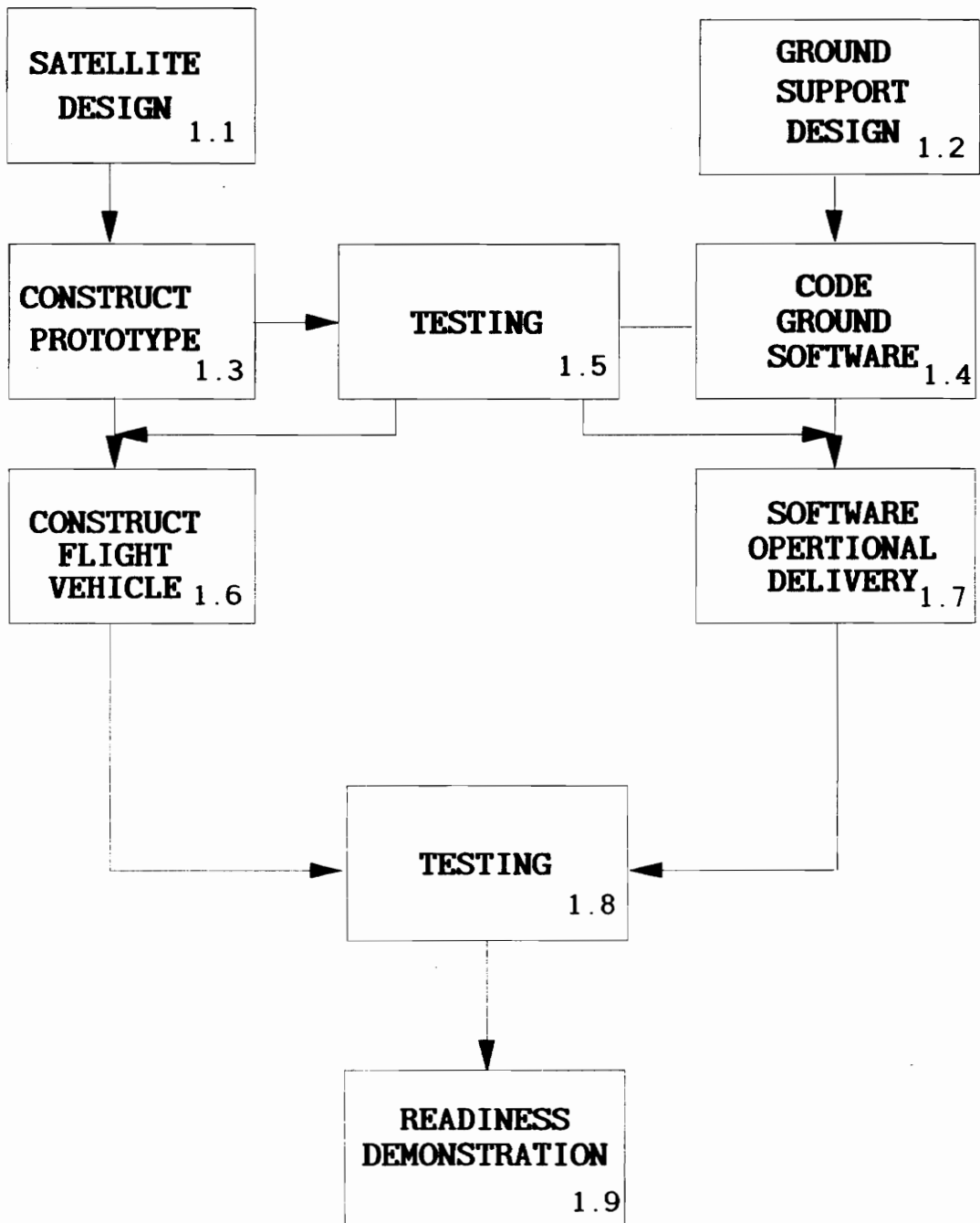


FIGURE 4 OTV LEVEL 2 BLOCK DAIGRAM
FOR BLOCK 1

eliminates the need to construct new ground facilities. Therefore, the construction of ground facilities is omitted from this system design. If, in the future, the fleet of OTV's grew to a large number, then the construction of a ground station would have to be considered.

Figure 4 takes the OTV design from conceptual design through to the delivery of an operational product. The time frame for figure 4 is two years'. Figure 5 takes the satellite design block from figure 4 and breaks it down into a second level diagram. The satellite design function takes the mission requirements and outputs all the specifications required to construct a prototype. Each block in figure 5 contains many functions that could be broken down further. For this paper blocks 1.1.1 to 1.1.2 are investigated. Figures 6 through 11 are first level functional block diagrams broken out from figure 3.

