Re-entry Crew Escape Module Concepts for Orbital Vehicles

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SUMMARY

This paper discusses the problems of emergency escape associated with multi-crew reusable re-entry vehicles with horizontal landing capability and space stations operating on long duration earth orbital missions. The critical conditions of escape during launch, orbit, re-entry and landing are discussed and various escape techniques are defined. It is concluded that for the vehicles under consideration a lifting re-entry module is required for escape. Re-entry module design criteria derived from a preliminary analysis indicate configurations with a hypersonic lift-drag ratio L/D from 0·3 to 0·5, low wing loading W/A and large nose radius. The solution lies in the use of expandable structures to reduce stowage volume and to achieve the desired re-entry configuration. An evaluation of four concepts that provide escape capability throughout the vehicle mission shows that the optimum concept for the re-entry vehicle is a nose capsule re-entry module and for space stations, an expandable disc re-entry module. The design and performance of the expandable disc re-entry module concept are described in more detail.

1. INTRODUCTION

Within the next ten years, manned space flight will involve operational multi-crew vehicles that will fly routinely long duration earth orbital missions. Two representative types of vehicles that are being considered are the re-usable re-entry vehicle with horizontal landing capability and a crew of three men, and the space station with a crew from 4 to 20 men. Re-usable re-entry vehicles may orbit the earth for 28 days at altitudes ranging from 200 up to 19,350 nautical miles, and space stations for one year at altitudes up to 400 nautical miles. The missions of such vehicles will be extremely hazardous for the crew so that provisions for escape from orbit and safe return to the earth's surface are mandatory. Moreover, an escape concept for the re-entry type vehicle must also provide capability for the other phases of the mission.

This paper discusses the critical escape conditions and some of the design aspects of re-entry escape concepts and defines the optimum concept for each type of vehicle. The object is to develop a lightweight, minimum complexity, multi-man module which does not affect the primary configuration and performance and provides escape capability throughout the vehicle mission. A specific design, the expandable disc re-entry module, appears to offer a good solution for space station applications.

This paper is based on studies$^{(1,\ 2)}$ performed by Canadair under the auspices of the Canadian Government Defence Research Board and the United States Government Air Force Flight Dynamics Laboratory.

SYMBOLS

A	reference area for drag and lift, ft^2
a	acceleration or deceleration, g units
C_D	drag coefficient, D/qA
C_L	lift coefficient, L/qA
D	drag, lb
g	acceleration unit, 32·2 ft/sec^2
h	altitude, ft
K_1	dimensional constant in heat transfer equation (7·95 Btu/lb$^{0\cdot 5}$ft$^{0\cdot 5}$sec)
K_2	dimensional constant $(K_1/\sigma)^{1/4} = 2015^\circ R\ \mathrm{lb}^{-1/8}\ \mathrm{ft}^{3/8}$
L	lift, lb
L/D	lift-drag ratio
N	number of recovery bases
q	dynamic pressure, $\frac{1}{2}\rho V^2$, lb/ft^2
$\dot{q}_{\max}$	peak heating rate, Btu/ft^2 sec
R	leading edge or nose radius, ft
S	vehicle surface area (envelope area)
T	thrust, lb
$T_{\max}$	stagnation point radiation equilibrium temperature, °R
T/W	thrust-weight ratio
t	time, sec
V	velocity, ft/sec
ΔV	velocity increment, ft/sec
$V^{2/3}/S$	volumetric efficiency, Volume $^{2/3}$/Surface area
W	vehicle weight, lb
W/A	wing loading, lb/ft^2
W/C_DA	weight-to-drag factor,lb/ft^2

α	angle of attack of disc at plane of symmetry
γ_o	entry angle, flight path angle relative to the local horizon, deg
ε	surface radiative emissivity
θ_r	escape rocket thrust angle relative to escape vehicle velocity vector, deg
ρ	density, slug/ft^3
σ	Stefan–Boltzmann constant, $0{\cdot}481 \times 10^{-12}$ Btu/ft^2 sec °R^4

