Project EGRESS

John P. Dunn* and Patrick C. Carroll†
Martin Company, Denver, Colo.

This paper describes the design and application of an escape capsule system to protect crew members in emergency situations during earth-orbital space operations and to provide for survival and recovery on a global basis. The Emergency Global Rescue Escape, and Survival System (EGRESS) design consists of the basic B-58 aircraft ejection capsule configuration with a circular, folding heat shield added to the rear. A hydrogen peroxide, manual attitude control system is added, along with a bleed-flow, expendable heat-sink environmental control system. An electrically operated rate gyro system provides reference for manual control. A small, low-power, wide-angle telescope and clock timer provide guidance. An active very high-frequency (vhf) communication link, a 243-Mc distress beacon, a retrothrust satellite timer, and a 100-w-hr battery complete the internal additions. Externally, high-temperature material for the clamshell door, a retrorocket package, an ejection rocket, a low-power catapult, and a drag stabilization system are added. The entire design is based on available components and existing technology.

Introduction

As space operations become more commonplace and additional manned orbital missions emerge from research to operational status, the man in the system increasingly will be exposed to frequent periods of extreme hazard. In addition to hazardous periods on the launching pad, during boost, rendezvous, re-entry and final landing, crews will spend extended periods in orbit. Many emergency conditions may not demand that the crew abandon the parent vehicle or space station. But years of experience in manned aircraft operations have demonstrated that catastrophic emergencies do occur, and in those situations quick-reaction escape techniques are required. For optimum use, the total escape device for space crews would have to be of minimum weight and size and as universally applicable to all space vehicles as the parachute has been to subsonic aircraft operations.

The Martin Company, in cooperation with the Stanley Aircraft Corporation, has completed the preliminary design of an encapsulated-seat system (Fig. 1) that evolved from Stanley's B-58 capsule concept. Some existing systems were modified, and others were added, to provide the capability for capsule operation primarily in orbit and during the re-entry heating phase. Flight-qualified B-58 subsystems were used where possible. Designs for the orbital and re-entry systems—such as environmental control, life support, heat shield, and attitude control—are based on proved Mercury vehicle technology. The EGRESS capsule, which weighs 716 lb, has been designed around off-the-shelf hardware parts and systems that, in many cases, are flight-qualified. Since it can provide escape over a complete range of flight profiles, it can be used in nearly all types of space vehicles and future aircraft, that is, for orbital space stations; for logistics, rescue, and inspection type vehicles; for experimental spacecraft and aircraft; and for recoverable boosters.

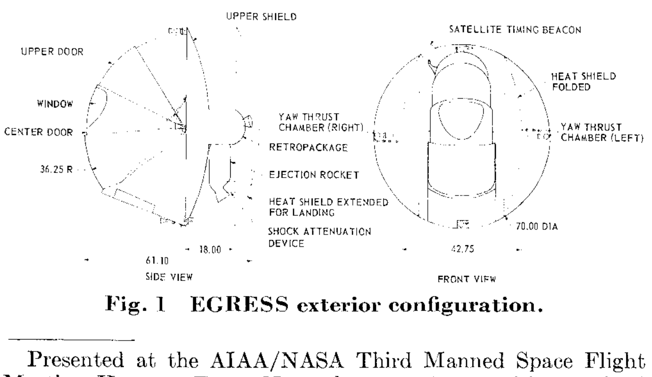

Fig. 1 EGRESS exterior configuration.

Presented at the AIAA/NASA Third Manned Space Flight Meeting, Houston, Texas, November 4–6, 1964; revision received December 2, 1965.

* Staff Project Engineer, Advanced Technology Department.
† Principal Engineer, Engineering Department. Member AIAA.

In the past, experimental test vehicles have been equipped with escape systems that do not provide complete escape capability during test maneuvers. As a result, the final escape system has been fitted within an already existing space envelope that usually imposes severe restrictions on system design and occupant performance. The EGRESS capsule can be designed into any vehicle from the outset as an off-the-shelf, universal crew escape system. The design also provides "plug-in" escape capability for any number of crew members using one- or two-seat capsules as shown in Fig. 2. The capsule is designed to provide safe escape during 1) abort off the pad and during booster thrust, including areas of maximum dynamic pressures; 2) high-g boost when thrust cannot be terminated; 3) orbit injection; 4) orbit; 5) re-entry, including maximum heating times; and 6) landing.