7. Two years design time is an engineering objective.

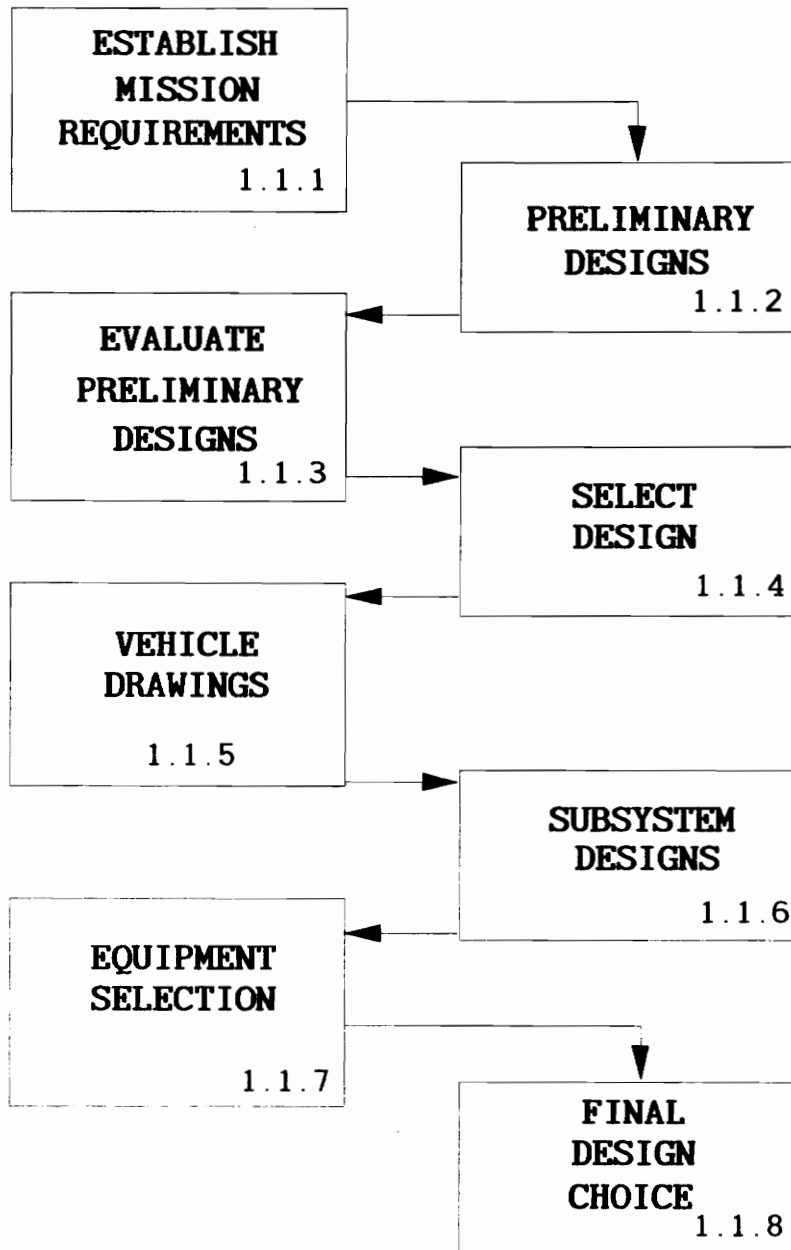


FIGURE 5 OTV DESIGN
LEVEL 3 BLOCK DIAGRAM

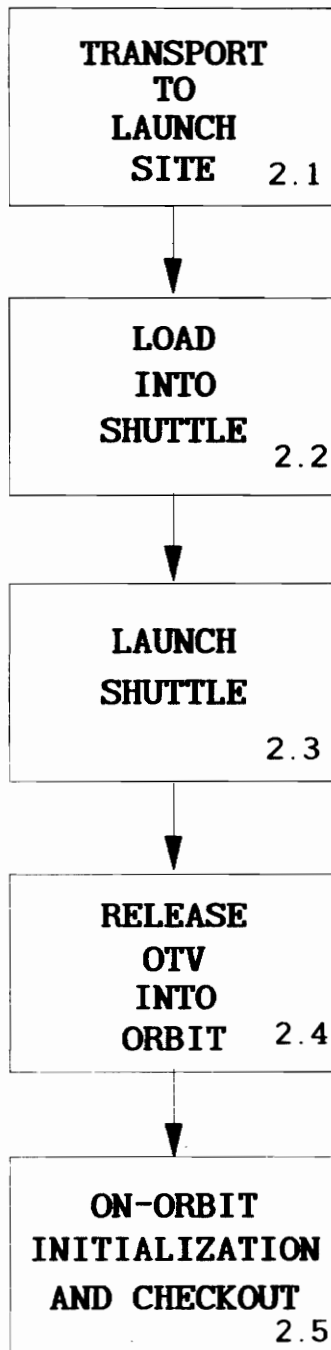


FIGURE 6 OTV LAUNCH AND INITIALIZATION
LEVEL 2 BLOCK DIAGRAM

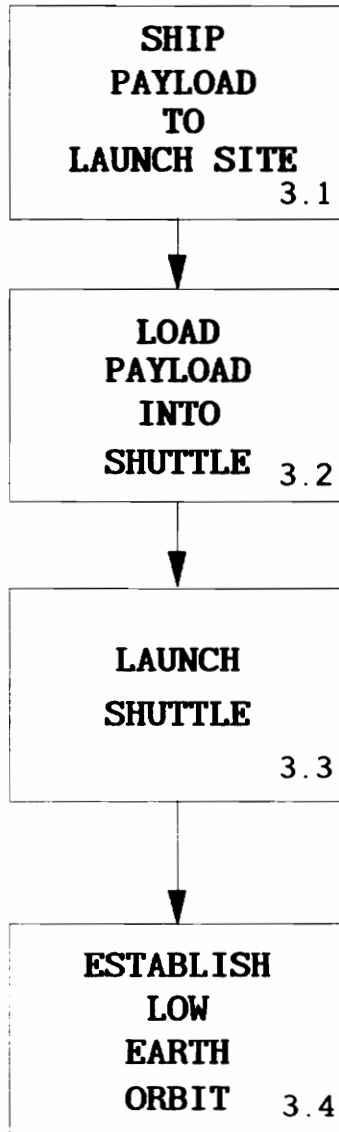


FIGURE 7 OTV PAYLOAD LAUNCH
LEVEL 2 BLOCK DIAGRAM

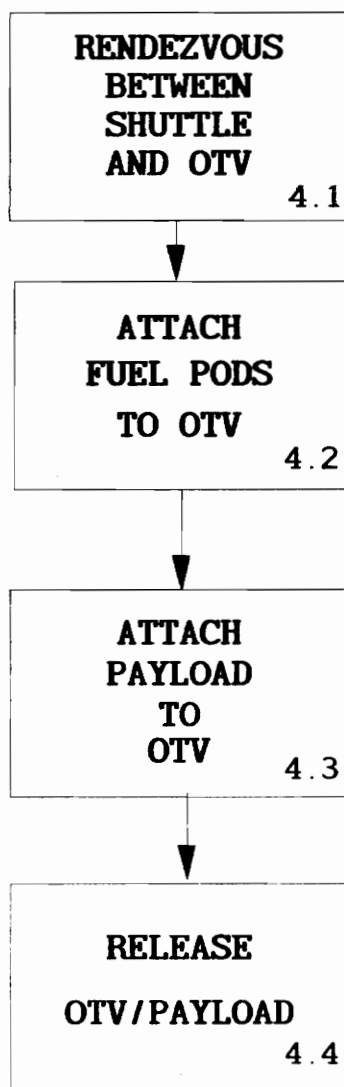


FIGURE 8 OTV/PAYLOAD ATTACHMENT
LEVEL 2 BLOCK DIAGRAM

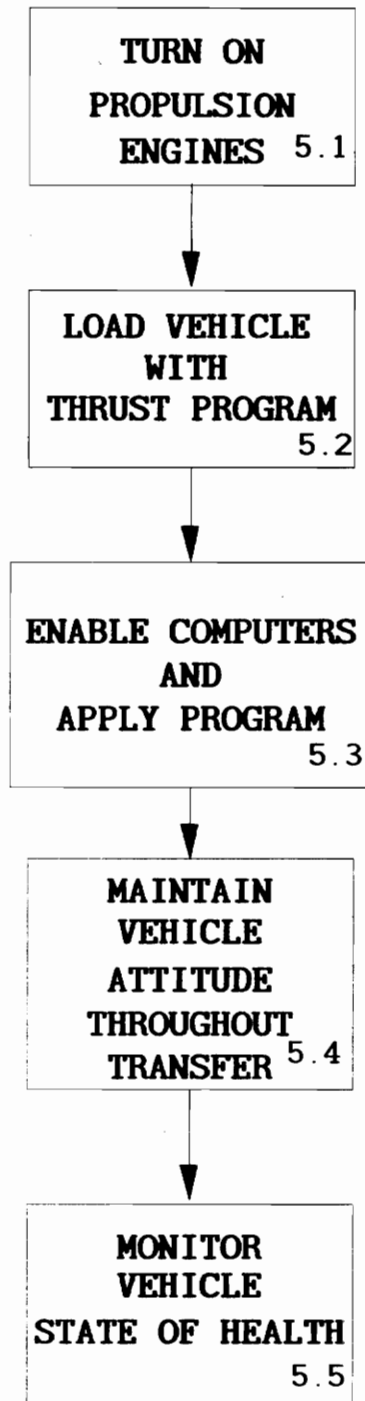


FIGURE 9 ORBIT TRANSFER
LEVEL 2 BLOCK DIAGRAM

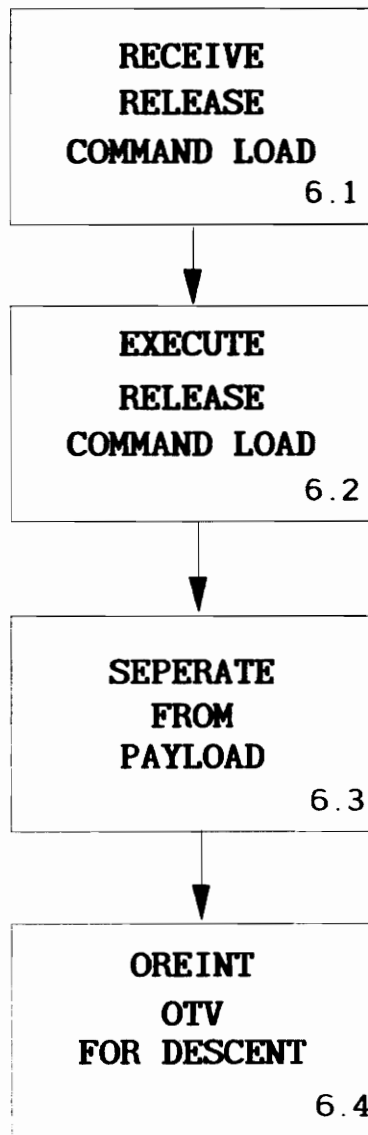


FIGURE 10 OTV PAYLOAD RELEASE
LEVEL 2 BLOCK DIAGRAM

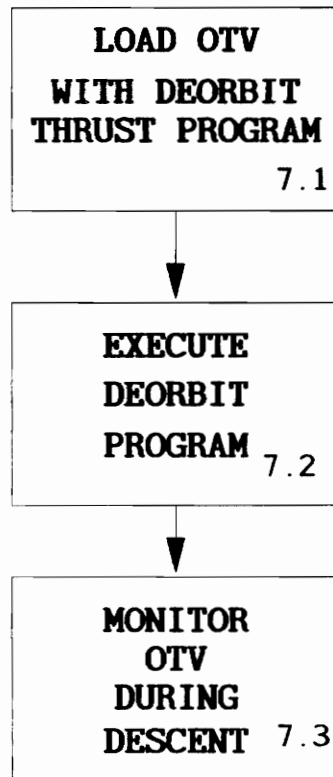


FIGURE 11 OTV DEORBIT
LEVEL 2 BLOCK DIAGRAM

6. SYSTEM CONFIGURATION

The functional analysis defines the major functions that the OTV system must accomplish. In this section the satellite functions are broken down into subsystem functions. Each subsystem lists the subsystem requirements and proposed components. In order to break the satellite down into subsystems, the initial parameters and design variable assumptions are used to derive a mass breakdown of the OTV. This mass breakdown is then used in the subsystem requirements. These values are also used in the discussion of feasibility at the conclusion.

6.1. INITIAL PARAMETERS

The design of the OTV system was based on given parameters required by the mission and on assumptions based on present and future technologies. All assumptions used in this design are based on current technological data^s. The initial parameters were used to build a preliminary design.

8. Current technology refers to 1961

The initial parameters demanded by the mission (mission specific) are:

1. Initial Orbit - LEO 100-150 mile circular (shuttle orbit)
2. Final Orbit - Any orbit greater than 100 mile circular.
3. Transfer Time - Up to six weeks. Although this is not a requirement, six week missions would coincide with shuttle launches, so the OTV should be in LEO whenever a shuttle is launched. Actual transfer time will be mission dependent.
4. Payload Weight - Up to 40,000 Kg. This number is arbitrary, but the number is near shuttle maximum capacity⁹.

These are the only mission dependent parameters. The rest of the initial variables are assumptions that deal with the specific vehicle design.

6.2. DESIGN VARIABLE ASSUMPTIONS

9. Nasa, Orbital Vehicle Concept Definition and Systems Analysis Study, N88-20339. July 1987. p. 15.

Some assumptions are made in order to have a starting point for the overall vehicle design . The following assumptions for an ion-driven OTV are given:

T = Transfer time = 4 weeks¹⁰

(This is the time for the average mission to go from 100 mile LEO to GEO orbit and back.)

α = Specific Power = .3 kw/kg¹¹

This is the smallest acceptable value of specific power that is feasible for this mission. A larger value would be better, but any smaller value would make the OTV mass too large, or the transferred payload too small.

10. Stuhlinger, Ernst, and Seitz, Robert N., "Electrostatic Propulsion Systems," Advances in Space Science, vol 2, New York:Academic Press, 1960, p. 333

11. *ibid.*

The preliminary design is based on these assumptions:

Terminal velocity (U)¹²

U = 6 km/sec (assumed)

Exhaust velocity (V)¹³

V = 60 km/sec

From these assumptions, the mass breakdown of the OTV can be derived. The mass breakdown of the OTV includes the mass of the propulsion system, the mass of the fuel required and the mass of the remaining OTV subsystems and satellite payload. The structural members needed to support the structure and the radiators required are included in the mass of the propulsion system. All other subsystems are included in the payload mass. The mass breakdown is given in equation 1.

$$M_0 = M_L + M_p + M_r \quad (\text{initial mass}) \quad (1)$$

12. *ibid.*

13. *ibid.*

where: M_L = Mass of Payload .
 M_p = Mass of propellant system
 M_f = Mass of fuel

(* M_L is the mass of all OTV sub-systems plus the payload satellite weight)

The empty or burn out mass M_e is the initial OTV mass minus the fuel mass. The empty mass is given in equation 2

$$M_e = M_L + M_p \quad (2)$$

Some other definitions are required in order to calculate mass breakdown. First, current (I), can be defined as :

$$I = M \cdot \dot{m}$$

where:

M = mass flow rate
 \dot{m} = the inverse of the specific charge of particles.

Voltage (U) is defined by :

$$U = \frac{V^2}{2} \frac{m}{e} \quad (4)$$

Where : V = exhaust velocity

m/e = specific charge of particles

So, therefore power (L) can be defined as :

$$L = IU = \frac{MV^2}{2} \quad (5)$$

For this derivation, mass flow rate (M) is defined as:

$$M = \frac{M_r}{T} \quad (6)$$

Substituting equation 6 into equation 5 gives :

$$L = \frac{M_f V^2}{2T} \quad (7)$$

The propulsion mass, M_p is defined as :

$$M_p = \frac{L}{\alpha} \quad \text{or} \quad \frac{M_f V^2}{2\alpha T} \quad (8)$$

The classic rocket equation:

$$U = V \ln \frac{M_o}{M_e} \quad (9)$$

relates terminal velocity, exhaust velocity, and vehicle mass.

Substituting equation 1 and equation 2 into equation 9 gives:

$$U = V \ln \frac{M_f + M_p + M_L}{M_p + M_L} \quad (10)$$

Solving equation 10 for a ratio M_o / M_L and introducing equation 8 gives :

$$\frac{M_o}{M_L} = \frac{e^{U/V}}{1 - V^2 / 2\alpha T(e^{U/V} - 1)} \quad (11)$$

Equation 11 defines the mass ratio of the OTV in terms of all assumed variables. Equation 11 gives a ratio of 1.44 for the values assumed in the previous section.

In this design, the payload mass is equal to 50,000 Kg.

Equation 11 gives a ratio of 1.44. This means for a payload of 50,000 Kg, the entire initial mass would be 72.2 tons in initial orbit. The mass breakdown of the OTV is derived as follows:

$$M_0 = 1.44M_L \quad (12)$$

$$M_0 = M_L + M_p + M_f \quad (1)$$

Substituting (1) into (12) gives:

$$1.44M_L = M_f + M_p + M_L \Rightarrow .44M_L = M_f + M_p \quad (13)$$

Substituting 8 into 13 gives :

$$M_f = \frac{.44M_L}{(1 + V^2 / T2\alpha)} \quad (14)$$

This relates payload mass to the mass of fuel required.