2. Re-entry Vehicle

Figure 1 shows the configuration and interior arrangement of a hypothetical re-entry spacecraft as it was defined for the purpose of the studies. It is a manoeuvrable lifting body type vehicle with a hypersonic lift-drag ratio, L/D, of 0·8 and good subsonic flying characteristics. The total re-entry weight is 24,000 lb and the wing loading, W/A, is 24 lb/ft^2. This configuration will cope well with re-entry heating, keep deceleration low and have lateral range and horizontal landing capability. Two small turbojets are included to provide go-around capability and increase the lateral range in the terminal phase for landing at a pre-selected site.

The spacecraft is launched by a three-stage liquid fuel launch vehicle with a thrust of 750,000 lb for the lower orbit mission and 3 million lb for the 24-hour orbit mission. Figure 2 shows launch ascent trajectory parameters.

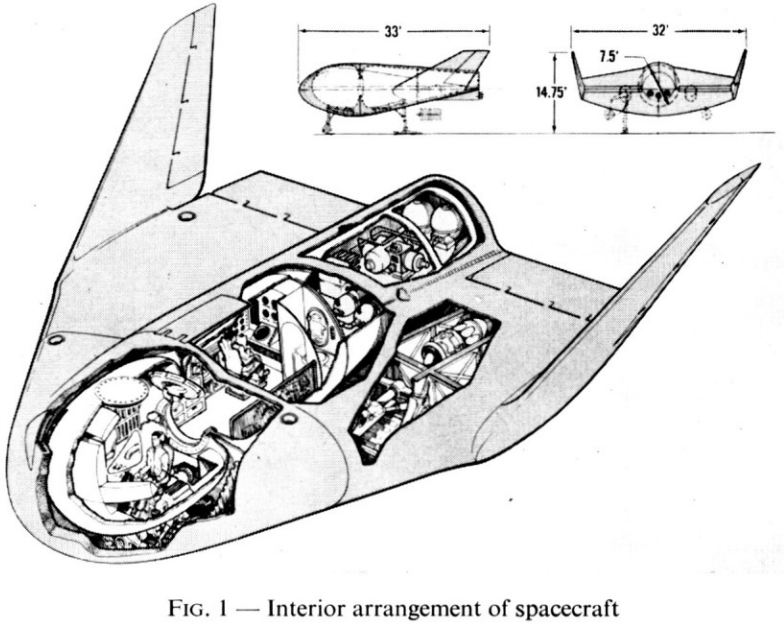


FIG. 1 — Interior arrangement of spacecraft

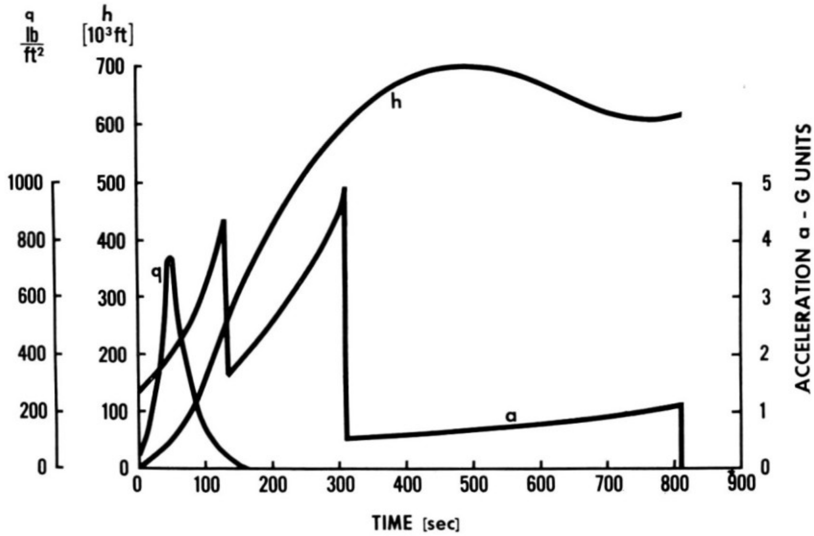


FIG. 2 — Boost trajectory parameters
(19,350 n. mile altitude orbit)