System Description

The EGRESS design consists of the basic B-58 capsule configuration with a circular, folding heat shield added to the rear. Other modifications and additions include high-temperature door materials and attitude control, guidance, environmental control, and propulsion systems (Fig. 1). A comparison of the requirements of the EGRESS and B-58 capsules (Table 1) shows the close correlation between the systems.

Table 2 is a detailed weight statement indicating not only the various weights, but also the items removed from and

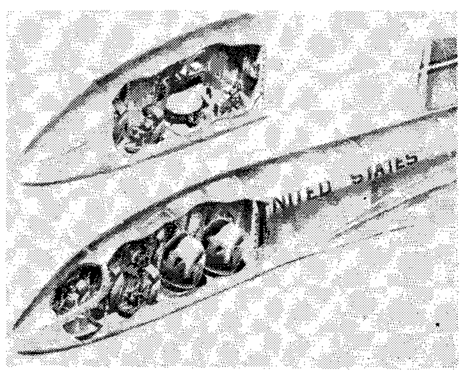

Fig. 2 EGRESS "plug-in."

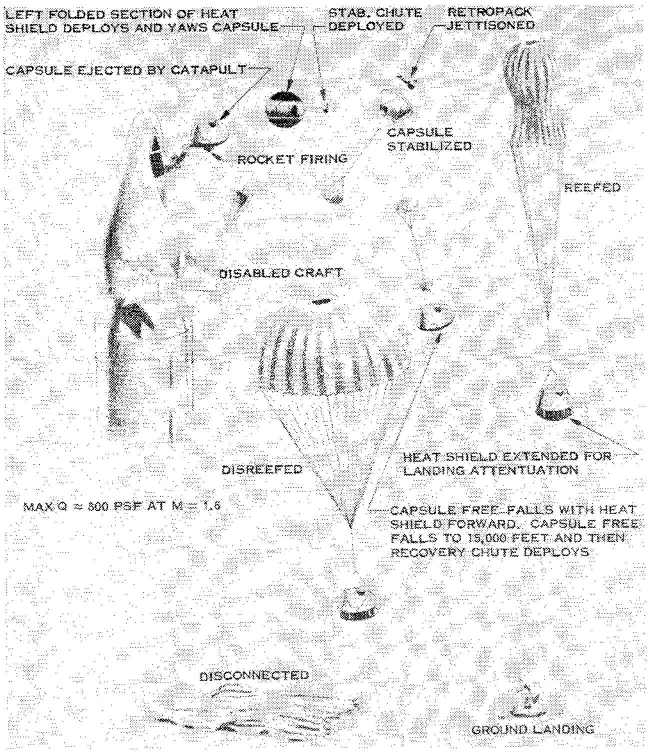

Fig. 3 Escape during boost phase.

added to the basic capsule. The weight statement is detailed, since accurate weights are available for off-the-shelf components. Estimated weights are conservative, as illustrated by allowing 47 lb for doors that are larger and made of materials that can withstand re-entry heating. The weight statement is based on the use of existing components where feasible. The over-all weight can be reduced from between 70 to 100 lb by redesigning the system for optimum weight. However, a conservative design based on available components is one to which actual flight hardware can be constructed at minimum cost.

System Operation

The system operation varies with different phases of the flight profile. Accordingly, the design incorporates a manual selector switch that allows the astronaut to pre-program the ejection and recovery operation to the particular flight profile phase. Figure 3 indicates the essential events that occur in escape during the boost phase. Following an explanation of the portion of the system operation that is common for any phase of the flight, the various critical abort conditions will be described.

The seat (identical to that now operational in the B-58 escape capsule) can be adjusted vertically, using an electromechanical actuator. In addition, the forward part of the seat pan may be adjusted manually in flight to redistribute body weight. The capsule accommodates 5th- through 95th-percentile people, as defined in Ref. 1. No pressure suit, integrated helmet, personal parachute, man-carried survival equipment, exposure suit, or life jacket is needed. The occupant can enter or leave the capsule by using only a three-point hookup, i.e., lap belt, torso harness, and communication facilities.

To provide the required escape in any phase of the complete mission, there are three programs for the escape events. For sequence selection, some of these phases are the same. In each case, the encapsulation sequence shown in Fig. 4 will have been operated previously. The astronaut ejects his capsule by squeezing one or both of the ejection triggers on the ejection handles or firing a canopy or hatch jettison actuator; after a 0.3-sec delay, the ejection catapult is fired, giving the capsule a separation velocity of 50 fps. The rocket provides an impulse of 3000-lb-sec, which is enough to insure tail clearance for a 1000-lb capsule at a dynamic pressure of 1600 psf. Since peak dynamic pressure during boost is only 800 psf, this combination of rocket and catapult should be sufficient to provide separation and attenuate decelerations.