For $M_L = 50,000$ Kg:

$$M_f = 6,700 \text{ Kg} \quad (\text{from equation 14})$$

$$M_p = 15,500 \text{ Kg} \quad (\text{from equation 8})$$

$$M_0 = 72,200 \text{ Kg} \quad (\text{from equation 1})$$

This gives the mass breakdown of the OTV. The power requirements are directly proportional to the mass of the vehicle.

For this mission, $M_p = 15,500$ Kg, so in order for specific power to be .3kw/kg, the power required for the OTV would be 4.65 Megawatts.

$$L = .3M_p = 4,650,000 \text{ watts} \quad (15)$$

The OTV will use a tungsten/cesium ion production system. The constant ϵ/μ (specific charge of the particles) for cesium is $.73 \times 10^3$ amps per second.

The mass flow rate of the OTV is simply:

$$M / T = .000275 \text{ Kg/second} \quad (16)$$

The required current I for the power system is given by:

$$I = M \frac{\epsilon}{\mu} = 2,000 \text{ amps.} \quad (17)$$

$L = IU$, so the required voltage for the power plant would be 2,325 volts. The thrust of the ion propulsion system on the OTV is given by $F = MV$ which is equal to 1.69 Kg. This gives an initial acceleration of the OTV of 2.29×10^{-4} g.

Note: Acceleration is not constant throughout the mission.

This outlines the derivation of the initial parameters used in the ion propelled OTV.

6.3. OTV SUBSYSTEMS

This section details the seven subsystems¹⁴ that make up the OTV. The seven subsystems that make up the OTV are:

Communication Subsystems

Electrical Subsystem

Propulsion Subsystem

Structural/Thermal Subsystem

Command and Control Subsystem

14. The division of the OTV into seven subsystems is an arbitrary division of vehicle functions

Attitude Control Subsystem

Navigational Subsystem

The mass of the propulsion and structures are 15,500 kilograms. Figures 12 & 13 show a possible OTV configuration¹⁵. Figure 14 gives an OTV subsystem overview that shows the interfaces between the different subsystems.

6.3.1. COMMUNICATION SUBSYSTEM

SUBSYSTEM REQUIREMENTS :

Transmission and receiving rates capable of supporting the OTV mission

Directional antennas capable of receiving signals at any vehicle orientation

Signal activated

Operates on regulated power input

43,800 hours of operation without failure

15. The OTV design in figures 12 and 13 is given for illustrative purposes only. This is not an actual engineering design.