3. DISTRIBUTION OF FAILURES REQUIRING ESCAPE

Figure 3 shows the estimated number of failures per 1000 missions requiring abort or escape and the relative number of launch vehicle and spacecraft

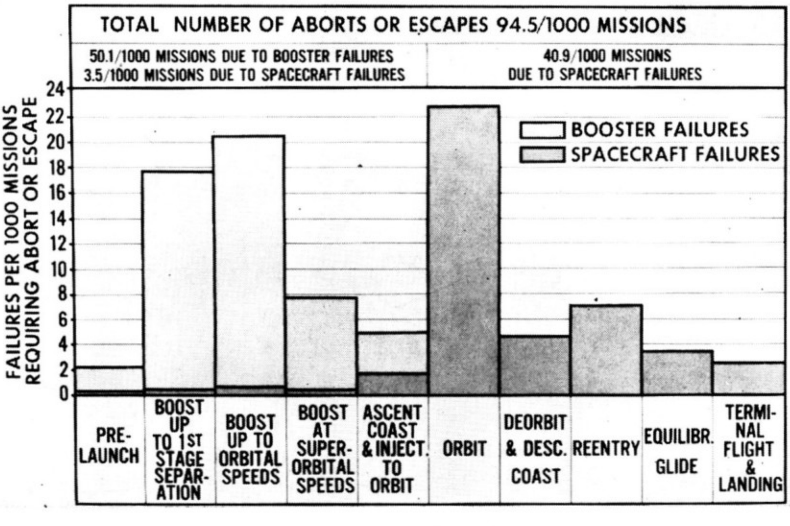


FIG. 3 — Distribution of failures, requiring abort or escape during each phase of the 19,350 N. mile orbital altitude mission

failures for each phase of the 24-hour orbit mission. The chart is based on statistical data and qualified opinion and should be regarded as a reliability goal for 1970. It can be seen that for a spacecraft without an escape system approximately 10% of the missions would be fatal. More than 50% of the failures are expected to be caused by the launch vehicle, *i.e.* during the first 15 minutes of the mission. 25% of the failures are expected to occur during the 28-day period in orbit, and 15% during the return to earth. It is evident, then, that an escape system is mandatory. Such a system must cope with all emergencies and provide safe return from all phases of the mission. To increase mission safety from 90 to 99·9%, the escape system reliability must be 99%.

4. CRITICAL ESCAPE CONDITIONS AND REQUIREMENTS

On the launch pad

On the launch pad, the requirement is escape from a launch vehicle explosion caused by the accidental mixing of the liquid fuel and oxidiser. For the largest vehicle considered here, the yield of explosion is equivalent to approximately 200 tons of TNT. Protection against the explosion hazards, overpressure, dynamic impulse, fireball and debris, is provided by quickly removing the crew, enclosed in a capsule, to a safe distance from the launch vehicle outside the dangerous overpressure zone, on a trajectory that lies outside the debris zone. For a design peak overpressure of 5 $\mathrm{lb/in^2}$, an escape module must achieve a distance of 710 ft from the largest launch vehicle within 2 sec warning time. This requires an acceleration of 11 g which is provided by rocket thrust. To clear the debris zone, escape must be effected in an upward direction within 30 degrees angle from the vertical, and the escape module must achieve an altitude and range greater than 3000 ft. Stability during escape rocket burning must be provided by other than aerodynamic means because of the very low dynamic pressure associated with this escape condition.

