INTRODUCTION

This study of Reentry Vehicle (RV) systems and their associated operations was conducted for the Department of Transportation/Office of Commercial Space Transportation. The purpose of the study was to investigate and present an overview of reentry vehicle systems and to identify differences in mission requirements and operations. This includes reentry vehicle system background, system design considerations, description of past/present/future reentry systems, and hazards associated with reentry vehicles that attain orbit, reenter, and are recovered.

A general literature search that included the OCST data base, NASA, Air Force, and other technical libraries and personal contact with various government or private industry organizations knowledgeable in reentry system vehicles was performed. A reference page is provided at the end of this report. A history of early manned reentry vehicle launches is shown in Appendix I. A listing of some of the agencies and companies found to be most knowledgeable in the reentry vehicle area is provided in Appendix II. The following sections provide more detailed information on reentry system vehicles.

A. Background - The development of reentry vehicles began in the late 1950's due to the need for Department of Defense and Central Intelligence Agency photo reconnaissance of Soviet ICBM sites. NASA has also been involved in the use of reentry vehicles since the early 1960's, including manned space programs Mercury, Gemini and Apollo. The following sections describe the evolution of reentry system development in the United States and foreign countries:

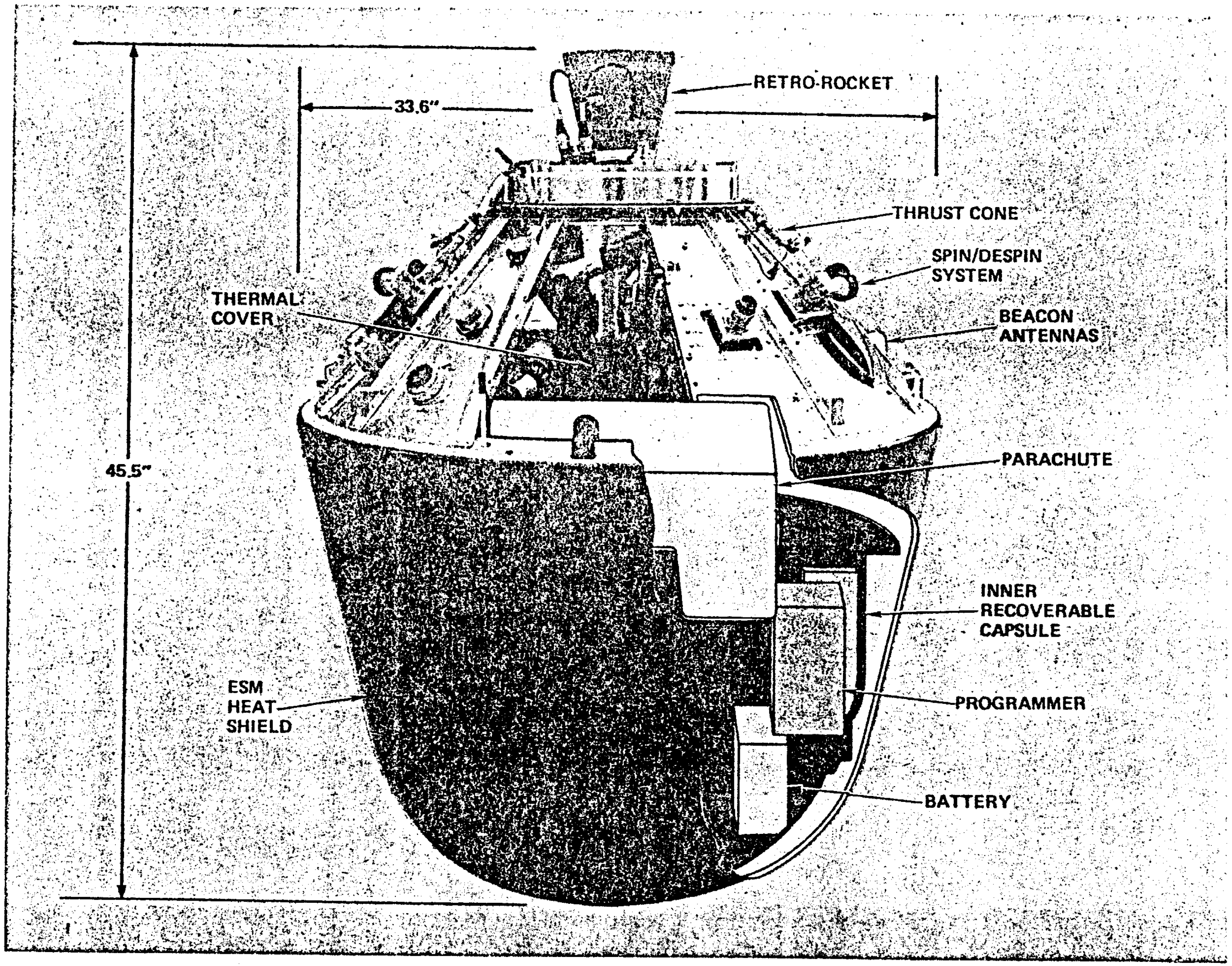
1. Discoverer[1] - The Discoverer program was of major importance because it provided a vehicle for testing orbital maneuvering capability and reentry techniques and it played a large role in enabling the first United States manned space flights to be conducted in Project Mercury. This program also advanced technology required for the development of the surveillance satellites used later by the Department of Defense.

Between 1959 and 1962, there were 38 launches conducted at Vandenberg Air Force Base by the US Air Force. The final three missions all had similar ejection capsules and were typical of many other missions. After 1962, this type of work was classified. The purpose of these missions was to provide military space research, develop reentry capsule recovery techniques, and perform biological research.

The Discoverer was built by General Electric and launched aboard a modified Thor Intermediate Range Ballistic Missile (IRBM). It was boosted into orbit by a second stage Agena A or B rocket. Once there, gas-jet thrusters oriented the vehicle so that the reentry capsule could deorbit. After the orbital portion of the mission was completed, ejection of the capsule from the nosecone was accomplished and retrorockets were fired to initiate reentry. After reentry into the atmosphere, and while descending over the recovery site, a parachute pulled the capsule away from its heatshield, which fell into the Pacific Ocean. See **Figures 1 and 2**[2]. The recovery capsule was then either retrieved by ship after impact in the ocean or, in several cases, air-snatched while descending by C-119 transport aircraft.

The final three Discoverer missions all had similar ejection capsules and were typical of many other missions. The orbiting vehicle, which included the Agena second stage and reentry capsule, was 7.62 meters long and 152.4 cm in diameter. The bowl-shaped capsule was 84 cm in diameter, 68.6 cm in depth, and weighed approximately 227 kg.

The Discoverer program, up to the final unclassified mission on February 27, 1962, resulted in 38 launches attempted, 26 spacecraft orbited, 23 attempted capsule recoveries, 8 successful air recoveries, and 4 successful sea recoveries. Two of the Discoverer missions did not contain reentry capsules. On November 22, 1961, the Department of Defense mandated that all military spacecraft launches would be classified. The *Tables of Earth Satellites*, compiled by Britain's Royal Aircraft Establishment, shows that 27 capsules were placed into orbit between 1963 and 1971, designated only as the vehicles on which they were launched (Atlas-Agena's B and D, Thor-Agena & Titan-Agena). **Table 1** shows a recap of past Discoverer missions between 1959 and 1962[3].



Source: Satellite Recovery Vehicle, GE Aerospace Doc. No. 89SDS2064, April 89

Figure 1. Discoverer Recovery Vehicle Design

Figure 2 is currently unavailable

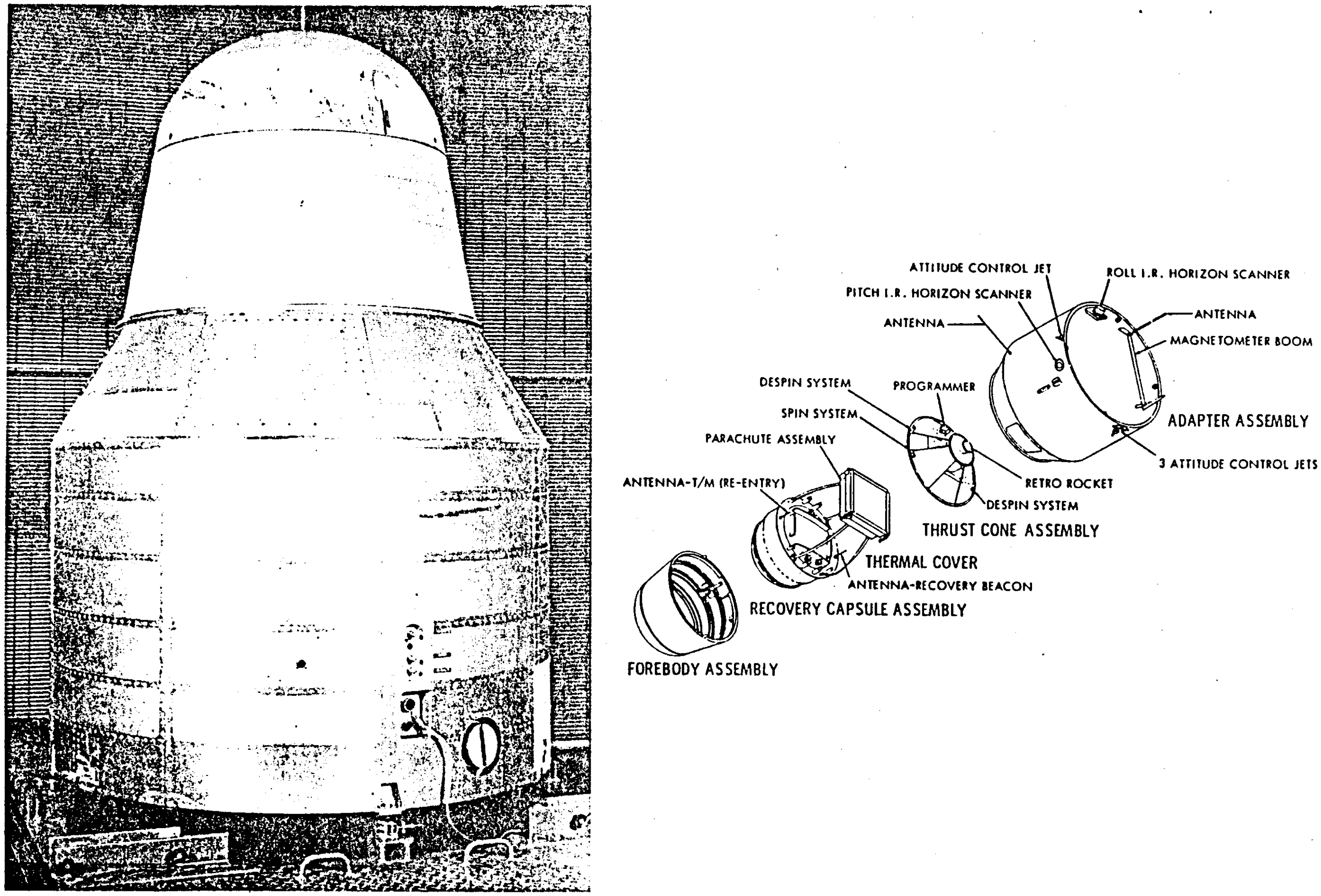
2. Biosatellite[1,4] - This late 1960's NASA program, directed by Ames Research Center and built by General Electric, was intended to study the prolonged effects of weightlessness and radioactivity on living organisms. The agency planned six Biosatellite flights: the first two with plants and organisms, the second two with monkeys, and the third pair with rodents. The program was suspended after the third flight.