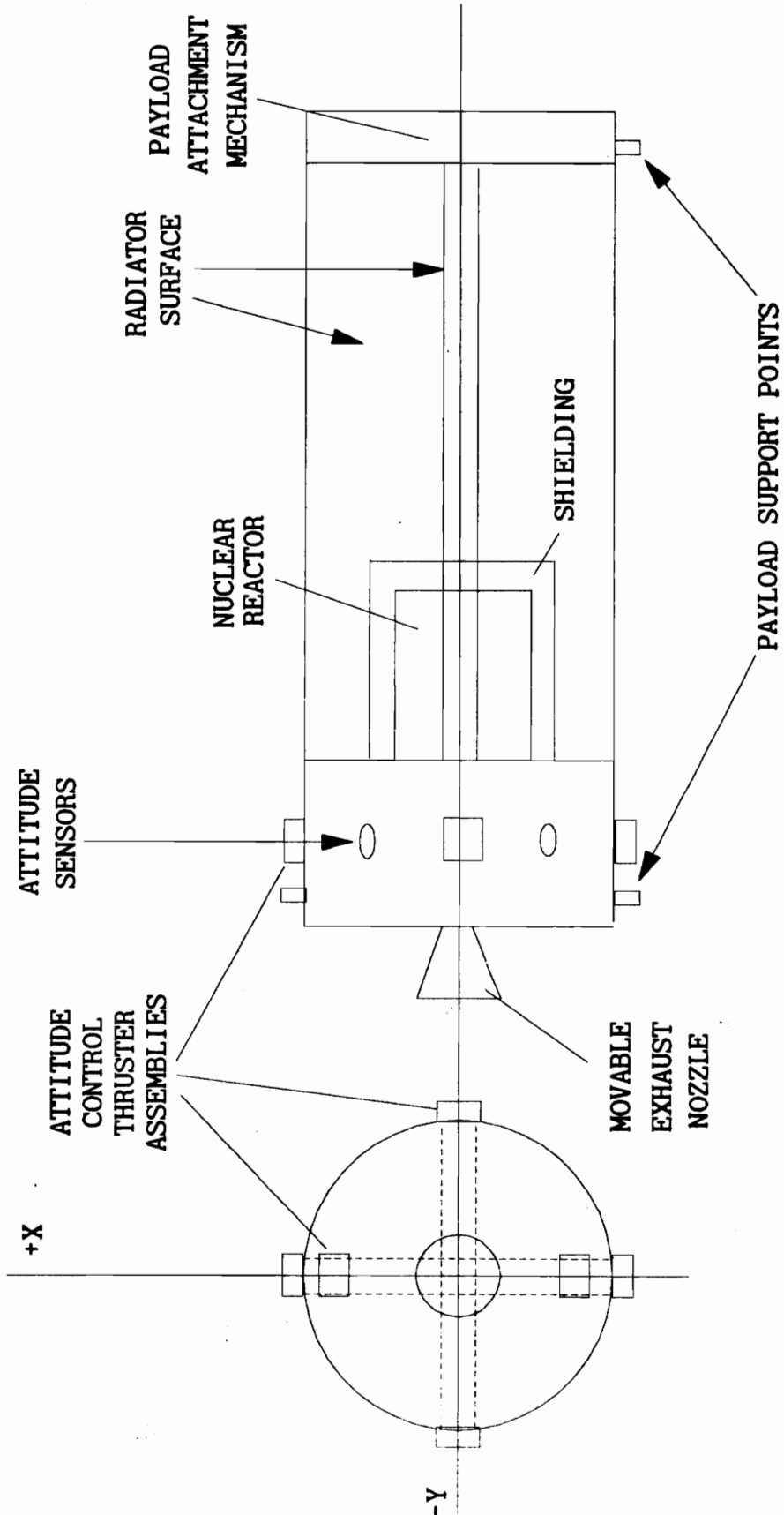


FIGURE 12. OTV CONCEPTUAL DESIGN

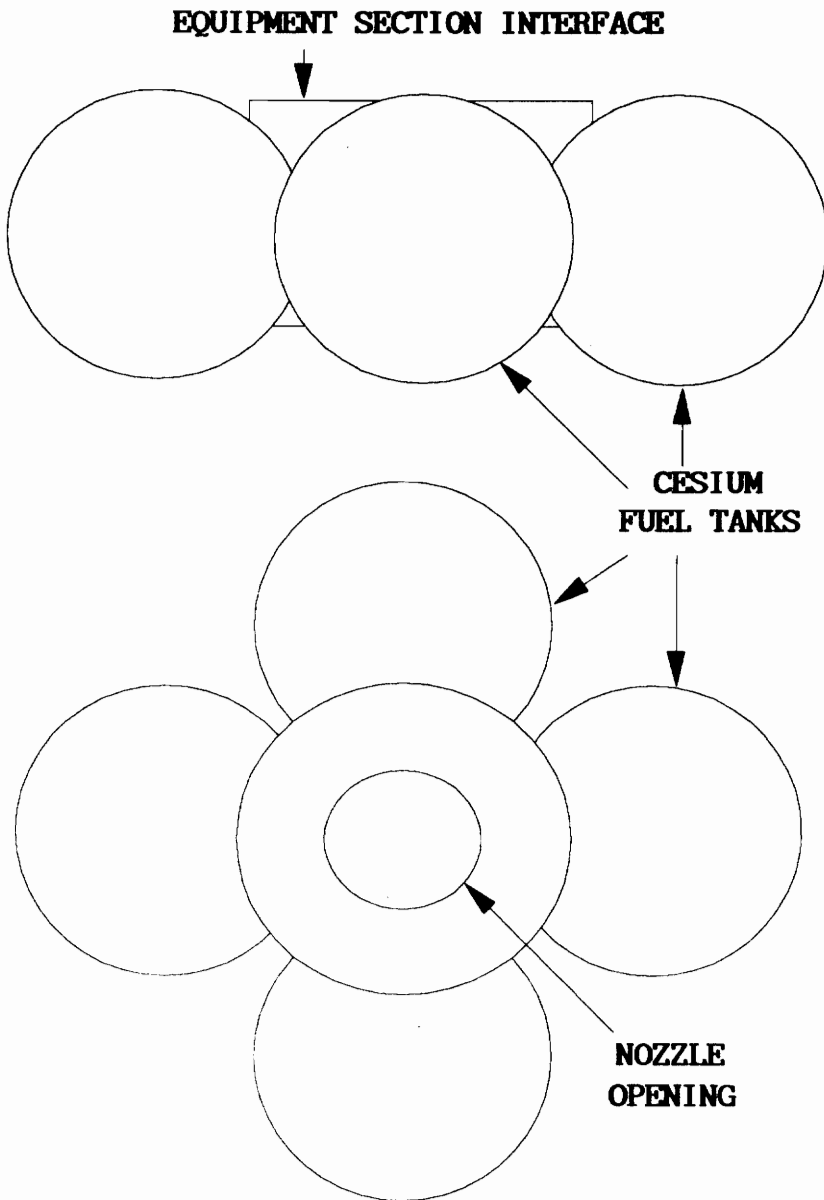


FIGURE 13. OTV REPLACEABLE FUEL POD

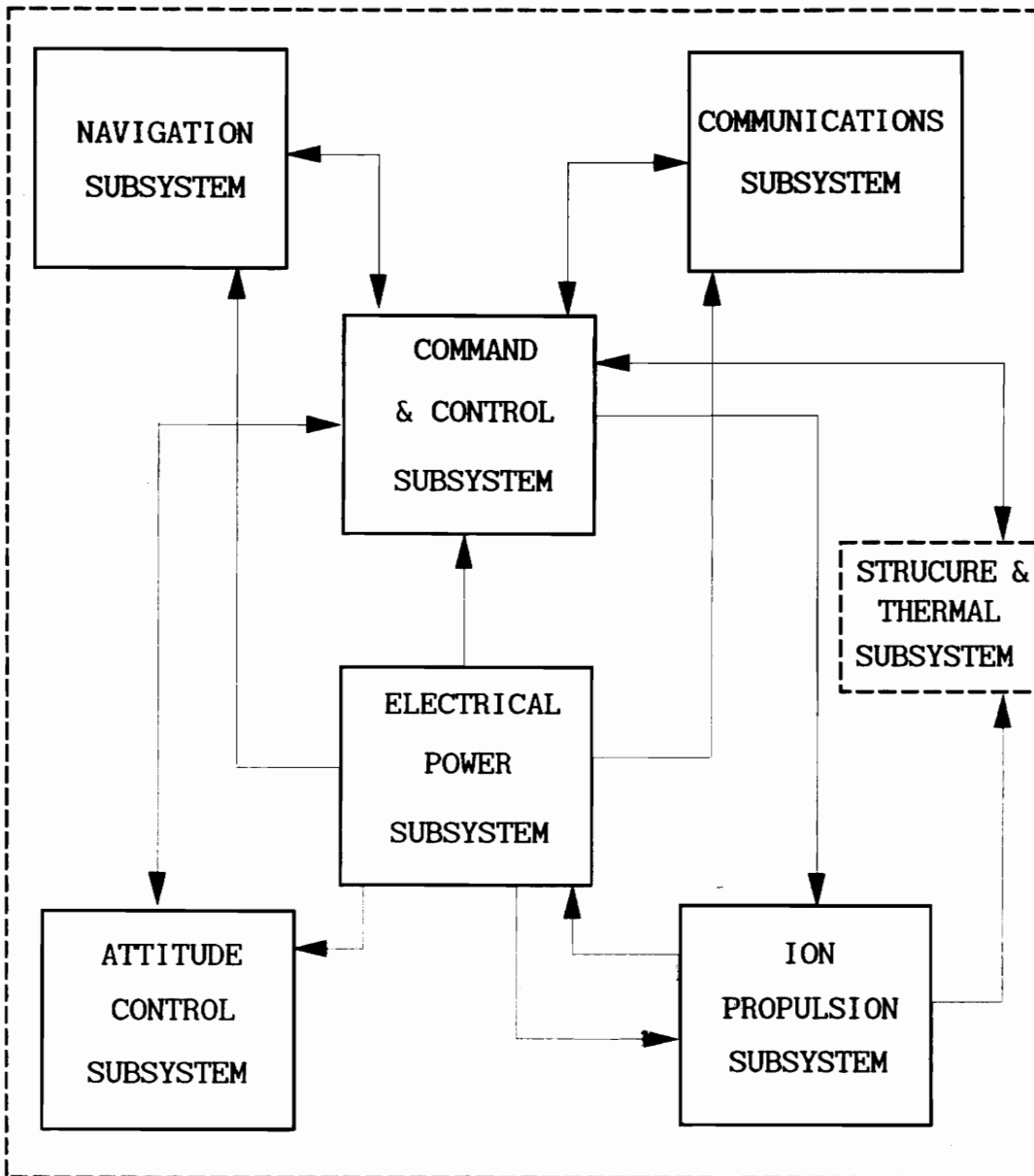


FIGURE 14 OTV SUBSYSTEM OVERVIEW

Ability to communicate with payload satellites

PROPOSED COMPONENTS :

Two omni directional antennas

Communication receiver

Communication transmitter

The purpose of the communication system is to provide a link from the ground to the OTV command and control subsystem that can receive commands and transmit telemetry. The system must have the required redundancy in order to last the mission life of five years. Major components of the communication subsystem are the receiver, transmitter electronics, and antennae assembly. A block diagram of this subsystem is given in figure 15. An elementary transmitter/receiver with omni directional¹⁶ antennae should be chosen for simplicity. Complete coverage is required since the vehicle travels with the -y axis facing the earth on transfer out, and the +y axis on the way back. Multiple antennae are not

16. Omni-directional means able to receive signals from any orientation.

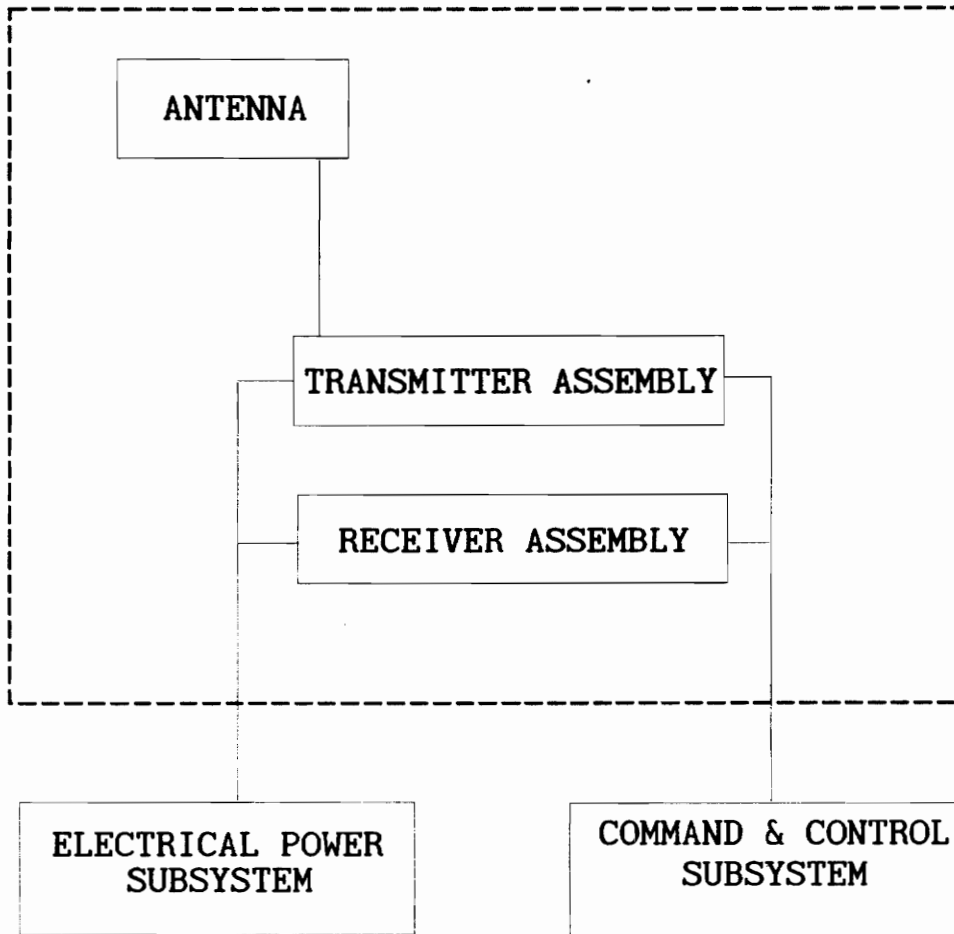


FIGURE 15. OTV COMMUNICATIONS SUBSYSTEM BLOCK DIAGRAM

necessary, but the redundancy brings the mass of each assembly down. At least two contacts per day are planned so each antennae will be cycled at least 1,825 times. If some problems arise, or more attitude correction is needed, more contacts will be needed, and the antennae will be cycled more. Each set of communication gear must be specified so that it can cycle 3,650 times without failure.

The OTV must provide an interface so that the payload satellites can be communicated with. This communication will be through the shuttle or through ground stations. The OTV must be able to accommodate a number of different kinds of satellite communication systems.

6.3.2. ELECTRICAL SUBSYSTEM

SUBSYSTEM REQUIREMENTS :

43,800 hours of continuous operation without failure

Receive up to 3,000 unregulated DC power

Receive up to 2,500 amps of current

Output seven lines of regulated 2,325 volt DC power

Output seven lines of regulated 2,000 amp current

Output five lines of regulated DC power

Output five lines of regulated current

PROPOSED COMPONENTS :

1 electric power distribution unit with 1 input and 12 outputs

Wiring and wire harnesses needed to supply power to all other subsystems

The function of the electrical subsystem is to take unregulated power from the nuclear power plant and deliver it to each subsystem in the regulated voltage required by each subsystem. The electrical power subsystem receives input power and outputs regulated power continuously throughout mission life. Subsystems that require electrical power are communication, computer, propulsion, attitude and control, and navigation and thermal control. The main component of the electrical power subsystem is the power distribution unit. This unit receives a single power input from the turbine on the power plant and distributes it to each subsystem in a regulated amount. Each subsystem must specify its power requirements, and give time of operation so that

reliability and redundancy can meet the five year mission life. A block diagram of this subsystem is given in figure 16¹⁷.

6.3.3. PROPULSION SUBSYSTEM

SUBSYSTEM REQUIREMENTS :

Produce 4.65 megawatts of power

Produce up to 3,000 volts of unregulated power continuously for 43,800 hours

Produce up to 2500 amps of current continuously

Provide at least 16.9 N of thrust to the OTV¹⁸

Provide six attitude thrusters at 6 points on the outside of the OTV not to exceed 15,500 kg

17. It may be necessary to use solar cells and batteries to provide the subsystems with low power, because it may be too costly to reduce the power flow from the reactor.

18. Stuhlinger, Ernst, and Seitz, Robert N., "Electrostatic Propulsion Systems," Advances in Space Science, vol 2, New York:Academic Press, 1960, p. 333

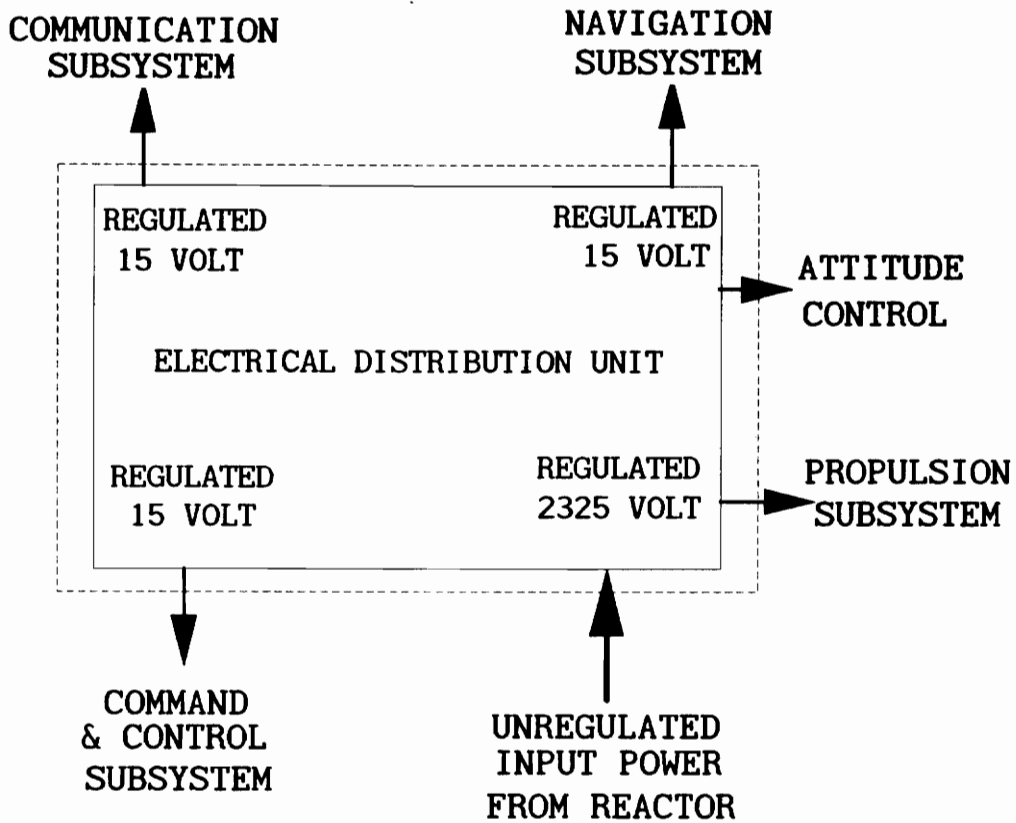


FIGURE 16. OTV ELECTRICAL POWER SUBSYSTEM
BLOCK DIAGRAM

PROPOSED COMPONENTS :