Nominal spinal accelerations imposed on a 50th-percentile man by the catapult are approximately 13 g. If the ejection occurs in any suborbital period, the sequence fires the ejection rocket. Since the capsule drag is quite high and is only partially offset by thrust, the vehicle deceleration rate can be as high as 22 g. As the capsule clears the vehicle, aerodynamic forces (if they exist) will position the capsule so that the heat shield is forward and positive acceleration (eyeballs in) is imposed on the capsule occupant. Stabilization is provided aerodynamically by the capsule/heat shield combination, and it is augmented by a drag chute stabilization system during sub-orbital periods.

If ejection occurs during orbit, the ejection rocket is locked out and the ejection sequence fires only the small ejection catapult. The catapult provides minor acceleration; thus the capsule is simply pushed out of the primary vehicle. At this point, the attitude control system is used to orient the vehicle manually and stop tumbling. The astronaut then uses the onboard clock for time information. Knowing the exact time, and using an onboard position location chart (based on time), the occupant decides when to initiate retrofire. The onboard life support system is designed to provide oxygen and environmental control for approximately 1.5 orbits to allow adequate landing site selection. Before retrofire, the capsule is oriented manually so that the telescope reticle is in line with the horizon. Manual retrothrust

Table 1 B-58 capsule and EGRESS comparison

EGRESS requirement	B-58 capsule	EGRESS capsule
Occupant's normal use of capsule as a seat	Qualified and operational	No change necessary
Adequate restraint in normal flight	Qualified and operational	No change necessary
Automatic body positioning for occupant in event of emergency	Qualified and operational	No change necessary
Capability of vehicle control while in encapsulated condition	Proved	Can be duplicated with minor changes or modifications
Pressure-tight sealing to provide habitable environment	Proved	Modification for increased service life
Ejection and stabilization at Q of 800 psf	Proved to Q = (1660 psf)	No change for structural strength is required. Rocket-catapult used on B-58 replaced by separate catapult and rocket units of proven design
Safe controlled descent from altitudes of 15,000 ft and below	Proved	Same basic design for automatic and forcible ejection of recovery parachute. Parachute diam increased to 50 ft
Landing	Proved	Similar principle for shock attenuation is used
Survival	Proved	No change necessary

then is initiated; alignment is maintained by using the large attitude control nozzles. After retrothrust, the capsule is oriented to the re-entry position and manually retained by using the attitude control system.

The 50-ft-diam ring-sail recovery parachute reduces the capsule's rate of descent to 25 fps. Ground impact forces are absorbed by four shock attenuators that are part of the heat shield attachments. The closed capsule can float without using auxiliary buoyancy devices. However, to provide stability in rough seas and maintain an upright attitude to open the upper capsule door, four outriggers with inflatable flotation bags are provided. The bags can be inflated quickly from a pressure container on the upper flotation outriggers. A hand-operated pump is provided for inflating the flotation bags on the lower outrigger. The most critically needed items of survival equipment are accessible to the occupan within the closed capsule. After landing, the capsule can serve as a shelter or as a life raft.

Abort off the Pad

The primary problem here is to develop an escape system that adequately will separate the crew capsule from an exploding booster. The distance required is determined by the amount of overpressure the escape system can tolerate, which depends on the type of booster and its TNT equivalent. For example, the Gemini system uses ejection seats to eject the crew members, and no overpressure protection is provided. The Titan II/Gemini launch vehicle uses storable, hypergolic propellants that have an equivalent TNT rating of about 2%, which is relatively low. Coupled with the booster malfunction detection system, the ejection seat system will be adequate, since usually there will be fairly low overpressures. However, both Mercury and Apollo require escape systems that provide not only higher accelerations, but also considerable overpressure protection, since the TNT equivalent of their boosters is relatively high.