The Biosatellite consisted of a conical reentry vehicle, which contained the recovery capsule, and a cylindrical adaptor section. The entire configuration was approximately 206 cm long and the adaptor was 145 cm in diameter at its base. See **Figure 3**[2]. Depending on the experiment weight, the capsule weight varied from 431 to 522 kg. The reentry vehicle consisted of a bowl-shaped fibrous glass heat shield 101.6 cm in diameter. It contained the thrust cone assembly, the recovery capsule, tracking equipment, and the parachute assembly. The recovery capsule, which was mounted inside the heat shield, was a blunt aluminum cone about 79 cm in diameter with 16,987 cu cm of payload space. See **Figure 4**[2]. Prior to reentry, position and attitude control were provided by high-pressure nitrogen gas, three motion-sensing gyros, and six cold-gas thruster jets. These components and the retrorocket, which initiated reentry, were located in the thrust cone assembly. The payload was launched aboard a Thrust-Augmented Delta N (TAD) on its first two missions and the Long Tank Thrust-Augmented Delta (LTTA-Delta) for its final mission.

Bios 1 was launched from Cape Canaveral Air Force Station (CCAFS) on December 14, 1966 on a TAD. A retrorocket failure left the recovery capsule stranded in its 302 x 326 km orbit where it eventually decayed and reentered on February 15, 1967, in the Australian area. Electronic and visual searches of the Australian land area were made; however, the capsule was not recovered. The most likely impact point was estimated by the recovery personnel to be on the eastern half of the continent or in the Tasman sea.

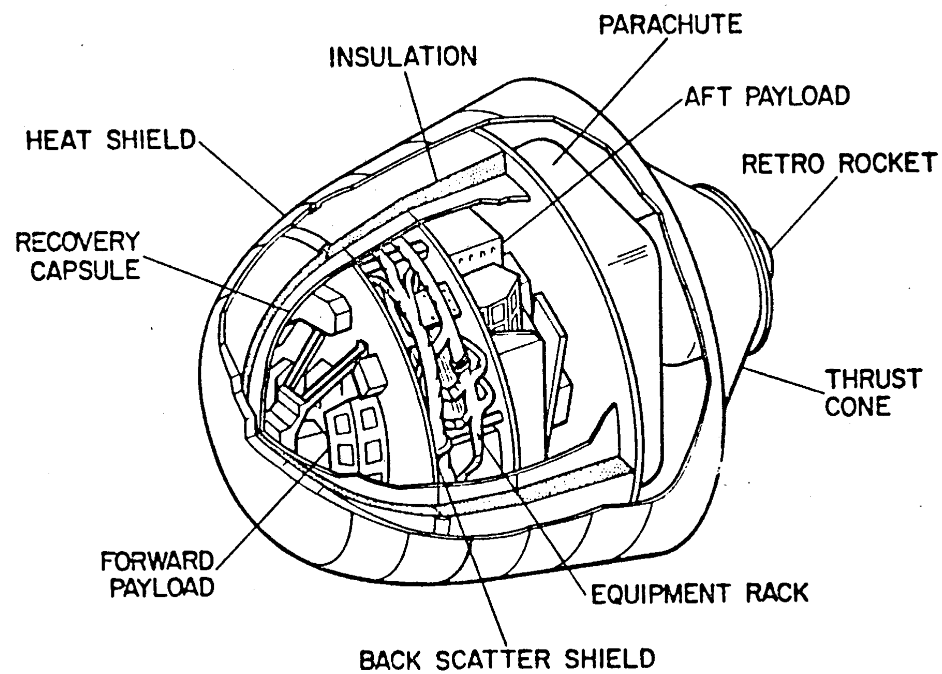
TABLE 1. RECAP OF PAST DISCOVERER MISSIONS

Mission Number	Launch Vehicle	Launch Date	Payload Weight (kg)	Orbit (kg) (incl °)	Results
1	Thor-Agena A	28 Feb 59	590	159X354 (90)	Vehicle tumbled in orbit, reent 5 days later, not recovered
2	Thor-Agena A	13 APR 59	730	229X354 (90)	Capsule ejected orbit 17 lost in Arctic, sat reent after 13 days
3	Thor-Agena A	03 JUN 59	753		Failed to orbit after second stage failure
4	Thor-Agena A	25 JUN 59	743		Failed to orbit after second stage failure
5	Thor-Agena A	13 AUG 59	781	219X724 (80)	Capsule ejected but not recovered
6	Thor-Agena A	19 AUG 59	783	210X850 (84)	Capsule ejected on orbit 17, but was not recovered
7	Thor-Agena A	07 NOV 59	794	159X835	Poor stabilization, capsule was not ejected
8	Thor-Agena A	20 NOV 59	795	193X1664(80.6)	Capsule ejected on orbit 15 but overshot recovery area
9	Thor-Agena A	04 FEB 60	765		Failed to orbit, premature first stage cut-off
10	Thor-Agena A	19 FEB 60	765		Failed to orbit, RSO destruct
11	Thor-Agena A	15 APR 60	790	170X589 (80.1)	Capsule was ejected on orbit 17 but was not recovered
12	Thor-Agena A	29 JUN 60	790		Failed to orbit, second stage attitude was unstable
13	Thor-Agena A	10 AUG 60	850	258X683 (82.8)	Capsule ejected on orbit 17 and recovered from the ocean
14	Thor-Agena A	18 AUG 60	850	186X805 (79.6)	Capsule ejected orbit 17 captured in mid-air by C-119
15	Thor-Agena A	13 SEP 60	863	199X761 (80.9)	Capsule was ejected on orbit 17 but was lost in the ocean
16	Thor-Agena B	26 OCT 60	1091		Failed to orbit, second stage & booster failed to separate
17	Thor-Agena B	12 NOV 60	1091	190X984 (81.9)	Mid-air capsule recovery on orbit 31
18	Thor-Agena B	07 DEC 60	1240	243X661 (80.8)	Mid-air capsule recovery on orbit 48
19	Thor-Agena B	20 DEC 60	1060	209X631 (82.8)	Infrared experiments, no reentry capsule
20	Thor-Agena B	17 FEB 61	1110	228X786 (80.4)	Programmer failure, no capsule ejection
21	Thor-Agena B	18 FEB 61	1110	240X1069(80.7)	Infrared experiments, no reentry capsule
22	Thor-Agena B	30 MAR 61	1150		Failed to orbit, second stage control system malfunction
23	Thor-Agena B	08 APR 61	1150	295X651 (81.9)	Capsule orbited, decayed 23 May 62
24	Thor-Agena B	08 JUN 61	1150		Failed to orbit, second stage ignition malfunction
25	Thor-Agena B	16 JUN 61	1150	222x409 (82.1)	Capsule recovered from ocean on orbit 33
26	Thor-Agena B	07 JUL 61	1150	228X808 (82.9)	Capsule recovered in mid-air on orbit 32
27	Thor-Agena B	21 JUL 61	1150		Failed to orbit, RSO destruct
28	Thor-Agena B	03 AUG 61	1150		Failed to orbit, second stage control system malfunction
29	Thor-Agena B	30 AUG 60	1150	152X542 (82.1)	Capsule recovered from ocean on orbit 33
30	Thor-Agena B	12 SEP 60	1150	235X546 (82.6)	Capsule recovered in mid-air on orbit 33
31	Thor-Agena B	17 SEP 61	1150	235X396 (82.7)	Capsule separation failed
32	Thor-Agena B	13 OCT 61	1150	234X395 (81.7)	Mid-air capsule recovery on orbit 13
33	Thor-Agena B	23 OCT 61	1150		Failed to orbit, launch vehicle shut down prematurely
34	Thor-Agena B	05 NOV 61	1150	227X1011(82.7)	Malfunction prevented capsule ejection
35	Thor-Agena B	15 NOV 61	2100	238X278 (81.6)	Capsule recovered in mid-air on orbit 13
36	Thor-Agena B	12 DEC 61	1150	241X484 (81.2)	Capsule recovered in the Pacific
37	Thor-Agena B	13 JAN 62	1150		Failed to orbit, malfunction following second stage ignition
38	Thor-Agena B	27 FEB 62	1150	208X308 (82.2)	Capsule recovered in mid-air after 65 orbits



Source: Satellite Recovery Vehicle, GE Aerospace Doc. No. 89SDS2064, April 89

Figure 3. Biosatellite II Spacecraft



Source: Satellite Recovery Vehicle, GE Aerospace Doc. No. 89SDS2064, April 89

Figure 4. Biosatellite II Spacecraft Components

The second flight was more successful though not all mission objectives were accomplished. The capsule, containing 13 plant and animal specimen experiments that would be subjected to doses of radiation, was launched on September 7, 1967 aboard a TAD from CCAFS and was scheduled to orbit for three days. The mission was cut short with a successful recovery at 45 hours due to communication problems and the threat of severe weather in the recovery area.