Nuclear reactor
Turbine
Generator
Thrust chamber
Propellant tank (removable)
Propellant pump
Ion source
Electron source
Radiator
Heat exchanger
Radiation shielding

The function of the propulsion subsystem is to provide thrust and attitude control to the OTV, and to generate electrical power for the OTV. A block diagram of this subsystem is given in figure 17. The ion propulsion system considered for this design uses a porous tungsten plug with cesium gas passed through it to produce ions. The power source is a nuclear reactor capable of producing at least 2,500 volts and 2,000 amps. The power plant will be in operation the entire life of the vehicle. The reactor must be placed in such a way that burn up is guaranteed in re-entry during de-orbit. The mass of the entire propulsion system with structural

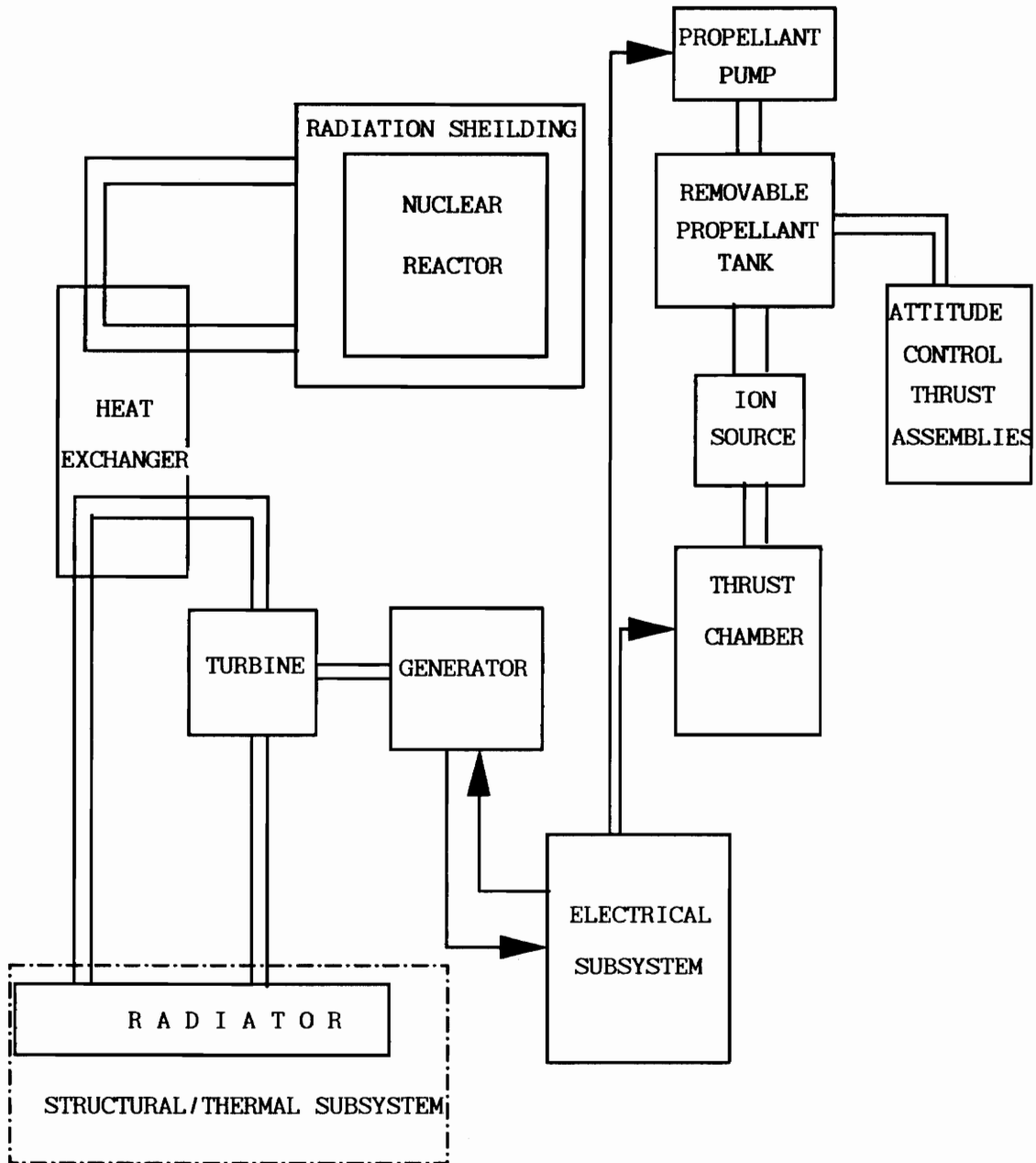


FIGURE 17. PROPULSION SUBSYSTEM
BLOCK DIAGRAM

elements is 15,500 kg. The entire propulsion system must have a specific power value of .3 kw/kg in order to ensure mission success.

There are six sets of attitude control thruster assemblies on the OTV that apply small torques that correct vehicle attitude. Each assembly will draw the needed current from the electrical power subsystem. Each assembly requires one thrust chamber and tungsten plug. Propellant is pumped from the central propellant tank to the thrusters so no separate fuel tanks are needed. The thrusters respond to commands by the command and control computer. Due to the very low amount of thrust produced by these thrusters, they will be on for long periods of time.

Accommodations by the space shuttle are needed in order to transport the volume of fuel needed by the OTV while in orbit. This fuel volume is larger than the shuttle cargo bay can handle. Modifications are being made to the external tank in order to provide cargo space for the required fuel. This modification is currently under way¹⁹.

19. Nasa, Orbital Vehicle Concept Definition and Systems Analysis Study, N88-20339. July 1987. p. 24.

6.3.4. STRUCTURAL/THERMAL SUBSYSTEM

SUBSYSTEM REQUIREMENTS :

Provide a skeleton that supports the vehicle

loads during all phases of vehicle life

Provide attachment points for all subsystem
components

Provide a thermally controlled environment for
all subsystem components

Provide for the radiation of excess heat generated
by the nuclear power plant

PROPOSED COMPONENTS :

Aluminum element skeleton

External vehicle skin

Hollow radiation elements

Heat conduction fluid

Payload attachment mechanism

Exchangeable fuel pods

Fuel pod interface mechanism

Shuttle cargo bay attachment points

The function of the structural/thermal subsystem is to support the power plant and payload, provide an interface for satellite payloads, and an interface for exchangeable fuel pods. The structure between the power plant and the payload will also be used as radiator surface for the power plant.

The structural subsystem will consist of a vehicle skeleton to which all subsystems can be attached. An attach mechanism (to be used by shuttle astronauts) to attach payloads, and a fuel pod mechanism that can be used to detach and attach pods of fuel²⁰. This fluid will radiate the heat of the OTV to space. Overall design should be as light as possible and be strong enough to handle all phases of mission life. The structural system must also provide load bearing points that can be used to hold the vehicle in the shuttle bay. These points are pins that can support the weight vertically while on the launch pad. There needs to be at least three load bearing points for the vehicle to be fully restrained. The structural system must also provide an interface for the shuttle to retrieve it from orbit, and hold it while attaching the payload to it. A special set up will have to

20. Nasa, Orbital Vehicle Concept Definition and Systems Analysis Study, N88-20339. July 1987. p. 36.

be designed for attachment since the shuttle has only one robot arm. The skeleton needs to be strong enough to support a 32,000 kg load through lift off and ascent. There is no failure for the struts but the release mechanisms will be cycled once during each mission. Each OTV can have a maximum of 42 missions in a five year period. The release mechanisms are not redundant and represent single point failures for the mission. Failure to attach or release a payload satellite means the end of useful life of the OTV. Therefore a large margin of safety is needed for each mechanism. Structural subsystem is designed to fit all subsystems and support required loads and give needed radiator surfaces. A block diagram of this subsystem is given in figure 18.

6.3.5. ATTITUDE CONTROL

SUBSYSTEM REQUIREMENTS :

Maintain x,y,and z axis at the commanded values²¹

Have a total system life of five years

21. *ibid.*, p. 39.

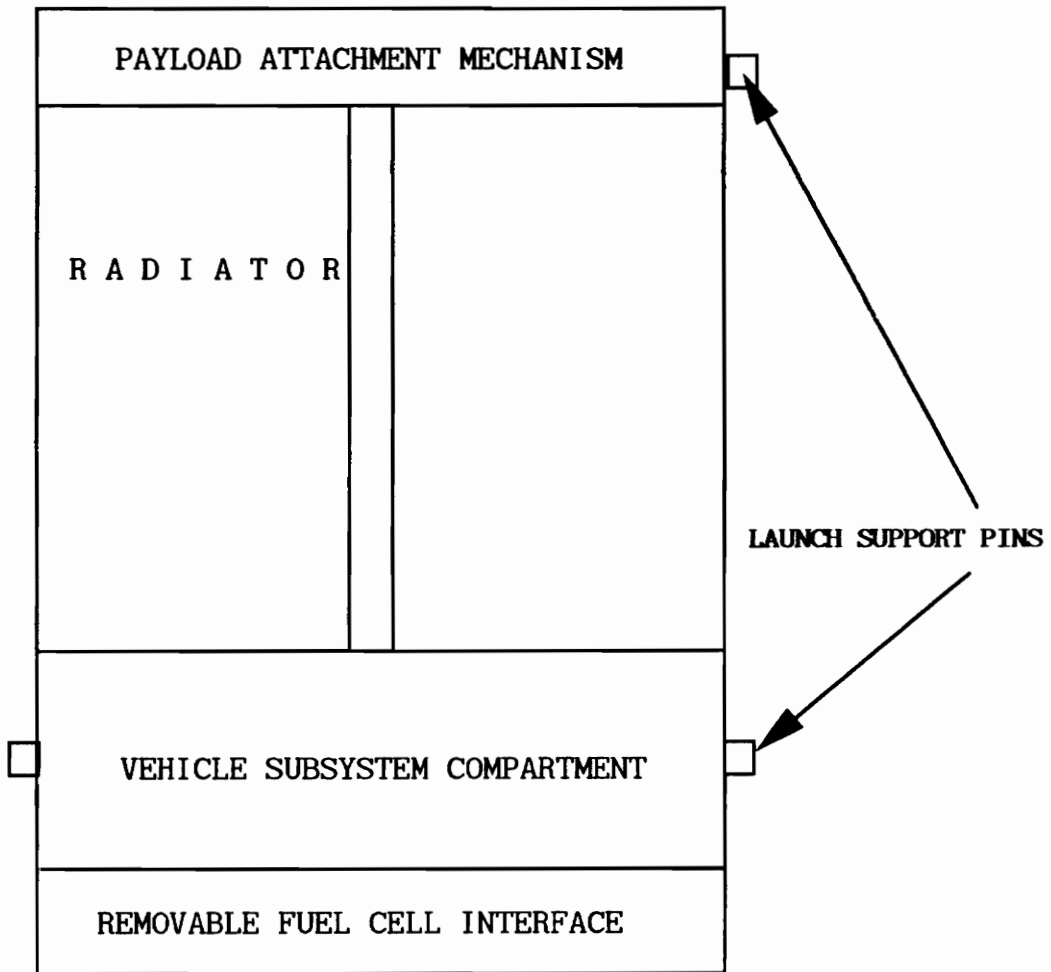


FIGURE 18. OTV STRUCTURAL/THERMAL SUBSYSTEM
BLOCK DIAGRAM

Receive commanded attitudes from computer (attitude commands)

Act on attitude commands

Provide attitude feedback to command and control system

Receive regulated electrical power from electrical power subsystem

PROPOSED COMPONENTS :

Rate sensing gyros, horizon, sun, and star sensors.