Table 2 EGRESS weight statement (lb)

B-58 capsule (as is, less man, installed weight)	449.20
Less the following:	
Stabilization frame system	39.30
Rocket catapult	58.9
Oxygen system	6.35
Pressurization system	5.31
Disconnect (capsule half only)	1.09
	338.25
Plus the following:	
Rocket	42.95
Catapult	19.05
70-in.-diam ablation shield	43.04[a]
Environmental control system	26.50[a]
100 w-hr, 28-v battery	10.00
Rate, retrotimer, display, wide-angle telescope	6.50
Recovery beacon	1.00
Whip antenna	0.50
Clock and navigation booklet	1.50
Satellite timing beacon	3.00[a]
Attitude control system	35.00[a]
Additional weight for larger hood and doors	47.62[a]
Retrorockets	82.00
Shock attenuators	40.00
Heat shield thrusters	5.00
Control pedestal	10.00[a]
Air bottle (50 in.^{3})	2.00
Additional weight for larger stabilization chute	2.00[a]
Additional weight for larger recovery chute	4.00
Disconnect (capsule half only)	0.31
Total	716.25

[a] These weights are estimated.

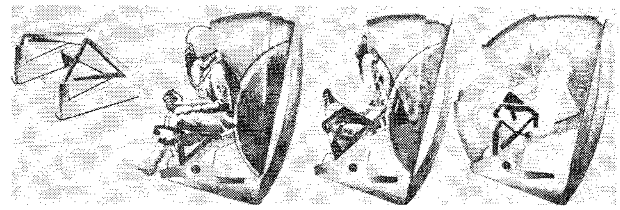

Fig. 4 Pre-ejection encapsulation sequence.

Separation during High-g Abort

The last stages of boost normally produce accelerations of approximately 8 g because the booster propellant is nearly expended and the entire system is much lighter. If escape must be initiated, and the normal ejection direction is along the booster flight path, booster thrust termination is important.

Although the chances of failure at this point are somewhat remote, clean separation is difficult to obtain. If the escape system ejects normal to the flight path, the problem is simplified. However, either system requires that the escape device (capsule or vehicle) have a re-entry capability.

Orbit Injection

This problem area is nearly identical to that of the last stages of boost, except that an additional escape restriction is placed on the system. That is, orbital velocity would be obtained by firing the escape rockets if the ejection direction were parallel to the booster flight path. Since the high-altitude ejection rockets normally are the retrorockets, the end result of this type of ejection would be orbit attainment without retrothrust capability. The EGRESS system has independent ejection and retrorockets, the ejection is normal to the flight path, and the capsule can disorbit after attaining an orbital condition.

Escape from Orbit

Present systems do not allow escape from the orbital vehicle after orbit has been attained. This philosophy prevails because the probability of system failure in experimental vehicles is less during orbit than during ascent or descent. However, for operational vehicles, this would be similar to providing present aircraft with escape systems for takeoff only; since the majority of accidents occur on takeoff, this is the only unreliable flight phase. This would, of course, be unacceptable.

An acceptable escape system is one that provides escape from the primary vehicle whenever an emergency occurs. Several factors dictate a less-than-optimum system, the foremost of which is weight consideration. Several problems are involved in excape from orbit. These include determination of position, accurate retrothrust, re-entry control, heat protection, and final recovery. Unless the precise retrothrust position is known, it is difficult to recover a vehicle from the ocean. Additional location aids will help in finding the vehicle after the general landing area is known.

Escape during Re-Entry

Escape during the maximum heating period is the primary problem in the re-entry phase. If a malfunction occurs during this period of re-entry, an excape device must be provided to separate from the primary vehicle, remain stable, impose no excessive accelerations on the occupant, and tolerate the heating environment.

Design Criteria

Typical operating requirements for present and future launch and space vehicles were considered. The orbital char-