Bios 3, with a pig-tailed monkey on board, was launched on June 28, 1969 on a LTTA-Delta from CCAFS. The monkey was attached to 24 sensors to study the effects of weightlessness on various bodily functions. He had been trained to feed himself by pushing various buttons, but once in orbit he became sluggish and refused to eat. NASA aborted the scheduled 30-day mission after nine days. The capsule containing the primate was successfully recovered.

3. DOD Satellite Film Canister Reentry Systems[1] - Beginning in the early 1960's the Air Force and the CIA began using reentry capsules to retrieve reconnaissance film from satellites. The project was conducted under the code-name "Keyhole" and successive satellite generations were given "KH" numbers that are still in use.

The early programs, Close Look and Area Survey, ran concurrently from 1962 until 1984 with over 250 missions to their credit. These programs were slowly phased out and used as fillers with the advent of Big Bird in 1972. Big Bird (KH9 Hexagon) was also known as LASP (Low Altitude Surveillance Platform) and provided US intelligence with a multitude of data. The final Big Bird was destroyed in the Titan failure at Vandenberg AFB in 1986.

The LASP had a mass of over 11,000 kg in orbit and was 15.2 meters long and 3 meters in diameter. It deployed two large solar arrays and a six meter antenna and carried four to six pods used to return exposed film. The Titan 3D was specially developed as the launcher. The earlier Area Survey and LASP satellites had both radio transmitting (for area survey pictures) and reentry pod capability (for close-look capability). As technology has advanced, imaging systems have developed to an extent that they can perform the close-look function, eliminating the need for film returns.

4. Current US and Foreign Reentry Vehicle Concepts/Programs[5] - US and foreign entities are increasing research and development of new reentry systems. Stanford University researchers have identified reentry capsule services as one of the fastest growing international aerospace markets in the 1990's. Estimates of the US market alone yield an average yearly growth of nearly 50% during the next five years, with 4-5 flights/year projected by

1995. Equal growth is anticipated in Europe and Japan. Most of the current reentry systems being researched and developed (domestic and foreign) are using technology from the 1960's. Though heat shield materials and spacecraft subsystems have been improved, the basic design remains the same. Most of the current and proposed capsules are ballistic in design to simplify mission operations.

a. Germany - Germany has vigorously pursued reentry capsule studies of 10-15 separate concepts during 1986-1990. Presently, the EXPRESS (EXPeriment REturn Service from Space) is under study. German experiments have flown on Chinese and Soviet capsules and are planned for additional flights over the next two years. Recent German studies have tended to larger capsules (over 800 kg) to accommodate a wide range of microgravity payloads. However, German industry and space agency management appear close to reaching a consensus that an initial capsule should employ smaller Western launchers in early missions.

b. Italy - Italian interest in reentry systems dates back to 1987-1988 and has focussed on small capsule options for available Western ELV's. Technical efforts by Aeritalia and support from the Italian Space Agency (ASI) are enabling Italy to develop technology for reentry systems. ASI support for reentry system technology has resulted in an extensive definition and preliminary design study of the Carina capsule.

c. France - France has not pursued reentry capsules as aggressively as Germany and Italy. Preoccupation with the major European programs (Hermes, Ariane 5), less emphasis on microgravity science within the French space effort and a solid domestic military reentry technology base have all contributed to placing a lower priority on reentry capsules. Instead, concepts proposed have been driven by a desire to fill secondary payload capacity on Ariane boosters. France is currently working with Germany to develop a large Apollo-type capsule (1,812 - 2,600 kg) for Ariane 4/5 and has completed a concept definition study. The Microliner, a Discoverer-type capsule flown to geosynchronous orbit, has also been proposed as an Ariane 4 secondary payload.

d. Great Britain - The British have a strong reentry technology base achieved during 1960-1980 through the development and operation of strategic weapons systems. During 1988-1989, British Aerospace proposed the Multi-Role Capsule (MRC) concept, which is a semi-ballistic configuration that can be adapted for manned ascent or rescue, or unmanned microgravity science missions. Work on the MRC was initiated to compete for the NASA Space Station crew rescue vehicle (ACRV) but it was not selected.

e. Japan - Japanese government and industry have targeted reentry capsules as a strategic technology for development during the early 1990's. The National Space and Development Agency (NASDA) and the Ministry of International Trade and Industry (MITI) agencies, with Nissan, Marubeni,Mitsubishi, and other industrial and trading companies, are closely monitoring US, German, and Italian capsule R&D programs. In addition, NASDA is sponsoring the domestic development of a small experimental capsule to collect reentry data in support of their manned spacecraft project. This capsule is scheduled to fly as a piggyback payload in 1993 on Japan's two-stage heavy launch vehicle, the H-2.

f. Soviet Union - The Soviet Union's hard currency requirements have pushed Glavkosmos, the Photon Design Bureau and Soyuzkarta to rapidly commercialize and market services in the West. An aggressive booster and services pricing policy, reliable technology and a wide range of services and systems have generated important successes, most notably in Germany; Kayser-Threde and Intospace changed suppliers to fly the Cosima-2 protein crystal experiment in September, 1989, on the Resurs-F. A good ground infrastructure capable of supporting Western scientists' laboratory, communications, and data requirements complements the on-orbit service during the pre-launch and post-recovery phases.

The Soviet Union has implemented incremental improvements in flight-proven systems flown for manned and military photo-reconnaissance missions. The original Vostok spherical module has been adapted for use as Photon, Resurs-F, and the life sciences Biocosmos capsules. Glavkosmos recently announced that its improved Nika reentry vehicle, outfitted with solar panels for long duration flights, is slated for commercial introduction in 1993-1994.
Outside the commercial realm, NASA and Soviet scientists continue to cooperate on joint Biocosmos biosatellite missions under the Joint US/USSR Biological Satellite Program started in 1975. Since this began, American space biologists have participated in seven missions covering biological and radiation physics experiments. An additional flight is expected in 1991 under current agreements.

g. China - The Chinese Academy of Space Technology (CAST) undertook development of domestic reentry system technology in the early 1970's in support of military photo-reconnaissance and earth resources missions. The first capsule flew in 1975 and has since flown over 10 missions with land recoveries in central China.
The China Great Wall Industry Corporation has shown interest in reentry system technology and has flown two microgravity experiments for Matra Espace of France in August of 1987.

h. United States - Presently, in the United States, two NASA-sponsored reentry capsule programs are expected during the 1990's. First, the NASA Office of Commercial Programs, CCDS (Centers for Commercial Development of Space), Center for Aerospace Research, issued Requests for Proposals for the Commercial Experiment Transporter (COMET) Flight Program in the summer of 1990. The COMET program is designed to be the first US space system to be launched, controlled, and recovered by the commercial sector. This university-managed program plans one launch a year for three to five years. Payloads will range between 20 and 120 kg, with 15-30 days mission duration.

In addition, the NASA Life Sciences Office LifeSat program is currently under study with first launch attempt planned for late 1994. LifeSat is a large sophisticated capsule (1,200 - 1,400 kg) flown on a Delta-class booster. It is intended for long duration (up to 60 days) radiation biology experiments in support of NASA's Human Exploration Initiative.

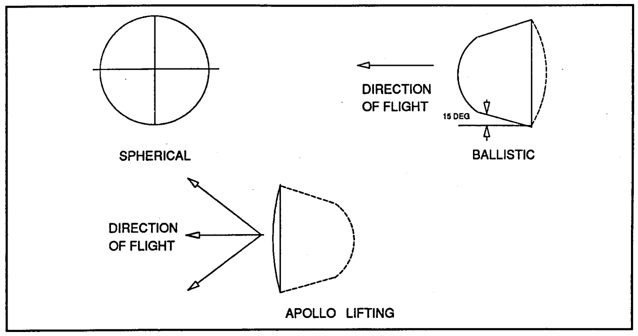
US entrepreneurial companies have been active in commercializing reentry technology that had been classified or government-sponsored. COR Aerospace, Instrumentation Technology Associates, Orbital Recovery Corporation, and Space Industries have proposed both ballistic and lifting reentry vehicle designs. **Table 2**[5] lists present reentry system projects in the US and abroad.

B. Reentry Vehicle Design Considerations - Reentry vehicles provide researchers in several diverse fields of interest with a method of access to space for extended periods of time and eventual intact recovery of the experiments on land, air or water. Some vehicle capability factors that are considered when designing these vehicles are: 1) being launched by a variety of launch vehicles, 2) operating in low earth orbit as a free-flying unmanned laboratory, and 3) an independent atmospheric reentry with an air-snatch recovery or a soft landing at a preselected site (land or water), providing the experimenter with rapid access to the payload. Some specific design considerations are as follows:

> **1. Shapes** - The aerodynamic shape configuration (ballistic or lifting) of a reentry vehicle determines the severity, duration, and flight path of reentry experienced by the vehicle. This, in turn, affects the vehicle systems complexity and the heating loads on the payload. See **Figure 5**[6].