The Function of the attitude control subsystem is to provide three-axis stable control of the OTV about the commanded attitude for all phases of flight . It shall respond to commands from the command and control subsystem and give attitude feedback based on received sensor inputs. The attitude control system must be able to maintain vehicle stability during all phases of operation and when considering the worst case offset between the OTV and payload centers of gravity. The components of the attitude control system are rate sensing gyros , horizon, sun, and star sensors and six ion reaction and control thruster assemblies. The command and control system will issue commands for attitude correction, the

ion thrusters will turn on, and resultant vehicle motion will be sensed by the gyros. This information along with sensor data will be fed back to the command and control system. This control loop will be used by the OTV for attitude maintenance. It may be found that all three sensor types are not needed to maintain the attitude accuracy required to fulfill the mission objectives. It is important to note that ion thruster assemblies are not capable of high impulse maneuvers, therefore, they will operate for long periods of time at low thrust, for this reason high accuracy attitude knowledge is needed by the ground software and the command and control subsystem. A block diagram of the attitude control system is given in figure 19.

6.3.6. NAVIGATION SUBSYSTEM

SUBSYSTEM REQUIREMENTS :

In track knowledge of OTV location

Provide orbital location information to the command and control subsystem

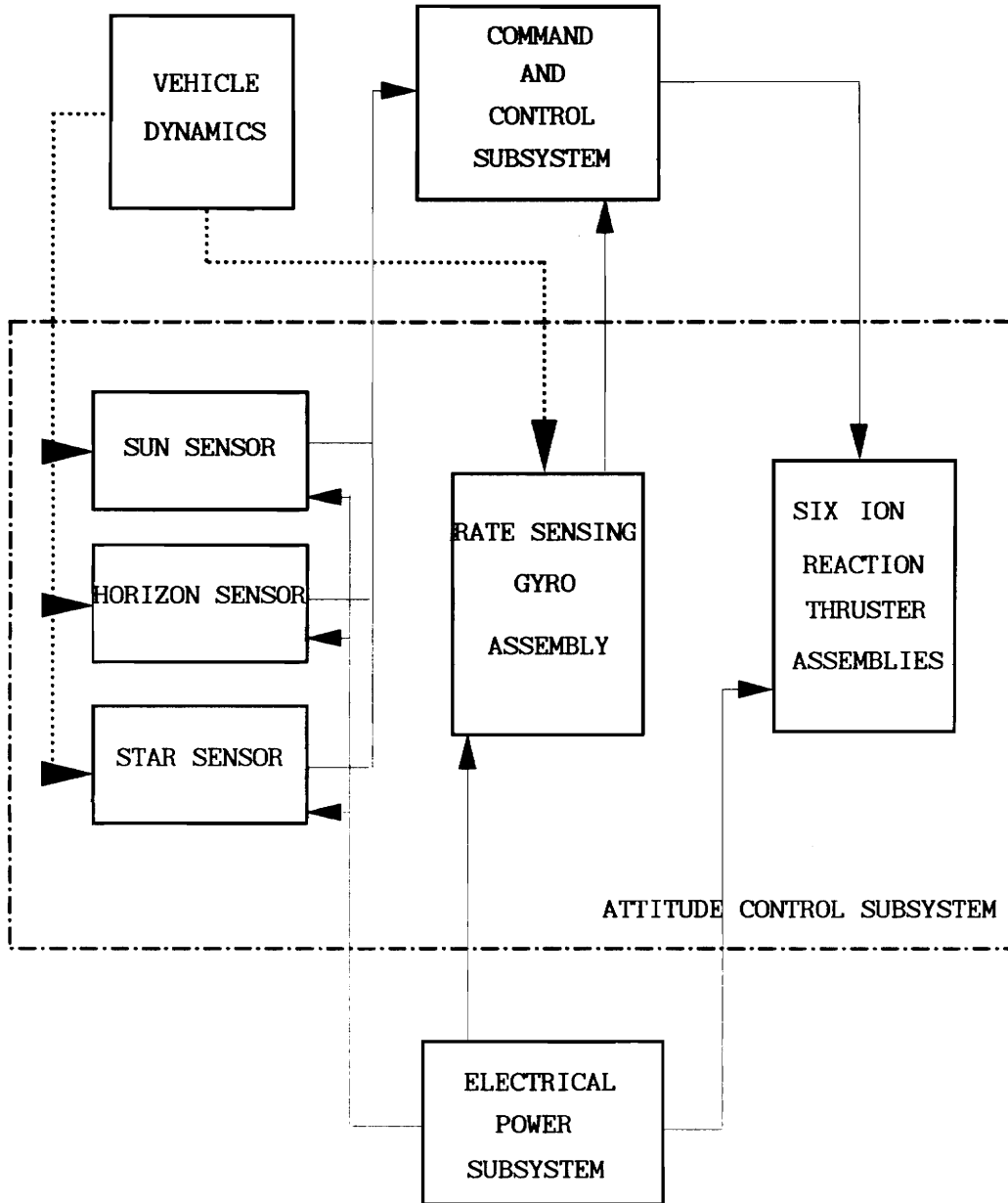


FIGURE 19. ATTITUDE CONTROL SYSTEM BLOCK DIAGRAM

PROPOSED COMPONENTS :**Navigational transmitters/navigational receivers**

The function of the navigational subsystem is to provide orbital location data to the ground. The actual orbit calculations are done by ground software and uplinked to the on-board computer. Precise orbital knowledge is required because of the slow corrections the ion propulsion system applies. Orbital location is also critical to payload injection. The inputs from the navigation subsystem are used in determining the trajectory of the OTV. A block diagram of this subsystem is given in figure 20.

6.3.7. COMMAND AND CONTROL SUBSYSTEM**SUBSYSTEM REQUIREMENTS :**

Ability to receive, store and execute commands uplinked from the ground

Ability to format and downlink vehicle health data

Ability to command all other vehicle subsystems

43,800 hours of continuous operation without failure

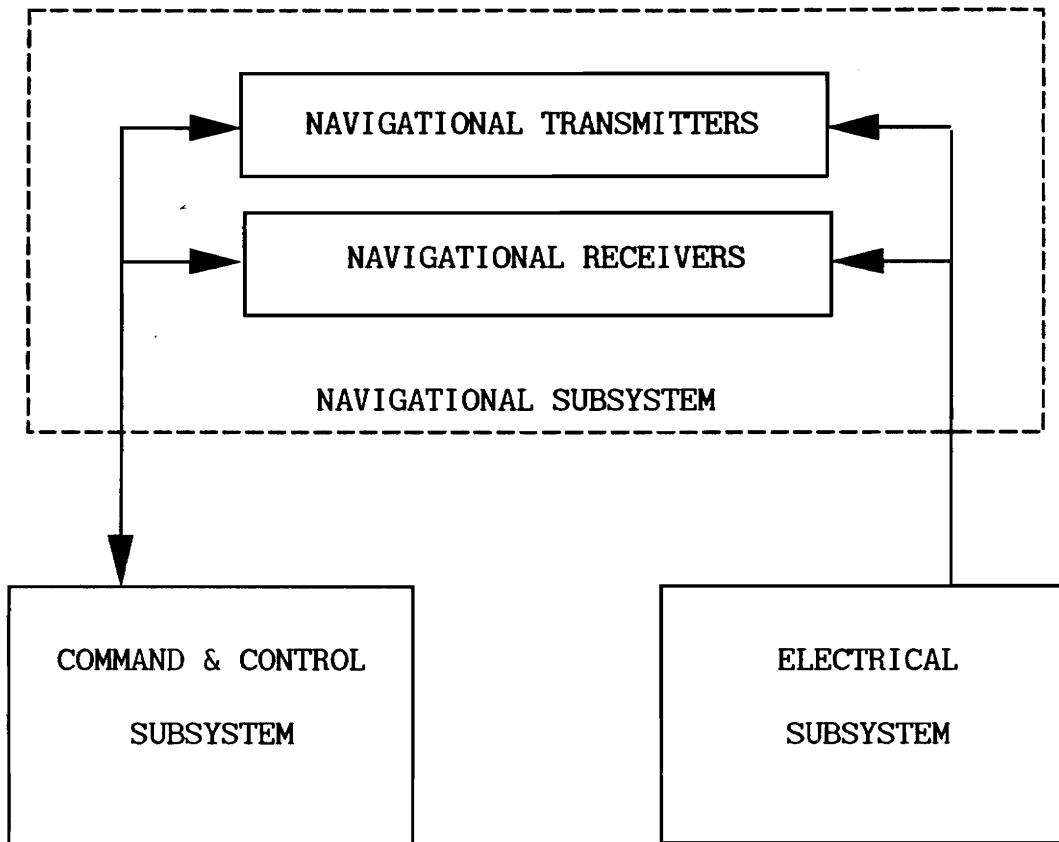


FIGURE 20. OTV NAVIGATIONAL SUBSYSTEM
BLOCK DIAGRAM

PROPOSED COMPONENTS :

Memory units

Central processing units

Data bus

Input/output processor

The command and control system stores and executes command loads generated on the ground, formats telemetry and downlinks it through the communication subsystem, and has the ability to control all subsystems on board the OTV. The design of the command and control system can vary greatly. There could be large areas of memory that could be used to store programs that would execute autonomously. The vehicle could be loaded with artificial intelligence code that sense vehicle attitude and location and compute it's own thrust program. The other alternative is to have all calculations done by ground software and have the vehicle perform routine state of health checks and report any problems it may have. The weight increase for increased vehicle intelligence is not great, but given the duration that the computer must operate without failure, the simplest design is the best. A balance between the two alternatives must be found that

will give the vehicle maximum capability with minimum risk of failure. A block diagram of this subsystem is given in figure 21.