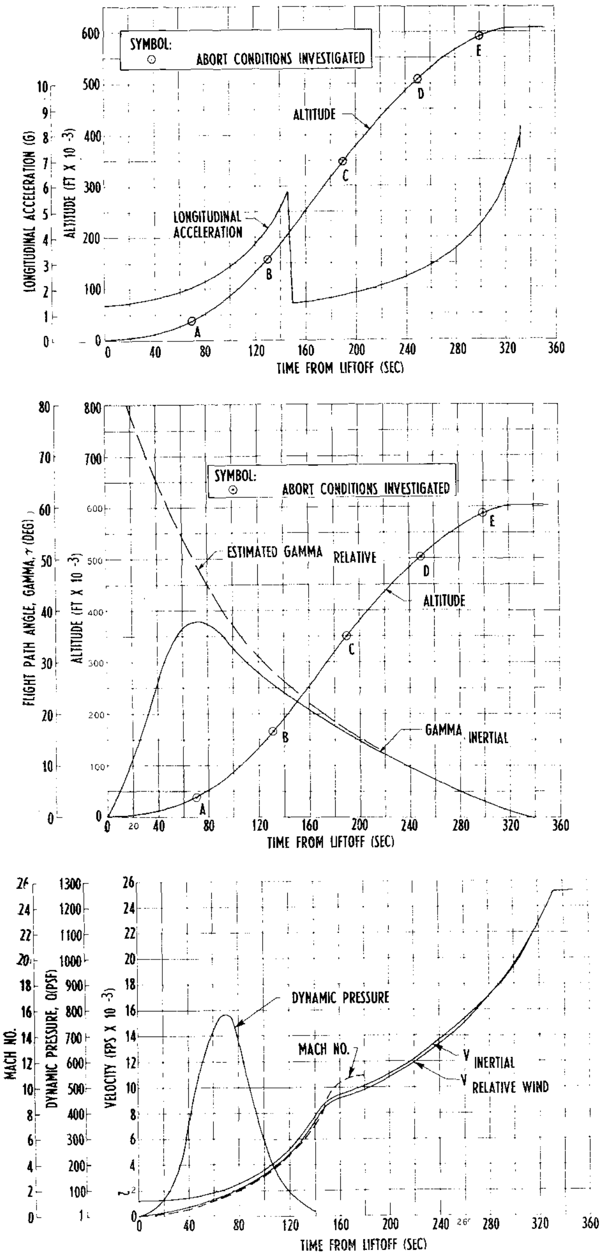

Fig. 5 Typical boost time history: a) acceleration and altitude vs time; b) Mach number, dynamic pressure, and velocity vs time; c) flight path angle vs time.

acteristics affect the escape system design only through environment limitations and the size of the retrorocket system. For altitudes above 400 naut miles, the natural radiation environment necessitates a shield that would impose a severe weight restriction on the payload. Artificial radiation levels from high-altitude experiments may limit the altitude to between 200 and 300 naut miles. A lower orbital altitude limit exists at approximately 70 naut miles where drag decay is severe and aerodynamic heating and airloads on the booster approach design limits. For these reasons, it is assumed that the orbital altitude is between 70 and 300 naut miles (no shielding requirement). Two factors for disorbit are considered: 1) a constant re-entry angle is desired; and 2) a constant velocity increment is available. Table 3 presents the departure conditions for both concepts. At a 460-fps velocity increment, it is impossible to depart from an altitude of 350 naut miles or higher.

Table 3 Disorbit departure conditions

Altitude, naut miles	Constant angle, $-2°$ (fps)	Constant velocity, 460 fps(deg)
75	910	-1.2
100	750	-1.4
200	445	-2.05
300	530	-1.30

Trajectory Data

The boost phase establishes design criteria for the maximum dynamic pressure and maximum airloads; the re-entry phase establishes design criteria for the aeroheating condition. The stability problems are somewhat different in these phases because of the differences in the Mach number and dynamic pressure combinations.

The escape environment has been investigated for several points during ascent, which comprises powered flight to a low perigee, coast, and final injection at the mission altitude. The escape conditions during the period of coast are not significantly different from the normal orbit conditions. A typical boost trajectory is presented in Fig. 5. Critical escape points are: 1) at launch, 2) at maximum dynamic pressure, 3) near staging, and 4) before orbit injection.

The initial abort condition is indicated in the top part of Fig. 5. Results that affect design criteria are summarized in Table 4; the first columns show the first critical conditions the capsule would experience when it is separated from the basic launch vehicle during boost; the second critical condition represents the period when the capsule falls back to earth or re-enters from the launch-abort trajectory.

The maximum airload and deceleration occur during case A, the low-altitude booster, maximum dynamic pressure condition. However, the heating rates are low in this case. The most critical combination of deceleration and heating occurs in case E, the near-orbit injection case. Although the initial flight path angle at abort is only $+3°$, the trajectory dynamics and velocity combine to give a return-to-earth, or re-entry, angle of about $-6°$ or $-7°$ at a velocity of about 20,000 fps and an altitude of 300,000 ft. This relatively steep re-entry angle results in high decelerations and heating rates.