Boost at maximum dynamic pressure

The most critical condition in the atmospheric phase is escape from a thrusting launch vehicle at maximum dynamic pressure, when attempts to shut down the launch vehicle before separation fail. The escape module must overcome large aerodynamic forces, be stabilised quickly and manoeuvre to achieve within 2 sec a safe separation distance, which for the largest vehicle is 400 ft. At no time after escape rocket burnout should the escape module and the launch vehicle come closer together than the safe distance because an explosion may occur at any time after escape rocket burnout. This requires the following of an escape trajectory pitching away from the launch vehicle trajectory to decrease the flight path angle. If the vehicle is tumbling, however, the escape module may separate with an initial velocity component cancelling completely or partially the velocity component away from the launch vehicle trajectory given by the escape rocket and this would result in a collision. In this case, thrust must be applied so that the escape module is pitching in the direction of the launch vehicle rotation. This requires sensing of the launch vehicle pitching and yawing velocities at the time of the emergency and ability to select rocket thrust direction.

Figure 4 shows the envelope of possible launch vehicle trajectories (dotted lines) and a safe trajectory of an escape module (solid line) after separation at maximum dynamic pressure. The envelope was obtained by simulating the trajectories of both a non-thrusting and a thrusting vehicle travelling at various angles to their longitudinal axes. In addition to keeping the safe separation distance, a safe escape trajectory must either lie outside or enter this envelope after the launch vehicle has passed ahead. It can be seen that fifteen seconds after separation, the launch vehicle is close but still at a safe distance from the escape module and then passes ahead. Safe escape trajectories were achieved only for thrust angles from 20 to 30 degrees to the escape module velocity vector.

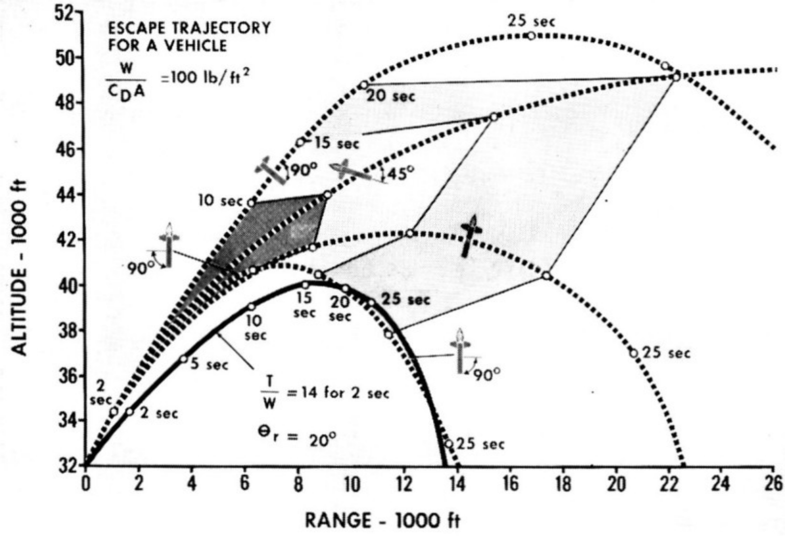


FIG. 4 — Escape during boost at maximum dynamic pressure

The aerodynamic forces at the maximum dynamic pressure condition determine the escape module rocket thrust level. Figure 5 shows the required

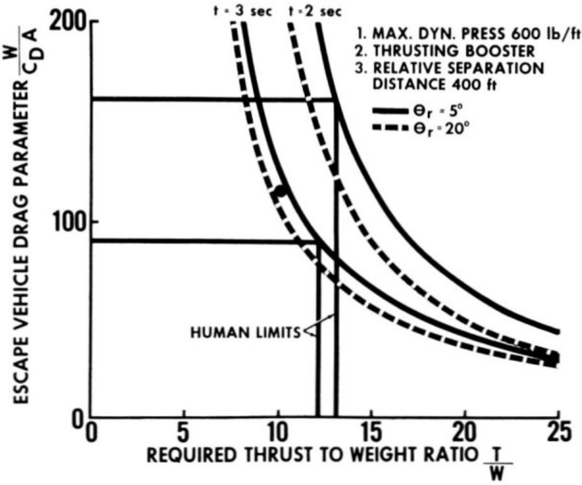


FIG. 5 — Escape rocket requirements

thrust to weight ratio as a function of the escape module weight to drag factor, W/C_DA, for 400 ft separation from a thrusting launch vehicle at a dynamic pressure of 600 lb/ft^2. Human tolerance limits to acceleration are also shown for escape rocket burning times of 2 and 3 seconds. For a blunt escape module configuration, *i.e.* W/C_DA below 100, the aerodynamic forces