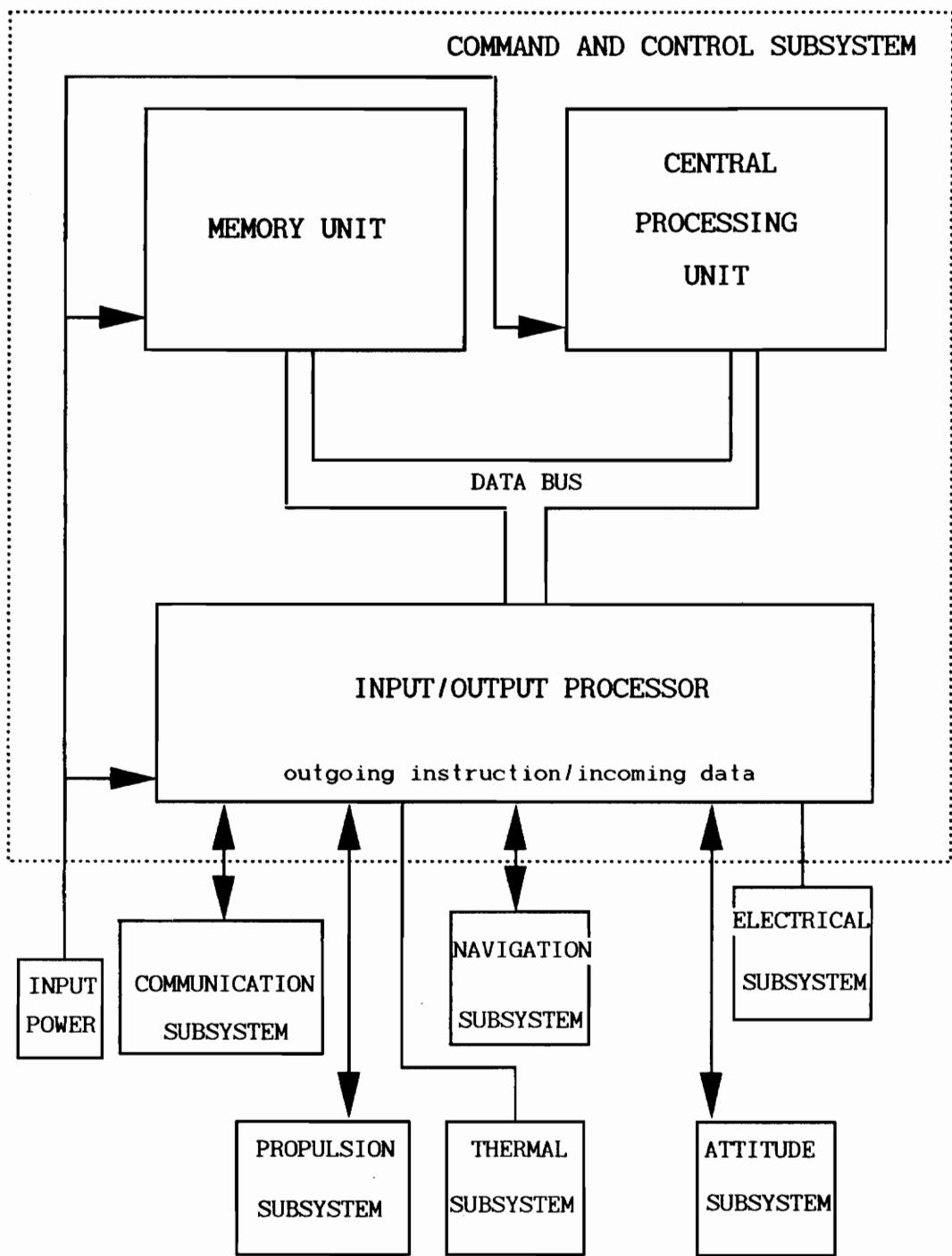


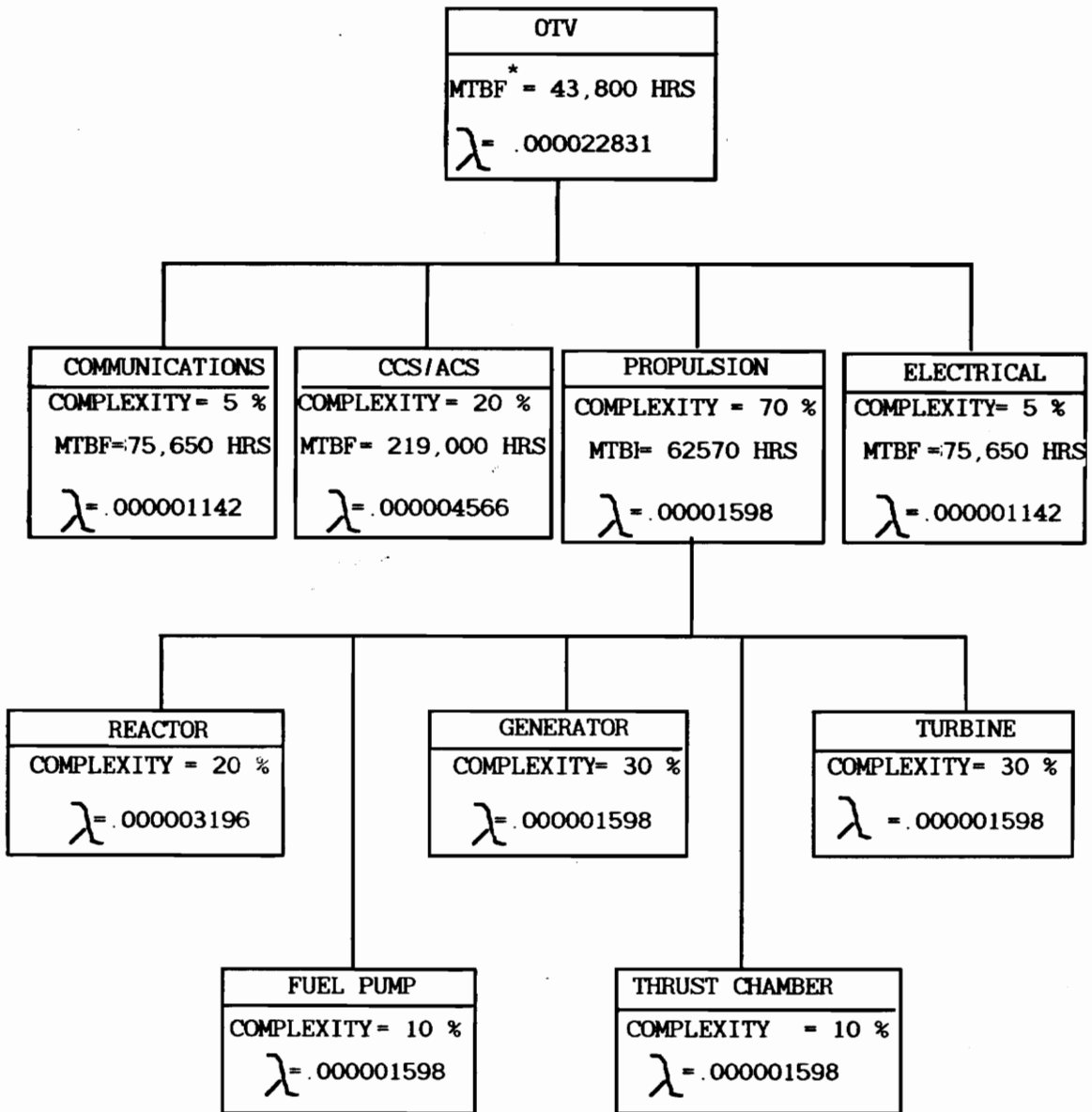
FIGURE 21. OTV COMMAND & CONTROL SUBSYSTEM
BLOCK DIAGRAM

7. SYSTEM RELIABILITY

The on-orbit mission life of the OTV is five years. During this time no major failures can occur or the mission is over. A major failure is any failure that prevents the OTV from completing its mission of transferring payloads from LEO to another orbit and returning to a precise LEO to repeat the process. Since this requirement is so stringent, internal and external redundancies are required. For the purpose of this section, the OTV subsystems are divided into four major groups : Communication (and navigation), Propulsion and Structures, electrical power, and command and control/attitude control. This results in a series²² network of four components. A major failure in any of these sub units will end mission life. An allocation of reliability requirements for these four groups, with the propulsion group broken down into further requirements is given in figure 22²³.

22. Series refers to equipment set up such that if one piece of equipment fails, they all fail.

23. All complexities are arbitrary.



*
MTBF=MEAN TIME BETWEEN FAILURE

FIGURE 22. OTV SYSTEM RELIABILITY BREAKDOWN

The OTV must be designed so that the MTBF is five years. For this design goal to be achieved, each of the four groups must meet the design goals in figure 22. In order to meet these design goals, internal redundancy is required. Each black box must use redundancy in order to meet these requirements. Another design alternative is to have modular replacement of subsystem components on orbit before they fail. As part of maintenance for the OTV, subsystem components can be replaced with new components as often as every six weeks. This would reduce the reliability of these components immensely, but would also increase maintenance costs. The navigation and communications subsystems can use field proven equipment that is already used in the space program. For example an S-band transmitter/receiver is proven in use and would require little investment cost to meet the reliability requirements. The electrical power subsystem would also require little research cost to meet it's reliability requirements. The attitude control/command and control system would require large development costs in order to meet their reliability requirements. The propulsion system would require the largest development cost because there are no existing ion propulsion systems of this size yet in orbit. An alternative to the strict reliability requirements would be to replace parts on orbit. This would reduce the reliability requirements but would in-

crease the maintenance costs. Due to the very large costs involved in on orbit maintenance, it is better to design the subsystems to meet these requirements, rather than plan for detailed on orbit maintenance. By far the most constraining factor in the OTV design is meeting reliability and weight requirements simultaneously, because redundancy increases weight. During detailed design it may be found that one group requires more redundancy than another, and therefore, more weight. It may also be found that the reliability of the entire OTV cannot be achieved with the initial weight estimates. At that point initial estimates must be refined and overall weight breakdowns rewritten. At worst, the compromise between vehicle life and vehicle weight would have to be redefined.

The ground software must also be able to support the OTV throughout its mission life. Software reliability is proven during testing and should not be an issue. Ground equipment and the shuttle are also included in the system, but their reliability is already set. Therefore these numbers are not calculated in this system.