Table 4 also shows the nominal orbital re-entry conditions for comparision. The orbital re-entry trajectory shows the most critical heating rates, but the dynamic pressures are about one-half those shown for case E. The critical design

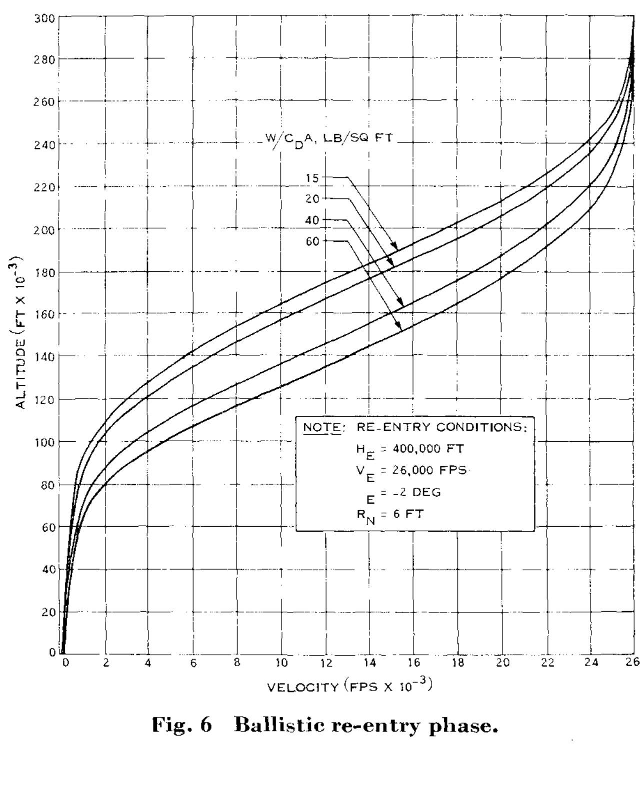

Fig. 6 Ballistic re-entry phase.

Table 4 Escape conditions during boost[a]

Abort conditions: During boost (Fig. 5)	Abort conditions: Initial flight path angle, (deg)	First critical condition, initial abort (up-bound): Dynamic pressure Q_{max}(psf)	Deceleration $G_{max}(G)$	Heat rate $Q_{max}\left(\frac{Btu}{ft^2\text{-sec}}\right)$	Second critical condition (down-bound): Dynamic pressure Q_{max}(psf)	Deceleration $G_{max}(G)$	Heat rate $Q_{max}\left(\frac{Btu}{ft^2\text{-sec}}\right)$
A	49.5	752	22.1	1.4	42	1.24	0
B	28.5	44	1.3	2.3	210	6.2	2.1
C	17.0	0	0	0	502	14.7	12.7
D	8.5	0	0	0	664	19.5	29.0
E	3.0	0	0	0	670	19.7	52.0
Typical re-entry trajectory	−2	310	7.8	60	...	...	...

[a] W/C_DA is about 34 psf for the vehicle facing forward with the heat shield ears closed.

limits imposed by the re-entry trajectory include maximum allowable decelerations encountered for steep re-entry, and large total heat loads and high re-entry dispersion encountered for shallow re-entry. The capsule retrorocket will provide a predetermined re-entry angle; the trajectory data shown in Figs. 6 and 7 represent the proposed capsule re-entry. If the capsule is ejected from a lifting parent vehicle during re-entry, the deceleration and aeroheating conditions generally will be no more severe since lift vehicles typically re-enter at shallow angles.

Aerodynamics

The re-entry design is based on the Mercury capsule configuration and uses a geometrically similar heat shield with curvature-to-diameter ratios equal to those of the Mercury capsule. For pitch and yaw angles below 20°, the aerodynamic, performance, stability, and aeroheating characteristics of the EGRESS capsule will be nearly identical to those of the Mercury capsule. At higher pitch and yaw angles, the afterbody effects become more important. The maximum deceleration (Fig. 7) is similar to that experienced by the Mercury capsule on re-entry at a gravitational force of about 8 g. No particular problem area would be anticipated other than that of off-center location of the center of gravity. Every effort should be made to locate equipment in such a way that the center of gravity will be symmetrically located with respect to the face of the heat shield. The capsule would be slowly rolled during re-entry to reduce the off-center gravity effects as was done during Mercury capsule re-entry.

Capsule stability problems probably are the most difficult design problems to define, and their solutions are difficult and expansive to substantiate. However, solutions appear to be within the state of the art for the proposed capsule.