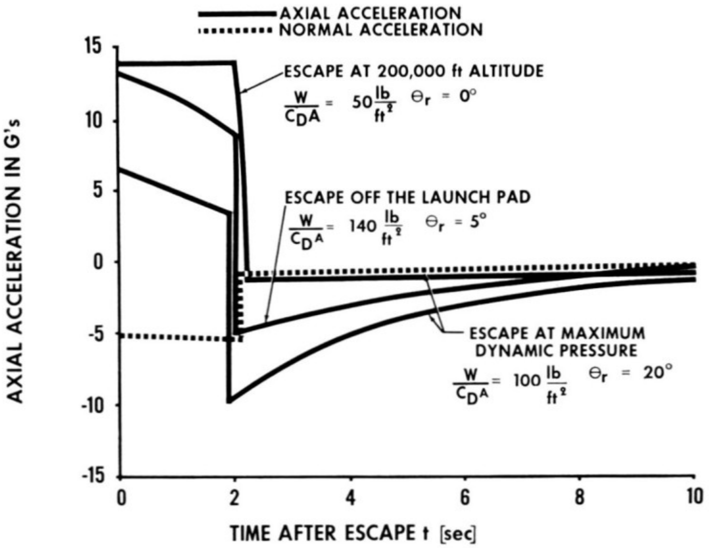


FIG. 6 — Acceleration profiles, due to operation of escape system at various mission phases

are large and the required thrust may result in exceeding human tolerance limits at escape conditions, such as on the launch pad and at high altitude where aerodynamic forces are low. Figure 6 shows acceleration histories for an escape system designed for the maximum dynamic pressure condition. Note that at maximum dynamic pressure the accelerations remain low due to drag, while under the other two conditions the accelerations are quite high. The normal component of the acceleration at the maximum dynamic pressure condition (dotted line) exceeds $5\,g$ requiring that the crew's attitude during escape rocket burning is with heads pointing toward the centre of the turn to avoid eyeballs-up acceleration.

Approach and landing

Escape requirements for the approach and landing condition are similar to those of a conventional aircraft. The optimum direction of separation is upward between 35 and 40 degrees angle to the long axis of the spacecraft. Escape rocket requirements are a thrust to weight ratio T/W of 10 and 0·75 sec burning time.

Ascent at suborbital and superorbital speed

At altitudes above 250,000 ft, overpressure is not a hazard and the probability of explosion is low. In most cases, it will be possible to shut down the launch vehicle and escape by separating the spacecraft with a small ΔV. The flight conditions at the escape point of the boost trajectory would determine whether or not the escape vehicle will re-enter, whether it will exceed deceleration and temperature limits on re-entry, and how far from the launch site along the ground track it will land.

Figure 7 shows the safe flight corridor during boost to the 24-hour orbit. The boost trajectory is shown as a plot of altitude versus time after launch. The shaded areas represent unsafe regions for escape. Escape from the critical regions at suborbital speed will result in a too steep re-entry of the escape vehicle whereby a deceleration limit of $10\,g$ or a temperature limit of 3500°R, or both, will be exceeded. Escape at superorbital speed will result in the vehicle moving away from the earth on an elliptical orbit with the perigee too high to be captured by the earth's atmosphere for re-entry.