8. SYSTEM MAINTAINABILITY

There are three major components of the OTV system that require maintenance. The ground station hardware, the ground station software and the OTV. Shuttle maintenance is not discussed, however, the OTV maintenance must be compatible with the shuttle maintenance concept. These three components have different requirements during different phases of the life cycle. The major phases of life cycle are construction, transportation, and operation of all three system components. Since the system uses ground stations that already exist, there is no construction phase for them. During construction of the OTV several pieces of equipment are used. This equipment varies in complexity and maintenance needs, however, the maintenance costs of this equipment during the construction phase are quite large. These costs are absorbed by the contractor who builds the OTV. Special test equipment is used for vehicle check out that is also absorbed by the contractor and the same is true for transportation equipment. This equipment is unique, complex, and expensive. All three components require organizational, intermediate, and depot maintenance during all three phases of system life. The operational phase of the OTV itself requires that fuel be loaded onto the vehicle at the

start of every mission. The empty fuel cell is returned, refilled, and reused again. This is intermediate maintenance.

The ground station requires hardware and software maintenance. The increase in maintenance costs due to the additional work load the OTV system would put on an existing ground station would be negligible. The maintenance costs of the software would also be negligible. The cost of maintaining the additional computers needed to support the OTV system would not be negligible.

9. SYSTEM SUPPORT REQUIREMENTS

"System support is viewed as the composite of all considerations necessary to assure the effective and economic support of the system throughout it's life cycle"²⁴. System support consists of supporting the ground hardware and software, the on-orbit OTV and the space shuttle.

Supply support includes all spares, repair parts, consumables, special supplies needed to support prime mission, oriented equipment, software test and support equipment transportation and handling, ground facilities and training²⁵. Supply support for the OTV system includes repair parts, consumables, special supplies, etc., (used by the ground station during operation), the OTV and software contractor during construction, and the OTV contractor during transportation.

Test and support equipment are needed by the OTV contractor during construction and transportation, and by the ground station during operation. The ground station

24. Blanchard, Benjamin S., and Fabrycky, Wolter J., Systems Engineering and Analysis (New Jersey: Prentice-Hall Inc., 1981), p. 449.

25. *ibid.*, p. 450.

test and support equipment should already be in place and new support equipment should not be necessary. The OTV test and support equipment will be complex, however the contractor test and support group should have this equipment available.

The OTV will be transported once from where it is constructed to where it will be launched. After that, the transportation and handling will no longer be needed.

Personnel needed for construction, testing, and transportation of the OTV are highly trained and specialized professionals. They are to be provided by the contractor in such numbers that the construction phase does not exceed five years. After the OTV is operational, two to six individuals will be required at the ground station to be dedicated to flying it's mission. Should any major problems arise, the vehicle contractor would be contacted and asked for assistance. Since the amount of failures that can be fixed from the ground is small, no permanent subsystem specialists will be retained. The ground software group will consist of individuals skilled in computer programming. There should be enough programmers such that the ground software would be operational within three years after design specifications are received from the contractor. The people at the station must be

trained to operate the software. After software delivery, the contractor will be asked to provide on-line assistance with any problems that may arise.

FACILITIES - The facilities required by the OTV system are:

OTV construction facilities/test
Launch facilities
Ground station
Software coding facility/test

DATA SYSTEMS - A computer system capable of supporting the OTV on-orbit is required. This includes all computers and data storage that the system would require.

SOFTWARE - Software written to support the OTV on-orbit, as well as the software contained on board the vehicle that is used to perform it's on-orbit functions are required by the OTV system.

10. LIFE CYCLE COST ANALYSIS

The total system cost²⁶ is made up of three parts; research and development, construction, and operation costs. Overall cost breakdown is given in Figure 23. An existing study²⁷ on the life cycle costs of an OTV system estimated total life cycle costs at 10.6 billion dollars for a chemical OTV system. The operations costs overwhelmed the research and construction costs. The total proportion of operating costs were estimated at 83% of total life cycle costs. This is due to the large cost of refueling and on-orbit maintenance. The cost of research and development was 15% of the life cycle costs and the construction costs were only 2% of the final costs. This life cycle cost analysis translates directly to an ion-propelled OTV. There would be more money needed for research and development, but this is a small fraction of the total life cycle cost. Using a factor of 1.5 times

26. *ibid.*, p.490.

27. Acaluori, Conrad and Jenkins, Technology Requirements for Future Earth to GEO Transportation Systems. Seattle Washington, 1980. N80-20269. p 12.

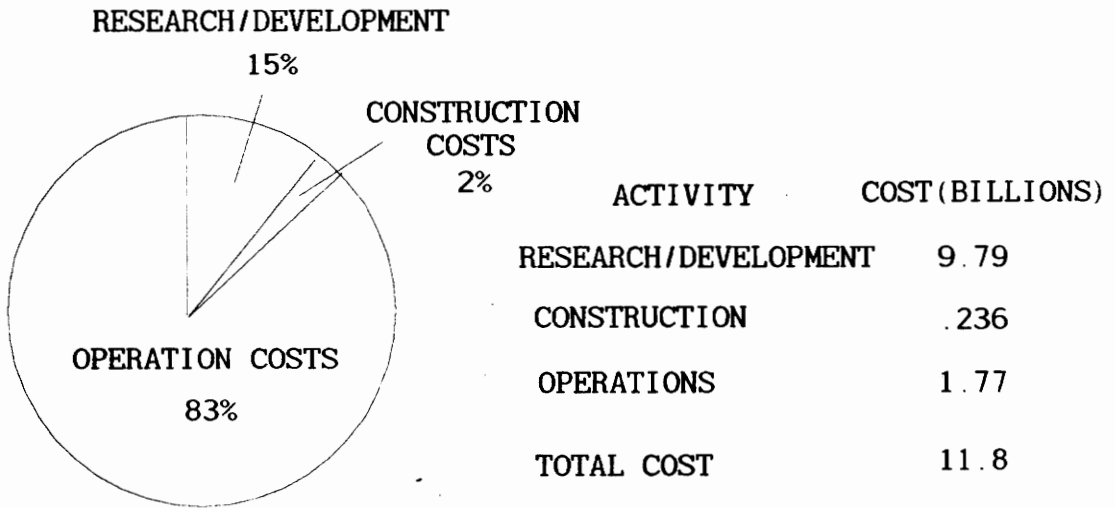
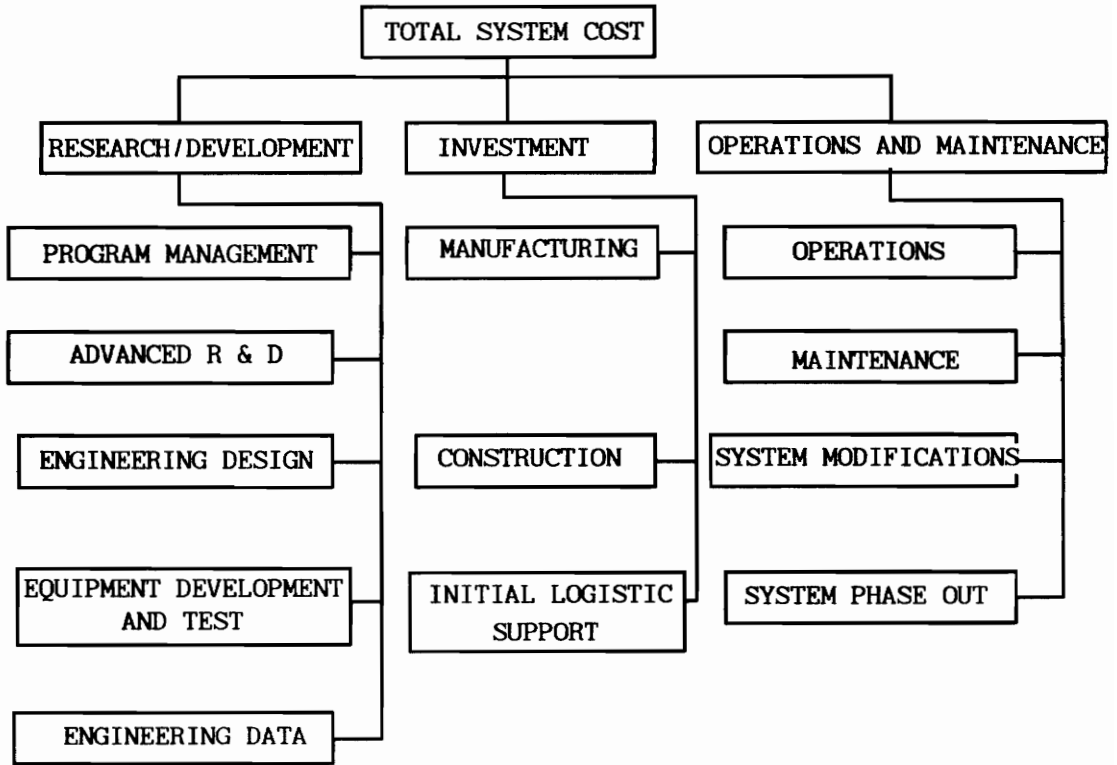


FIGURE 23. SYSTEM COST BREAKDOWN

design cost, a life cycle cost estimation of 11.8 billion is achieved. The costs for this system include all research and development, construction and operating costs. The operating costs would be largely paid by the customer whose satellite is being transported, but they are still important so that the appropriate fares can be charged to the customer

Retirement of the system is treated as part of operations, since the de-orbit procedure is just like another mission. No production or transportation equipment needs to be retired. The additional computers (if any) can be absorbed by the ground station to do other work.

11. CONCLUSIONS

The feasibility of an ion-propelled vehicle that is more economical than a chemically or nuclear propelled vehicle depends on the specific weight of the power plant. In this paper a value of .3 kw/kg was used in the mass calculations. This number is not achievable with present technologies. Present values are five to ten times less than .3kw/kg. This means that the mass of the power plant presented in this design is 62 to 140 metric tons too small. In relation to the rest of the vehicle, this presents an impossible proportion. The .3 specific power was based upon research done in 1961 that predicted this as a reasonable estimate for future systems. If the shuttle capacity is used as a limiting factor, then the smallest acceptable specific weight ratio is .175. This has not been realized. For this reason the ion-propulsion concept has not been selected by NASA for it's orbital transfer vehicle. NASA has contracted Martin Marietta to build a chemically propelled OTV.

If breakthroughs in power production and materials can permit the specific power of ion-propulsion systems to increase, they will become an alternative to chemically propelled vehicles.

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13. VITA

RICHARD WYATT BREWSTER JR.

D.O.B. AUGUST 20, 1961

**EDUCATIONAL BACKGROUND : BACHELOR OF SCIENCE FROM THE
PENNSYLVANIA STATE UNIVERSITY IN AEROSPACE ENGINEERING.**

**EMPLOYMENT HISTORY : WORKED FOR GENERAL ELECTRIC SPACE
SYSTEMS DIVISION AS A TEST AND EVALUATION ANALYST FROM
1985 TO 1989.**

**CURRENTLY WORK FOR LOCKHEED MISSILE AND SPACE COMPANY
AS A SYSTEM ENGINEER.**

R. W. Brewster