TABLE 2. CURRENT US AND FOREIGN REENTRY CAPSULE PROGRAMS

Country	Sponsor (Capsule)	Capsule (Configuration)	Booster	Diameter (in)	Total Mass (kg)	Payload Mass (kg)	On-Orbit Duration
USA	NASA/CCDS	TBD	Small ELV	TBD	TBD	80-120	15-30 Days
USA	NASA (Lifesat)	Discoverer Type Ballistic	Delta	80	1363	409	60 Days
USA	COR Aero (Deliver 24)	Sphere Ballistic	Small ELV	24	311	113	N/A
USA	COR Aero (Cheops 64)	Discoverer Type Ballistic	Small ELV	64	1180	714	N/A
USA	ORC (Zeus)	Discoverer Type Ballistic	Taurus	75	1270	730	7-60 Days
USA	SII (N/A)	Gemini Type Ballistic	Small ELV	N/A	N/A	N/A	N/A
Germany	Dornier (Raumkurier)	Gemini Type Ballistic	Long March 2	90	1500	450	7-30 Days
Germany	MBB/Dara (Express)	Discoverer Type Ballistic	M-3SII Conestoga	55	800	300	7 Days
Italy	Aeritalia (Carina)	Gemini Type Ballistic	Scout II	44	530	100	7-21 Days
France	MAN Technologie (Ariane 4/5)	Apollo Type Ballistic	Ariane 4 Ariane 5	142	1812-2600	400-900	7-21 Days
France	Matra Espace (Microliner)	Discoverer Type Ballistic	Ariane 4	52	1005	290	Up to 90 Days
UK	British Aero (Multi-Role)	Apollo Type Semi-Ballistic	Ariane 4	156	7000	290	12-30 Days
Japan	NASDA (Exptl)	N/A Ballistic	H-2	39	200	N/A	N/A
USSR	Glavkosmos (Photon)	Sphere Ballistic	N/A	72	6300	500	14-30 Days
USSR	Glavkosmos (Resurs-F)	Sphere Ballistic	N/A	72	6300	500	14-30 Days
USSR	Glavkosmos (Biocosmos)	Sphere Ballistic	N/A	72	6300	500	14-30 Days
USSR	Glavkosmos (Nika)	Sphere Ballistic	N/A	72	N/A	1200	TO 120 Days
China	China GWIC (FSW-1)	Discoverer Type Ballistic	Long March 2	63	1900	20-150	5-8 Days
China	China GWIC (FSW-2)	Discoverer Type Ballistic	Long March 2	63	1900+	150-300	10-15 Days



Source: NACA Research Memorandum L58E07a
Figure 5. Comparison of Capsule Shapes

A lifting reentry vehicle has many operational advantages over a non-lifting vehicle. Primarily, the reentry loads can be minimized to almost any desired level, with flexibility in landing site selection. The vehicle has the ability to deviate its reentry trajectory to reach selected landing sites "cross range" from the orbital track, and to fine tune deorbit propulsion system errors. Spherical and ballistic vehicles can only deorbit to selected sites which are on the orbital ground track. Spherical shapes are used on the Soviet Photon spacecraft, and the ballistic reentry shape is used on the German EXPRESS (EXPeriment REturn Service from Space) reentry vehicle.

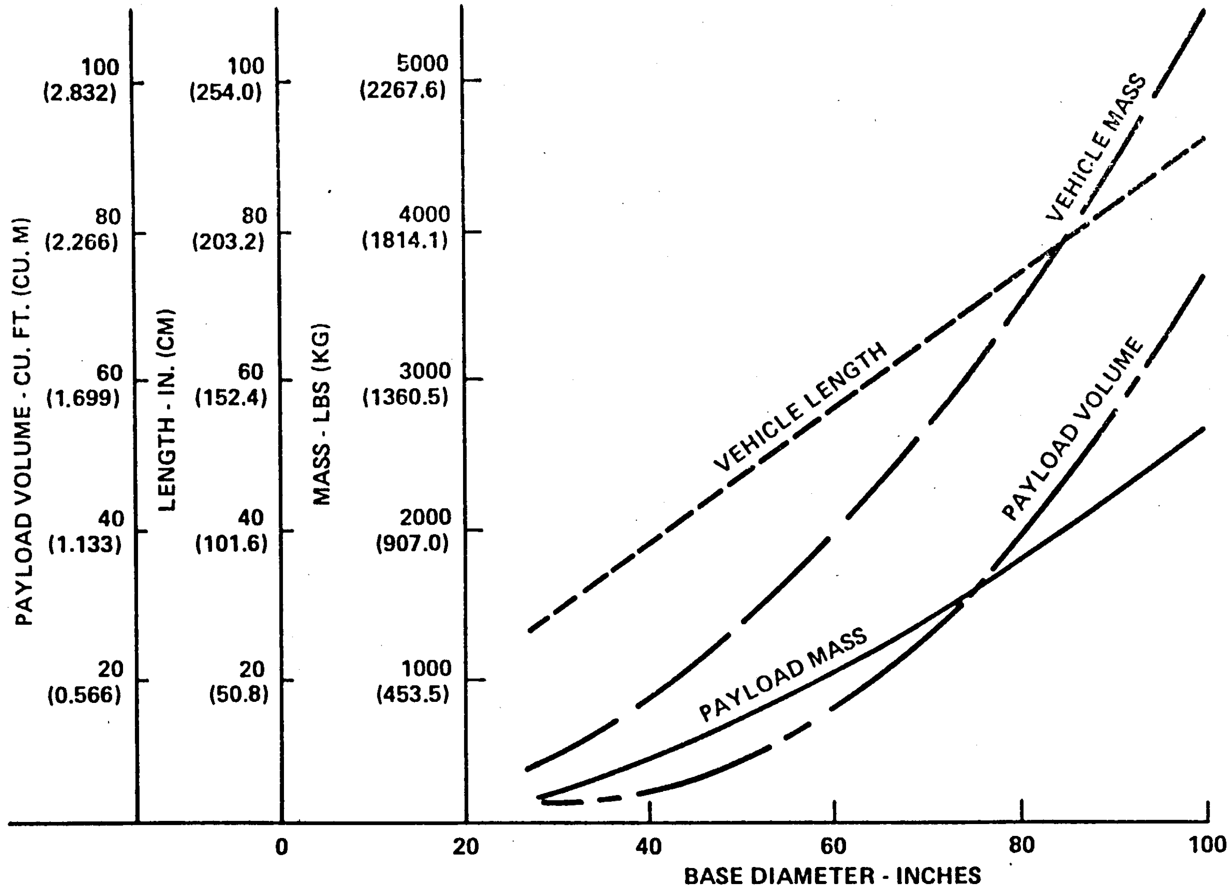
A disadvantage of the lifting shape over the non-lifting shape lies in the complexity and high cost associated with guidance and control of the lifting vehicle. A failure of the guidance or control system could render the vehicle uncontrollable and cause it to diverge a great distance off course.

The simple, blunt-body configuration similar to the NASA Biosatellite, the Air Force Discoverer, and the Chinese capsule shapes is the shape most often used. Once reentry has been initiated, the body essentially falls uncontrolled through the atmosphere with little excursion from the nominal trajectory; however, there is the penalty of higher g-loadings than a lifting shape. Various payload mass-volume combinations for the blunt-body configuration are shown in **Figure 6**[2].

2. Sizes - The size of a reentry vehicle has depended, for the most part, on the capabilities of available launch vehicles. For example, the largest size of a blunt-nose configuration that is compatible with the Scout launch vehicle is one with a 96.5-cm diameter base, while a Delta II can accommodate a vehicle with a 254-cm diameter base. However, Ariane now offers a limited capability to configure the launch vehicle to meet the boost requirements of the reentry vehicle. In general, the government-funded vehicles have been designed for the large (Delta II) class of expendable launch vehicles while commercial design has been targeted to a smaller class, such as the Scout, Pegasus, or Amroc. The reentry vehicle user (government or commercial) has the option of using a fully dedicated launch vehicle, or riding "piggyback" as a secondary payload.

Other considerations that determine size are sufficient resources for life science and other payloads, the adequacy of available power, and costs. There are many other tradeoffs and options associated with reentry vehicle design. See **Table 3**[7] for candidate RV launch vehicles. See **Table 4**[7] for the results of tradeoff studies by NASA Ames Research Center for a set of selected vehicle sizes.

3. Subsystems Requirements - A payload module is normally used in a reentry vehicle to separate the experiment from the support systems. However, in some very limited cases, where an experimental payload may not require any support during the mission, the payload could be mounted inside the payload envelope within the vehicle. In addition to a payload, which contains life sciences, materials or other experiments, a reentry vehicle usually requires several support subsystems.