The techniques for alleviating these problems are to apply corrective thrust by means of a rocket and use lift to change the flight path angle. For escape at suborbital speed, the corrective thrust, to be effective, should be applied just before entry into the atmosphere at a 90 degree angle to the local horizon in an upward direction. This procedure will produce a maximum change in the entry angle for the available ΔV, reducing deceleration and heating loads and, at the same time, increasing the range. The orientation manoeuvre for rocket firing can be executed while the escape vehicle is coasting above the atmosphere. After firing and jettisoning the rocket, the escape vehicle is re-oriented at the proper angle of attack for a lifting re-entry. The rocket firing and reorientation manoeuvre would require from 30 to 40 sec and sufficient time must be allowed for executing it just before an excessive build-up of dynamic pressure, *i.e.* above 250,000 ft altitude(3).

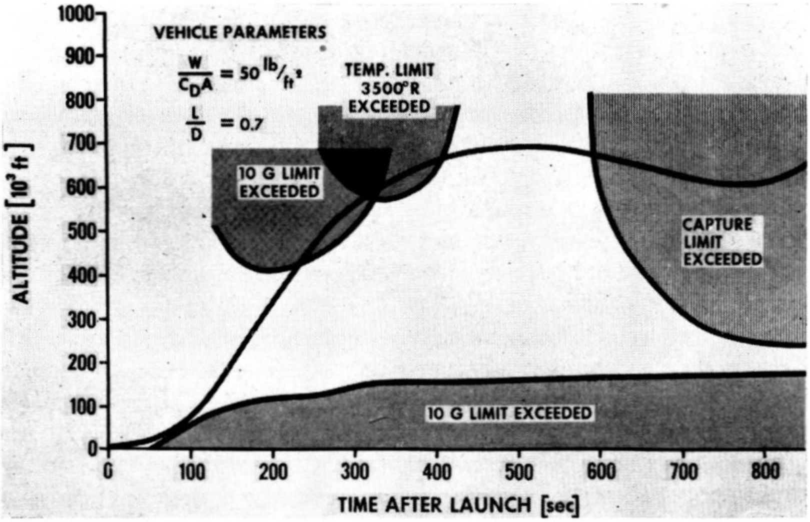


FIG. 7 — Safe flight corridor during boost to 19,350 nautical mile altitude orbit without escape rocket

Escape at suborbital speed may result in landing anywhere between 500 and 5000 nautical miles down range. The number of landing points can be reduced by using lift and propulsion to control the range. However, with the amount of propulsion that may be available, it will not always be possible to satisfy both range and re-entry deceleration requirements. It appears that range rather than reducing re-entry decelerations will be the governing factor in determining how much ΔV should be used for each escape trajectory.

For escape at superorbital speed and an immediate return to earth, the corrective thrust should be applied immediately after separation since ΔV requirements increase rapidly as velocity, altitude and time increase. A manoeuvre is required to position the escape vehicle to apply the thrust downward at a 110 degree angle to the local horizon to change the flight path angle so that the escape trajectory intersects the atmosphere. After jettisoning the rocket, the escape vehicle is positioned at a negative angle of attack for re-entry along the overshoot boundary. At this attitude the lift vector is counteracting the centrifugal force, thus holding the vehicle in the atmosphere while decelerating to orbital velocities. A roll manoeuvre technique is then used to control range for landing near a recovery base. For re-entry along the undershoot boundary a positive lift attitude is required. The pilot will have several minutes to perform the orientation manoeuvre between rocket firing and re-entry.

Propulsion requirements depend on the launch trajectory and the escape vehicle parameters $W/C_D A$ and L/D. For the trajectory and vehicle parameters shown in Fig. 7, a corrective thrust ΔV of 2000 ft/sec is required to reduce entry deceleration at suborbital speed below 10 g. For an immediate return after escape at burnout, a ΔV of 5200 ft/sec is required. This amount of propulsion may be available in a vehicle that is to be de-orbited from a synchronous orbit. For low altitude orbits, however, the maximum ΔV available may be only 800 ft/sec, which is that required for escape at the maximum dynamic pressure condition. By shaping the trajectory it is possible to avoid the unsafe regions or reduce the ΔV requirement. However, shaping of the trajectory would have to be weighed against weight penalties of a non optimum mission profile.