The two major problem areas are 1) stability with the ablative heat shield forward, with and without auxiliary drogue devices; and 2) stability as the capsule separates during boost or re-entry with the ablative heat shield initially facing aft.

For the first case, which normally occurs during a re-entry from orbit, the stability conditions are similar to those of the Mercury capsule re-entry, since the trajectory conditions and the heat shield geometry are similar. If the astronaut can position his capsule accurately before re-entry and continue to hold position and angle of attack near zero during the early portion of re-entry when the reaction contols are effective, the characteristic divergence condition will be minimized as the capsule approaches an altitude of 100,000 ft. The drogue chute can be deployed manually to supply drag stabilization and reduce oscillations, as was done in some of the Mercury re-entries

In the second major problem area, the capsule enters the airstream in the reverse position, and the inherent stability as well as an auxiliary drogue device is relied on to yaw the capsule 180° to orient it with the stable ablative heat shield in the forward position. This position also places the occupant in the best attitude to withstand high deceleration forces. Another possible technique for producing a yawing moment to initially turn the capsule is to deploy one side of the folding portions of the heat shield. Figure 4 shows how the sides of the heat shield have been separated and folded to facilitate stowage in the parent vehicle.

Shortly after the capsule starts to rotate (a yaw angle of about 90°), the second side of the heat shield would be deployed and the capsule again would be symmetrical. A drogue chute or other drogue device probably would be required to damp the yaw oscillations even though the capsule is basically stable when the heat shield is in the forward attitude.

In the high dynamic pressure conditions of boost, the Mach number is low enough that a conventional drogue parachute would operate satisfactorily. In the re-entry flight phase, some other drag device such as a ballute (balloon-parachute) might be required because of the adverse Mach effects on conventional parachutes and because of aeroheating problems.

Separation

The main ejection rocket is used selectively for separation only when the parent vehicle is in the atmosphere (on the pad, during boost, during re-entry, and landing). Aerodynamic forces therefore are available in the form of drag devices to

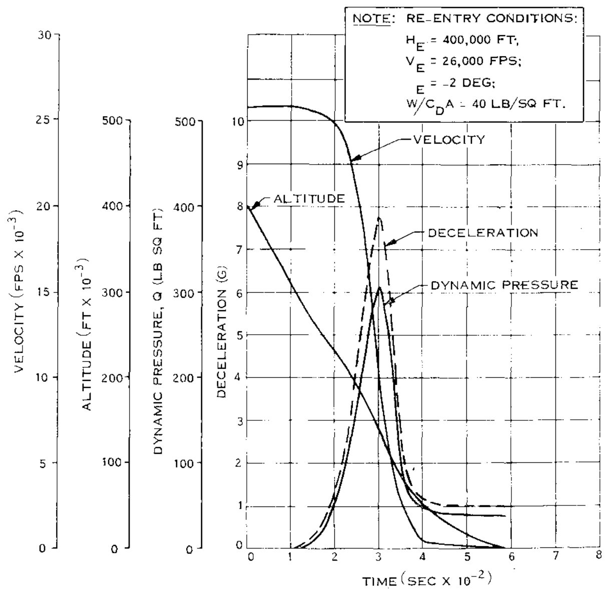

Fig. 7 Ballistic re-entry phase time history.

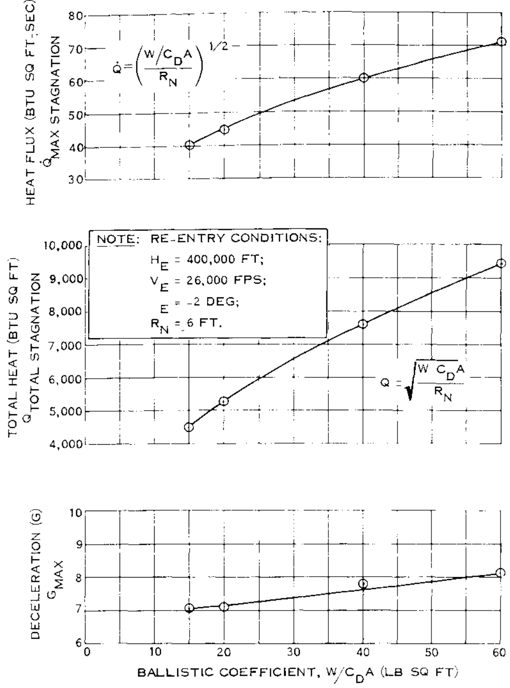

Fig. 8 Stagnation-point aerodynamic heating and deceleration vs ballistic coefficient.

assist in stabilization, reorientation, and reduction of capsule rotation due to misalignment. For separation during orbit injection, in orbit, or before actual re-entry, only the catapult is used. The thrust is terminated before the capsule leaves the mounting rails, so a minimum of rotation is imparted to the capsule. Any rotation under no-atmosphere conditions is easily controlled by the manually operated attitude control nozzles.