Source: Satellite Recovery Vehicle, GE Aerospace Doc. No. 89SDS2064, April 89

Figure 6. Reentry Vehicle Mass-Volume Combinations

Table 3. Candidate RV Launch Vehicles

Launch Vehicle	Manufacturer	Orbit (Km)	Inclination (deg)	Payload Cap(Kg)	Price ($Mil)	$ Per Kg
DELTA II 6920	MCDAC	370x370	28.7	3682	33	8963
DELTA II 7920	MCDAC	370x370	28.7	4773	33	6914
FBM	Lockheed	370x370	28.5	505	12	23783
ILV-1	AMROC	370x370	90	1368	12	8771
ILV-S	AMROC	370x370	90	268	7.5	27966
LIBERTY 1A	Pacific Am. Launch Serv.	370x370	90	182	2	11000
PEGASUS	OSC/HERCULES	370x370	0	273	6	22000
TITAN II	Martin Marietta	185x370	63.4	2045	UNK	UNK
PROTON SL-12	Glavkosmos USSR	370x370	51.6	10682	14	1310
H-2	Heavy Industries Japan	370x370	32	8727	UNK	UNK
LONG MARCH CZ-3	Great Wall Industries China	370x370	31.1	6059	30	4951

Table 4. Reentry Vehicle Characteristics

BASE DIAMETER - cm	97	132	163	191	218	254
SPACECRAFT MASS - kgs	204	463	771	1134	1361	2540
BALLISTIC COEFFICIENT - kg/M^2	385	449	517	567	591	680
PAYLOAD + BATTERY MASS - kg	82	227	374	563	925	1497
PAYLOAD MASS - kg	41	113	204	318	408	567
PAYLOAD SIZE - Dia X Ht - cm.	69X31	89X48	107X61	125X76	140X76	163X76
PAYLOAD VOLUME - cu cm	11325	31143	59454	93428	116078	167038
BATTERY ENERGY - KWhrs	7	20	31	45	50	170
EXPERIMENTS ACCOMMODATED	1	1-2	2	3	4	6
CANDIDATE LAUNCH VEHICLE	SCOUT	SCOUT	AMROC	AMROC	AMROC	DELTA

Many of these systems provide the same support that is used for any other orbiting satellite, such as providing the payload with electrical power, thermal control, command signals and telemetry capability. However, for a reentry vehicle, additional subsystems are normally used to effect controlled deorbit, reentry, and an intact, soft landing or air recovery of the vehicle. See **Figure 7**[8] for a block diagram of typical reentry vehicle subsystems. Some typical spacecraft subsystems are as follows; systems that apply only to a reentry vehicle are shown in italics:

a. Attitude and Spin Control Subsystem - This system normally is composed of sensors, control electronics and several low thrust thruster assemblies that perform a variety of functions, such as:

- to stabilize the reentry vehicle,
- to convert errors in orbit placement or *to trim the orbital period to adjust a projected orbital ground track,*
- to maintain reentry vehicle orbital altitude,
- *to spin the reentry vehicle to induce artificial gravity or to inertially fix the direction of the main retro-rocket(s) thrust vector, and*
- *to trim the deorbit maneuver to null errors in the performance of the solid rocket burn.*

b. Deorbit Propulsion Subsystem *- This system provides the required velocity decrement to deorbit the reentry vehicle and place it on a trajectory that is aimed at the landing site. A typical change in velocity requirement to do this may be approximately 290 m/sec for low-altitude satellites in near-circular orbit and for landing sites in the orbital plane.*

c. Structures - Structural design takes into consideration, in addition to the loads imposed on any other satellite, *the loads imposed during deorbit, reentry, and landing.*

d. Power Subsystem - The power source for the reentry vehicle is a critical item, as with other satellites, and is typically a tradeoff among batteries (and types of batteries) vs fuel cells vs solar power systems.

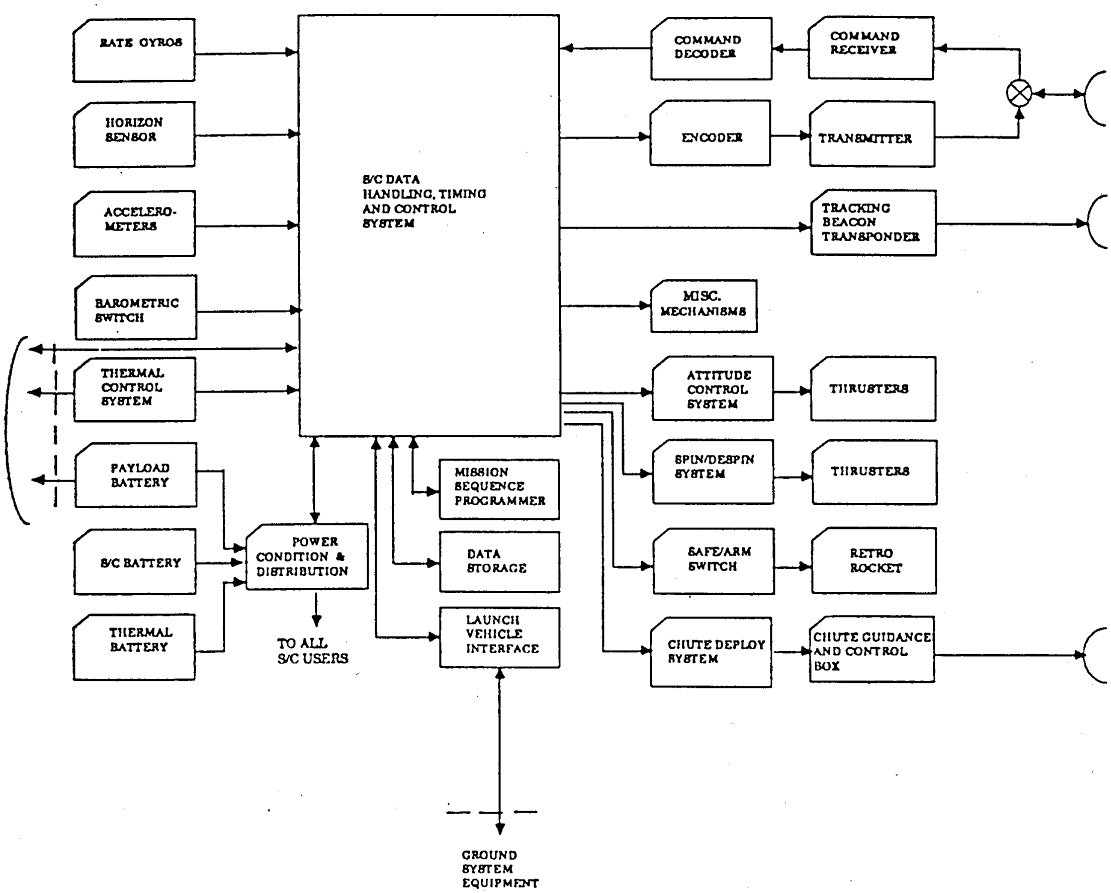
e. Power Interface Units - These units control and distribute primary power to the payload and the reentry vehicle.

f. Tracking *- A tracking aid, such as a transponder, is normally required in the reentry vehicle as an aid in recovery.*

g. Communications Subsystems - Each payload normally has its own dedicated data and control system that controls payload functions and collects and stores its data between reentry vehicle to Earth communication periods.

h. Reentry Vehicle Parachute Subsystem (or other retardation system) *- This system is designed to retard the reentry vehicle's vertical velocity and provide a relatively soft touchdown. For systems that have parachutes, two types could be used for this application: a conventional type and a lifting parafoil. The advantages of a conventional parachute are reduced weight and less complexity. The lifting parafoil has three advantages over the conventional type: 1) being able to reduce the dispersions associated with the deorbit and reentry trajectories by using its maneuverability to glide to a predetermined point, 2) having the capability of being manually controlled to minimize landing area impact dispersions and, 3) by flairing, to reduce the vehicle impact shock at touchdown.*

i. Reentry Thermal Protection Subsystem *- The function of this system is to protect the reentry vehicle from aerothermodynamic heating during atmospheric entry. Ablative material such as phenolic nylon, elastomeric silicon material (ESM), and white oak have been used in the past to protect against excessive heating. For protection against the considerably lower heating rates that occur on the conical skirt of the vehicle, two types of thermal protection systems have been used: the ablative type or a ceramic-based surface insulation type. Other methods have been investigated, such as reusable heat shields.*



Source: NASA Technical Memorandum 101043, Oct 1988

Figure 7. Block Diagram of a Typical Reentry Vehicle Subsystem

j. Thermal Control Subsystem - The reentry vehicle poses some unique design problems concerning the thermal control and management aspects of the vehicle. If the modular payload concept is used, the vehicle is intended to support and accommodate a wide range of payloads through a generic interface. This wide range of payload types with different associated thermal requirements also implies that the reentry vehicle and payload thermal control system must accommodate a wide range of thermal loads. This includes those generated by biological specimens. The payload module may, depending upon the type of payload, require atmospheric controls within the module. Some controls normally required are:

- *Control of temperature, humidity, and pressure*
- *Control of contaminate levels*
- *Provide for circulation of atmosphere*
- *Provide venting*

C. Reentry Vehicle Operations[8]

1. Pre-Launch - Prior to launch, the payload is integrated into the reentry vehicle. Installation of some experimental specimens and support equipment into the reentry vehicle may be performed before the reentry vehicle is mated to the launch vehicle; however, final installation is normally accomplished on the launch pad, with final payload and reentry vehicle closeout being completed as close to launch as practical. This is done to avoid contamination of the payload and to allow monitoring of the experiments.

2. On-Orbit Considerations

a. Orbital Lifetime - An important advantage of the reentry vehicle is its ability to maintain experiments in orbit for long periods of time, depending on the experiment and limited by the capability of the RV support systems. Several factors affect the lifetime of an RV and these include the power requirements, orbital altitude and inclination, atmospheric density, vehicle mass, coefficient of drag and exterior geometry of the RV.

b. Orbit Selection - The RV can operate in a variety of user-specified orbits or orbits specified by the requirements of a shared launch. The microgravity specifications of the experiment normally drives the altitude of the orbit. Circular orbits within the altitude range of 350 to 900 kilometers are normally used. With a non-lifting RV, which has no lateral maneuvering capability during atmospheric reentry, it is necessary that the orbit inclination of the RV be equal to or greater than the latitude of the pre-selected landing site in order to land at that site.

Although the nominal mission lifetime may be of a specified duration, certain payloads may require shorter durations and emergency deorbit due to an unexpected experimental condition. Another consideration is that recovery at a single site could be delayed by one or more days because of local weather conditions, and a missed deorbit opportunity could cause a considerable delay while waiting for the RV orbit to reposition itself coincident with the landing site. Finally, if parachute recovery is used, it is less difficult to recover during daylight, especially during the cool morning hours when the surface winds are generally lower.