After launch vehicle burnout at superorbital speed, the corrective thrust ΔV requirement increases so that it may not be possible to effect an immediate return with the amount of fuel available. Also, an immediate return may not be desirable from the viewpoint of radiation exposure which, for some escape trajectories, may be as high as 20 Roentgen. Therefore, elliptical trajectories with the apogee above the high flux regions would be preferable to those with the apogee, or those dwelling for a long time, in the high flux regions.

Orbit

Escape from orbit requires an escape module with de-orbit and re-entry capability. Separation from the disabled spacecraft may be accomplished at a low relative velocity (ΔV). A direct descent is considered impractical because it requires the maintenance of a great number of recovery bases or a high hypersonic lift-drag ratio (L/D) configuration. The alternative is to transfer to a holding orbit and de-orbit at the appropriate time for landing near a recovery base. For return from a 200 nautical mile polar orbit with a lift-drag ratio (L/D) between 0·3 and 0·5 and a small number of recovery bases distributed around the world, a maximum of three delay orbits would be required.

After a long exposure to weightlessness, the crew will probably not be able to tolerate the $8g$ deceleration associated with a ballistic re-entry and a lifting re-entry would have to be used solely to reduce the maximum deceleration. Lift capability (L/D) is even more desirable for re-entry from the higher altitude orbits where deceleration and corridor width are more critical than for low altitude orbits.

Figure 8 shows computed lifting re-entry trajectories and corridor limits for the spacecraft configuration. The re-entry corridor is defined by the capture and deceleration limits for re-entry speeds above 26,000 ft/sec and by the equilibrium glide and deceleration limits for re-entry speeds below 26,000 ft/sec. Stagnation point radiation equilibrium temperature lines have also been plotted to show the maximum structural temperatures associated with these trajectories. These are 3500°R (1670°C) for re-entry from 200 nautical mile orbit and 4150°R (2040°C) for re-entry from the 24-hour orbit. The trajectories are characterised by three phases, pull-up, constant altitude and equilibrium glide, and to fly them would require ability to manoeuvre and a skilled pilot.

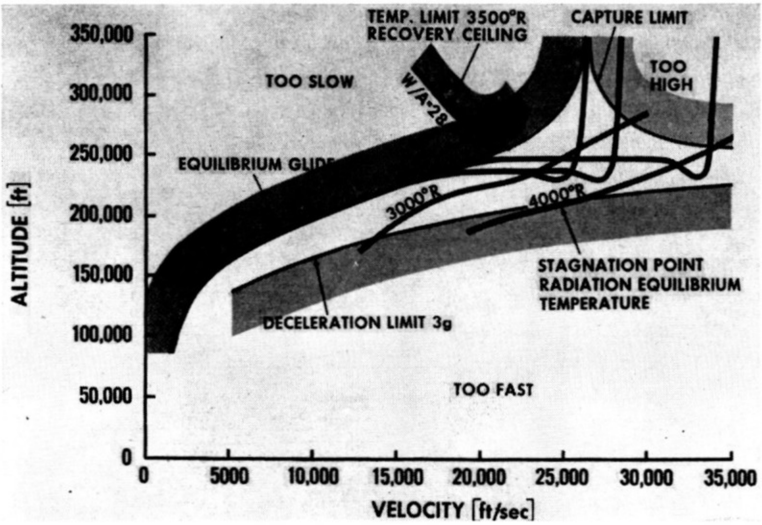


FIG. 8 — Re-entry from 200, 2000 and 19,350 n. mile altitude orbit

Essentially, the escape module must have an efficient re-entry configuration to cope with the re-entry heat problem, lateral range capability for landing near a recovery base, adequate propulsion for de-orbiting, trajectory control and stability, a guidance and control system and must provide adequate protection and life support during escape and after recovery on the earth's surface.