Aeroheating

The aeroheating environment (Fig. 8) is nearly identical to that of the hardware-proved Mercury capsule. The proposed capsule heat shield has a slightly smaller diameter than the Mercury shield (70 in. as compared with 74.5 in.), and the W/C_DA is about one-half (25 psf vs 55 psf). The effects of W/C_DA on aerodynamic heating are shown in Fig. 8, for a typical re-entry angle of $-2°$. No particular problem areas are anticipated for the forward ablative heat shield, since the heating rates of 50 to 60 Btu/ft^2-sec and heat loads of 6000 to 8000 Btu/ft^2 are similar to those experienced by the Mercury capsules.

For escape from the parent vehicle during re-entry, the capsule may eject at a maximum heating condition. In this event, the ablative heat shield briefly faces rearward until the capsule can rotate (yaw) 180°. A check of the yaw maneuver showed low total heat loads on the doors.

Human Factors Considerations

The restraint harness developed by Stanley Aviation Corporation, which incorporates 35% more bearing area than the Air Force operational harness, has been tested mechanically and proved satisfactory by numerous tests. In sled tests at Holloman Air Force Base, N. Mex., the harness provided effective restraint from impact accelerations to 50 g. An Air Force officer was ejected safetly from the B-58 at Mach 0.8 and at an altitutde of 20,000 ft.

The capsule comfortably supports its occupant in both the open and closed positions. When closed, the capsule supports the occupant in a pseudofetal body position. In a 72-hr survival test conducted in a cold water environment, the occupant was confined to the pseudofetal position for up to six consecutive hours with minimum discomfort. As a result of these survival tests, it was proved that the occupant can survive for 72 hr after landing in cold or warm water. The findings of the tests also indicated that a human can use the capsule as a basic survival item for at least 72 hr in a cold land environment.

Capsule Design

With an encapsulated seat system, the problems associated with ejection at high dynamic pressures, such as arm and leg flailing, helmet and mask loss, hail and rain impingement, and air engorgement are eliminated. Since the high dynamic pressures immediately following ejection are exerted on the external shell of the capsule, the restraint harness for the encapsulated seat prevents the occupant from being thrown forward. The lap belt and upper torso harness carry the major part of the loading associated with this decelerative force. With a properly designed harness that has webbing surfaces sufficiently broad to distribute this load, the occupant experiences no undue discomfort.

The occupant's legs are drawn to the fetal position by the leg retraction mechanism, which prevents them from experiencing harmful motions under any ejection condition while in the capsule. The legs are prepositioned by pulling the ejection handles and are contained by the leg retraction mechanism so they also are prevented from inadvertent movement within the capsule. The capsule doors, when closed, restrain the occupant laterally to prevent buffeting within the capsule.

The powered inertia reel automatically positions, then locks the occupant's upper torso in the restrained position before the capsule door closes. A conventional lap belt serves as the pelvic restraint. The occupant can free himself quickly from the entire harness and capsule by operating two simple releases: one on the upper torso harness and one on the lap belt. (The oxygen mask hose and intercommunication microphone leads also must be disconnected. However, this is a simple one-step operation.)

The entire encapsulation sequence is completed between 0.5 and 1.25 sec, depending on whether the system is operated at $-65°$ or $160°$. The entire system, including inertia reel, torso harness, leg retraction, and capsule door closure, has been tested many times with human subjects under these extreme temperature conditions. Further, it has been tested with humans in a simulated g field under hot and cold conditions. The complete system has been demonstrated over 2000 times, using human subjects.

Two-Man Capsule

The basic escape capsule concept can be applied to two crewmen with no conceptual changes. For vehicles where a pilot and copilot normally sit side by side, it is feasible to provide a two-man capsule. The total system weight per man undoubtedly can be significantly reduced over that of one capsule per man. This application is well suited particularly to large recoverable booster stages and spaceplane concepts. Orbiting space stations may use the two-man capsule concept and take advantage of the weight savings.

Reference

[1] Wright Air Development Center Rept. 52-321.