One approach to accomplishing these requirements is to choose a proper altitude, inclination and nodal placement to ensure that the ground track of the satellite permits deorbit and landing at a designated recovery site twice a day during the mission. These orbits are termed "integer orbits" in that the orbits have a repeating ground track each day. Some correction of the orbital parameters after launch may be necessary to adjust for insertion errors and to synchronize the integer orbit ground tracks with the landing site. Other corrections may be required to adjust for drag effects, however, in most cases these will be negligible. It should be noted that the above orbit selection scenario is probably only possible for a dedicated launch of an RV. Shared launches may not permit the independent selection of all orbital characteristics.

If the first payload deposited in orbit is an RV, all orbital maneuvers are limited by the capabilities of the RV Attitude Control System (ACS). These maneuvers may be necessary to make the projected ground track coincident with the landing site. However, if the RV is the last payload deposited in orbit, it is possible that the launch vehicle upper stage may have sufficient remaining performance (if it is restartable) to alter the RV orbital parameters.

3. Deorbit - At the completion of the orbital flight phase, the vehicle may be commanded by ground control, or by on-board sequence programmer commands, to position itself for the deorbit retrothrust maneuver. In an example of a deorbit maneuver, the Attitude Control System takes readings on the local horizon in two orthogonal directions and uses gyroscope measurements to determine the flight direction. The Attitude Control System thrusters position and stabilize the longitudinal axis (and therefore the thrust vector) in the correct attitude with respect to the orbital velocity vector. Thrusters then spin the vehicle about the longitudinal axis to stabilize inertially the thrust vector to within +/- 1^0 (a commonly used 3-sigma tolerance) relative to the required deorbit attitude. Thereafter, at the appropriate time, the main retrorocket(s) fire to decelerate the vehicle and provide a sufficient velocity decrement to deorbit the RV and place it on a trajectory that brings it to a descent over the landing site.

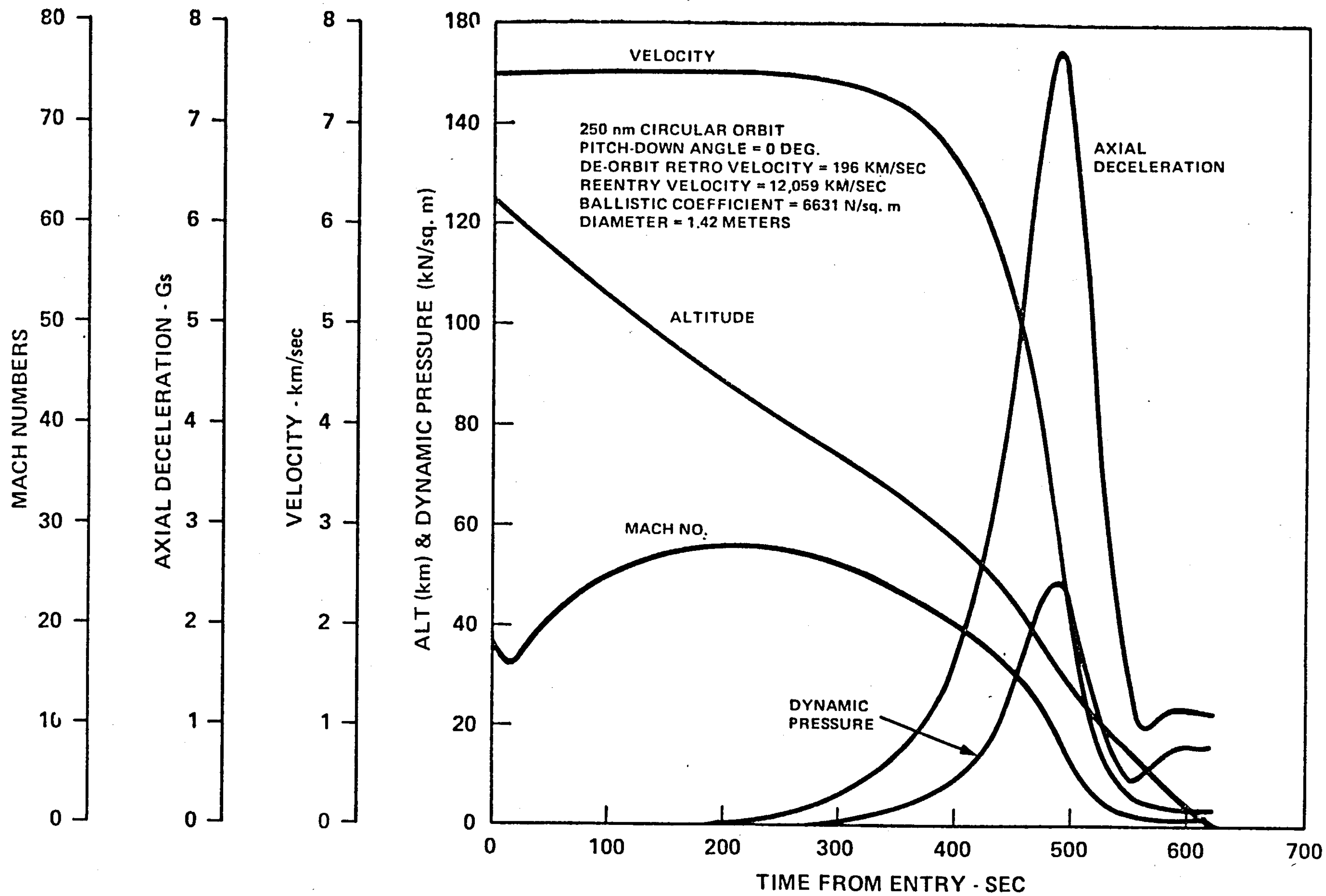
4. Reentry - Following the deorbit maneuver, a set of reverse spin thrusters are used to despin the RV to a relatively low rate of spin in anticipation of entering the upper atmosphere. The ballistic RV, for example, retains the attitude of the deorbit burn maneuver and encounters the atmosphere at an angle of attack of approximately 90 - 110 degrees, depending primarily on orbital altitude. At a low rate of spin, the RV reorients itself into a nose-forward attitude. A lifting RV must be reoriented after the deorbit burn to a nose forward attitude and must be attitude-controlled throughout the reentry phase because of the location of the center of gravity. A summary of the time history of altitude, velocity, and acceleration for a typical ballistic atmospheric entry is shown in **Figure 8**[9]. As an aid to recovery, a radar beacon is normally used on the RV to give the landing site personnel knowledge of the vehicle track from reentry to landing.

Debris is a potential safety and liability concern during reentry. This results from the jettisoning of capsule parts. The jettison technique is useful in reducing the reentry and recovery weights, and simplifies the ablative shield and parachute systems design due to the reduced weights. However, it increases the amount of debris and the associated hazards due to unplanned impacts. Technological developments in the areas of ablatives and parachute systems design have resulted in the capability of RV's to reenter as a single unit. This reduces orbital and reentry debris while reducing the subsystem assembly replacement requirements.

5. Terminal Descent - The RV descends over the landing site through the altitude range of the generally prevalent high winds (i.e., the jet stream) to approximately 6000 meters, for a typical system, where deceleration is initiated. Deceleration for RV's has been accomplished primarily by parachute. At the appropriate altitude, a pilot chute is deployed, which pulls out a drogue chute, thereby slowing and stabilizing the vehicle. The drogue chute, in turn, pulls the main parachute from the RV.

The parachute may be of conventional form or may be a ram-air-filled lifting parafoil. If a conventional parachute is used, the RV will descend vertically to the surface (or to the air-snatch site) somewhere in the area defined by the nominal landing dispersions. If a parafoil is used and is deployed at an altitude of approximately 6000 meters, typical performance characteristics provide the RV with a maneuvering circle of about 16 km in radius.

6. Retrieval Methods - Three retrieval methods have been used to recover RV's. Of the three RV system retrieval methods, air-snatch, water and land, water recovery has been the most widely used by the United States. However, each of the methods has its own distinct advantages and disadvantages. Following is a brief discussion on each of these methods:



Source: NASA Ames, RRS - A Multipurpose Reentry Satellite

Figure 8. Typical Reentry Trajectory Data

a. Air-snatch - This method was used only to support Air Force programs and used modified military aircraft to intercept the descending reentry vehicle parachute lines over the ocean. This reduced impact loads and contamination risks, and removed retrieval operation activities from populated areas.

Air-snatch places costly demands on the retrieval operation, however, as it requires skilled pilots and modified aircraft. Contingency recovery plans, either water or land, must also be incorporated into the design to allow for poor weather in the retrieval zone or missed air-snatch attempts.

b. Water recovery - This has been the most widely used method for the retrieval of unmanned reentry vehicles. It is advantageous over the air-snatch method because it reduces the retrieval crew training requirement. However, this method may require a large recovery crew to insure rapid access to the RV following splashdown. The RV system design is also complicated by the need for flotation systems and recovery aids such as dye markers and beacons. Additional factors include the risk of loss of the RV if the flotation systems fail, as well as the increased refurbishment demands caused by exposure of the RV to seawater.

c. Land recovery - This is being considered as a retrieval method for some reentry vehicle systems. State-of-the-art parachutes and/or parafoils should provide the capability to land an RV without damage to the payload. Various mechanisms such as crushable material in the nosecone may have to be included in the vehicle design to absorb the impact loads and diminish their effects on the payload module.

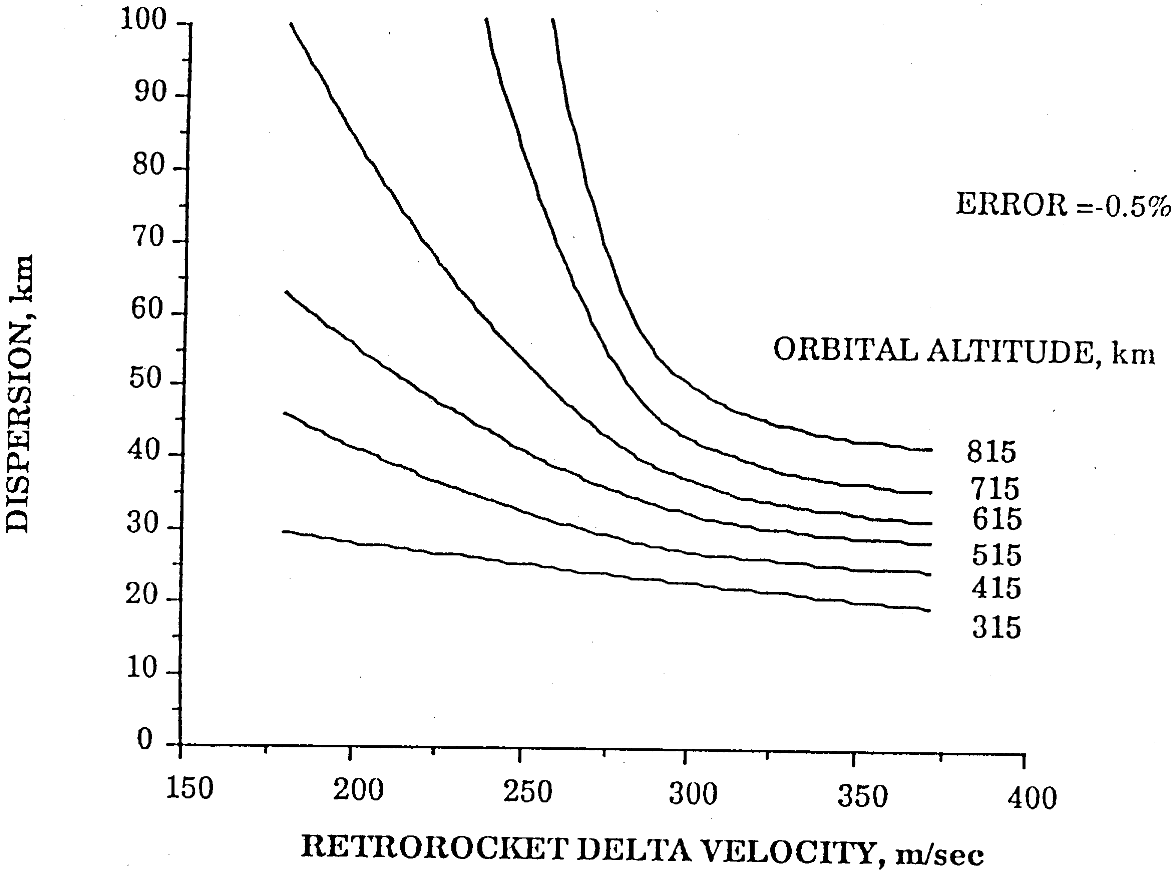
It is desirable by some experimenters that retrieval personnel be able to access the RV quickly to ensure minimum thermal damage to the payload as a result of being exposed to the local environment of the landing site. One major concern with land-based recovery is that it presents additional safety considerations because of population centers.

D. Reentry Vehicle Hazards - The problems associated with launching reentry vehicles differ from other launches into space in that a planned deorbit, reentry, and recovery of the payload is an integral part of the mission. This poses potential hazards should a failure occur during the deorbit, reentry, or recovery phases of the mission. The primary risks are from impact of the payload, impact of other RV debris, or the possible dispersal of hazardous materials. Failures of the payload attitude control system, deorbit propulsion system, and/or reentry deceleration systems influence the location of the impact area of the RV hardware. Most inland landing sites have populated areas either near or in the surrounding areas that could be exposed to impact hazards resulting from failures or errors during deorbit and/or reentry. If a system failure occurred which left the RV in orbit, it will eventually reenter, and potentially survive to impact somewhere on the surface of the Earth. If a normal deorbit is achieved and a subsequent failure occurs, the impact dispersion area may become larger but should remain centered around the planned impact point.

As an example, for a nominal 479 km altitude orbit, the change in velocity required for deorbit is 290 m/sec. A retrorocket has been estimated to deliver the total impulse required for this velocity change to within +/- 0.5% (3-sigma). For a given retrovelocity increment, a non-lifting RV will follow a deorbit trajectory resulting in along-track dispersion due to errors in thrust impulse. Shown in **Figure 9**[8] is an analysis of dispersion for various orbital conditions with a thrust impulse error of -0.5%. For a nominal 479 km altitude, the total dispersion footprint due to the combined 3-sigma errors of +/- 1^{0} in thrust direction and +/- 0.5% in the thrust magnitude is shown in **Figure 10(a)**[8]. The impact dispersion shown is approximately 30 km uprange, 29 km downrange, and a crossrange dispersion of 6 km due to an out-of-plane thrust direction error of +/- 1^{0}. The Attitude Control System (ACS) thrusters may be used to supplement the main retro-thrust in order to fine tune the velocity increment, thereby reducing the dispersions due to thrust magnitude errors. This is possible by using on-board, high-precision accelerometers and a microprocessor to compute the actual velocity decrement achieved. This shows how much plus or minus velocity increment must be supplied by the ACS thrusters. Knowing the velocity error, the ACS thrusters are activated to null this error in the total velocity. The resultant dispersion ellipse, using this method, is about 6 km in radius as shown in **Figure 10(b)**[8]. This example is for deorbit from 479 km altitude;

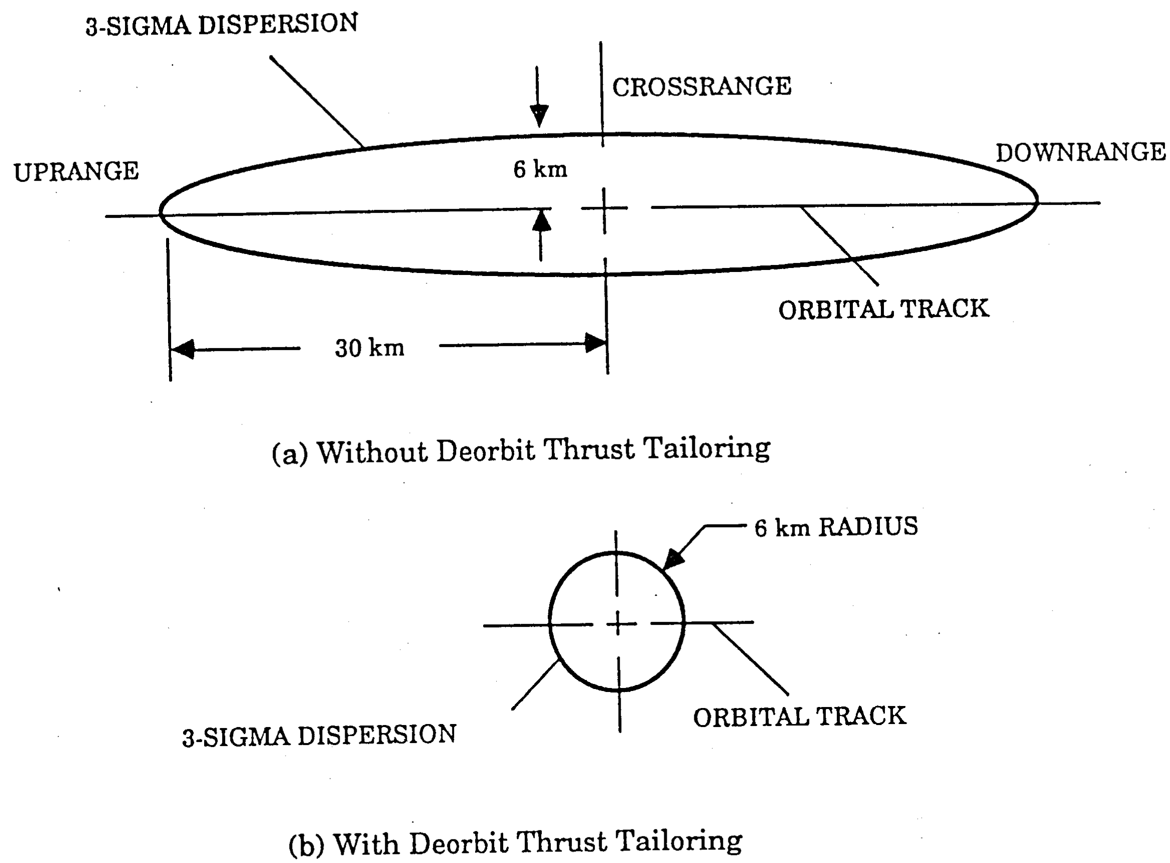
for higher orbits, the dispersions will be proportionately larger for the same amount of retropropulsion.

It should be understood that this example uses a ballistic, non-lifting RV and that the impact dispersions determined in the analysis are due only to errors in thrust direction and magnitude. Other factors may cause significantly larger dispersion areas, such as errors in orbital parameters, timing sequences, and variations in atmospheric density. In addition, for a lifting RV, attitude control system errors could cause very large dispersions by causing the vehicle to "pitch" out of the planned trajectory. Also, this example does not include dispersion areas for other reentry vehicle component parts that are jettisoned during reentry and terminal descent.



Source: NASA Technical Memorandum 101043

Figure 9. Dispersions for Various Altitudes



Source: NASA Technical Memorandum 101043

Figure 10. Typical Landing Footprints of a Reentry Vehicle

APPENDIX I - Manned Reentry Programs

1. Project Mercury[1] - NASA's first manned space program launched its initial research and development flight on September 9, 1959 aboard an unmanned Atlas D. The program consisted of two more unmanned flights, two with chimpanzees aboard and six manned flights. Though the capsules used for the primates and the astronauts were not reusable, they did employ much of the technology learned from the Discoverer missions.

The Mercury capsule, which could accommodate one astronaut, was conical with a cylindrical neck at the top. It was 3 meters tall and 180 cm in diameter at the base. The body of the capsule was covered with titanium skin and the ablative fiberglass heat shield and retro-rocket package were attached to the base. The typical Mercury capsule weighed approximately 1300 kg while in orbit. The final five Mercury missions were flown on a modified Atlas D, which provided 360,000 pounds of thrust. The launch vehicle weighed 118,000 kg and its height, including the 5-meter escape tower, was 28 meters. **Table A.1**[3] illustrates key facts about the Mercury program.

TABLE A.1 RECAP OF PROJECT MERCURY MANNED MISSIONS

FLIGHT	LAUNCH VEHICLE	LAUNCH DATE	PAYLOAD WEIGHT (kg)	ORBIT (km) (incl)	RESULTS
MR-2	REDSTONE	31 JAN 60			Carried Ham the chimp who endured 17*g* during lift-off and splashdown 212 km from target in a leaking spacecraft after six minutes of weightlessness
MR-3	REDSTONE	05 MAY 61	1280		First American in space, Alan Shepard reached an altitude of 116.5 miles, Freedom 7 capsule recovered 303.8 miles downrange
MR-4	REDSTONE	21 JUL 61	1276		2nd US manned spaceflight, Virgil Grissom reached altitude of 118.3 miles, Liberty Bell capsule was not recovered
MA-5	ATLAS D	13 SEP 61	1200	156X248 (32.6)	Enos the chimp completed two of three planned orbits, a flight length of 3 hrs. 16 min.
MA-6	ATLAS D	20 FEB 62	1352	159X265 (32.5)	John Glenn became the first American to orbit the earth aboard Friendship 7, capsule was recovered 64.5 km from target
MA-7	ATLAS D	24 MAY 62	1349	154X260 (32.5)	Scott Carpenter and his Aurora 7 spacecraft missed the landing target by 420 km
MA-8	ATLAS D	03 OCT 62	1370	153X285 (32.5)	Sigma 7 with Wally Schirra recovered within five miles of the carrier after six orbits (9.2 hrs.)
MA-9	ATLAS D	15 MAY 62	1370	161X267 (32.5)	Gordon Cooper and Faith 7 recovered after 22 orbits, 34.3 hrs., Completed Mercury program

2. Project Gemini[1] - NASA's second set of missions leading to a moon landing used a two-man spacecraft and had astronauts practicing docking maneuvers, extravehicular activities and guided reentry. The Gemini capsule was an outgrowth of the Mercury capsule's conical design. The reentry module had rendezvous and recovery, reentry control, and cabin sections (50 percent more than Mercury) and was 230 cm in diameter at the base. It was made primarily of titanium, with external skin of beryllium and nickel alloy. The adaptor module, which was jettisoned before deorbit, contained retrograde and equipment sections.

Modified Titan II ICBM rockets were used for all the Gemini missions. The hypergolic liquid propellant vehicle with a 430,000 pound-thrust first stage and the 100,000 pound-thrust second stage had a total height of 33 meters. **Table A.2**[3] gives highlights of Project Gemini.

TABLE A.2 RECAP OF PROJECT GEMINI MANNED MISSIONS

FLIGHT	LAUNCH VEHICLE	LAUNCH DATE	PAYLOAD WEIGHT (kg)	ORBIT (km) (incl)	RESULTS
GEMINI 3	TITAN II	23 MAR 65	3220	160X240 (32.5)	First manned flight in the program, Virgil Grissom and John Young completed 3 orbits in 4.9 hours
GEMINI 4	TITAN II	03 JUN 65	3569	162X281 (32)	Edward White performed a 20 minute EVA, landed with James McDivitt after 66 orbits, 97.9 hours
GEMINI 5	TITAN II	21 AUG 65	3600	197X303 (32.6)	First extended US manned flight, Gordon Cooper and Charles Cooper landed after 128 orbits, 190.9 hours
GEMINI 7	TITAN II	04 DEC 65	3658	100X204 (28.9)	Frank Borman and James Lovell went a record 220 orbits, 330.6 hours, served as Gemini 6 rendezvous target
GEMINI 6	TITAN II	15 DEC 65	3546	258X271 (28.9)	Wally Schirra and Tom Stafford rendezvoused within one foot of Gemini 7, landed after 17 orbits 25.9 hours
GEMINI 8	TITAN II	16 MAR 66	3789	159X265 (28.9)	Docked with target launched aboard an Atlas Agena on the same day, short circuit forced an early landing after 6.5 orbits, 10.7 hours, Neil Armstrong and David Scott were the astronauts
GEMINI 9	TITAN II	03 JUN 66	3750	270X272 (28.9)	Rendezvous and EVA tests carried out by Tom Stafford and Gene Cernan, landed after 47 orbits, 72.3 hours
GEMINI 10	TITAN II	18 JUL 66	3757	160X268 (28.9)	Docked with target launched aboard an Atlas Agena D, EVA to Gemini 8 target, John Young and Mike Collins landed after 46 orbits, 70.8 hours
GEMINI 11	TITAN II	12 SEP 66	3793	161X280 (28.8)	Docked with target launched aboard an Atlas Agena D, Charles Conrad and Richard Gordon landed after 47 orbits, 71.3 hours
GEMINI 12	TITAN II	11 NOV 66	3655	243X310 (28.9)	Docked with target launched aboard an Atlas-Agena D, after 63 orbits, 94.6 hours, James Lovell and Buzz Aldrin conducted EVA experiments

3. Project Apollo[1] - NASA's premier project of the 1960's culminated in July 1969 when Neil Armstrong took his one small step on the lunar surface.

The Apollo reeentry vehicle, which housed a three-man crew, was 3.66 meters high and had a base diameter of 4 meters. The interior structure was primarily aluminum and the sides were stainless steel eith an ablative coating. The base was covered by an ablative heat shield. The total weight of the module was about 5400 kg. Onboard systems included communications, guidance and navigation, environmental control, attitude control, batteries and drogue and main parachutes for earth landing.

The saturn V rocket, which launched all but the first manned Apollo mission, was 111 meters high and weighed 2.7 million kg. Its three stages had a combined throust of 8.7 million pounds.

Table A.3[3] gives a summary of the manned Apollo missions.

TABLE A.3 RECAP OF PROJECT APOLLO MANNED MISSIONS

FLIGHT	LAUNCH VEHICLE	LAUNCH DATE	PAYLOAD WEIGHT (kg)	ORBIT (km) (incl)	RESULTS
APOLLO 7	SATURN 1B	11 OCT 68	14674	231X297 (31.64)	Reentered 10/22/68, first manned flight, 163 orbits, 260.2 hours
APOLLO 8	SATURN V	21 DEC 68	28833	191X191 (32.6)	Reentered 12/27/68, recovered in mid-Pacific after 10 lunar orbits, mission lasted 147 hours
APOLLO 9	SATURN V	03 MAR 69	36511	203X229 (32.6)	Reentered 3/13/69, first manned flight of LM, splashdown after 151 orbits, 241.9 hours
APOLLO 10	SATURN V	18 MAY 69	42530	183X184 (32.5)	Reentered 5/26/69, second circumlunar flight, piloted LM within 9.26 miles of moon, splashed down after 192.1 hours
APOLLO 11	SATURN V	16 JUL 69	43811	183X184 (32.7)	Reentered 7/24/69, first manned lunar landing, Eagle landed on Sea of Tranquility and stayed for 21.6 hours, splashdown after 195.3 hours
APOLLO 12	SATURN V	14 NOV 69	43848	183X199	Reentered 11/24/69, LM stayed 31 hours on moon's surface, mission lasted 244 hours
APOLLO 13	SATURN V	11 APR 70	43924	156X156 (33.5)	Reentered 4/17/70, failure of onboard oxygen tank 56 hours into mission caused abort, splashdown after 143 hours
APOLLO 14	SATURN V	31 JAN 71	44456	186X186 (32.5)	Reentered 2/9/71, lunar landing on 2/5/71, mission duration of nine days
APOLLO 15	SATURN V	26 JUL 71	46723	169X173 (32.5)	Reentered 8/7/71, lunar landing on 7/30/71, mission duration of 295 hours
APOLLO 16	SATURN V	16 APR 72	46733		Reentered 4/27/72, longest solo flight in command module, mission duration of 266 hours
APOLLO 17	SATURN V	07 DEC 72	46743	169X178 (32.5)	Reentered 12/19/72, last lunar landing, mission duration of 302 hours

APPENDIX II

The following is a limited list of primary agencies and organizations, foreign and domestic, that have done research in developing reentry vehicle systems. It should be noted that NASA Ames Research Center is the lead governmental agency in the US that is doing this research.

<u>UNITED STATES</u>
NASA Ames Research Center
GE Aerospace
Stanford University
University of Tennessee
Science Applications International Corporation (SAIC)
COR Aerospace
Instrumentation Technology Associates
Orbital Recovery Corporation
Space Industries, Inc.
<u>GERMANY</u>
Dornier
MBB/ERNO
<u>FRANCE</u>
MAN Technologie
Matra Espace
<u>ITALY</u>
Aeritialia
<u>GREAT BRITAIN</u>
British Aerospace
<u>JAPAN</u>
National Space and Development Agency (NASDA)
Ministry of International Trade and Industry (MITI)
<u>CHINA</u>
Great Wall Industry Corporation
<u>USSR</u>
Glavcosmos

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2. GE Aerospace, "Satellite Recovery Vehicle", April, 1989

3. TRW Space Log 1957 - 1987

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6. NASA Technical Memorandum L58E07a

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8. NASA Technical Memorandum 101043, Oct 1988

9. NASA, "RRS - A Multipurpose Reusable Reentry Satellite"