Re-entry

During re-entry, the requirement is escape from a disabled spacecraft operating near its maximum temperature capability. The escape propulsion system will be used to place the module quickly in a safe environment. Aerodynamic interference between the spacecraft and the separating escape module will affect separation performance by causing instability with the associated increase in aerodynamic heating and structural loads. Interference effects are worse if the separation takes place aft of the spacecraft nose, whereby the module must traverse the spacecraft flow field and pass through the bow shock. However, the maximum temperatures experienced by the escape module in this case are lower than for near the nose separation(4).

Heat protection requirements depend on the escape module aerodynamic configuration, wing loading and separation technique. Associated with each re-entry trajectory is the temperature recovery ceiling which is shown in Fig. 8 for a structural temperature limit of 3500°R (1670°C) and an escape module wing loading W/A of 28. If the escape module passes through the recovery ceiling into the shaded area above, it will later descend too fast, thus exceeding its maximum temperature capability. For escape modules with higher wing loading, the recovery ceiling is lower and therefore more critical.

The escape manoeuvre requires stability and control of trim angle of attack to avoid excessive structural and temperature loads. Both aerodynamic and reaction controls are satisfactory for accomplishing this manoeuvre. Reaction controls, however, have poorer damping characteristics(4).

5. CREW ESCAPE RE-ENTRY MODULE DESIGN CRITERIA

A preliminary analysis based on minimum-size modules of simple blunt shapes has established re-entry module parameter trends which are plotted in Fig. 9 as a function of the hypersonic (L/D) max for three-man modules. From the viewpoint of volumetric efficiency and minimum weight, a three-man module is a better solution than three one-man modules. High values of these parameters and a low number of recovery bases are desirable. One can see that although an L/D of only 0·25 provides acceptable vehicle parameters, it is not acceptable from the viewpoint of cost of maintaining a large number of recovery bases. On the other hand there is little advantage in increasing $(L/D)_{\max}$ above 0·5.

Figure 10 shows the effect of wing loading and nose radius on maximum stagnation temperature during re-entry from 200 nautical mile orbit for hypersonic L/D of 0·2 to 0·6. The desirable characteristics are low W/A, which in effect means a large plan area A, and a large nose radius R. However, escape modules that are housed in the spacecraft must be ejected through a hole which is limited to 7 ft diameter by pressurised cabin structural strength and weight considerations. The example of Fig. 10 illustrates that, even for a compact module, the dimensions of the re-entry configuration are larger than 7 ft. Therefore, such escape modules must use an expandable structure so that

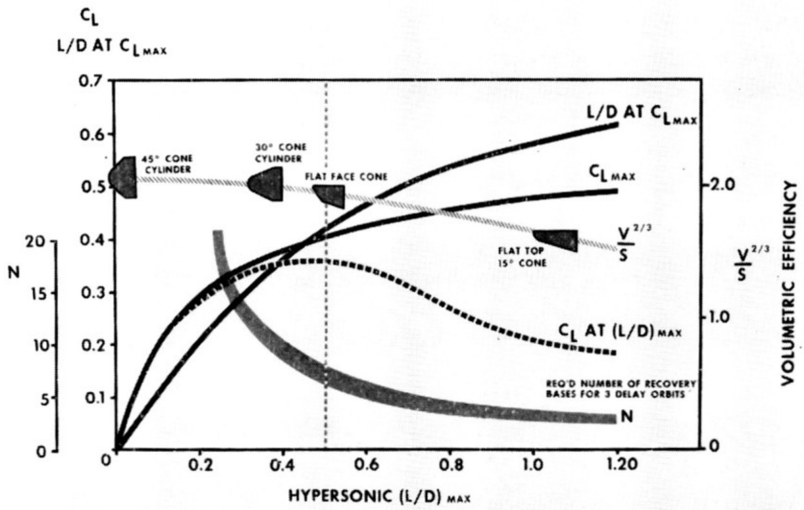


FIG. 9 — Crew escape re-entry module parameters

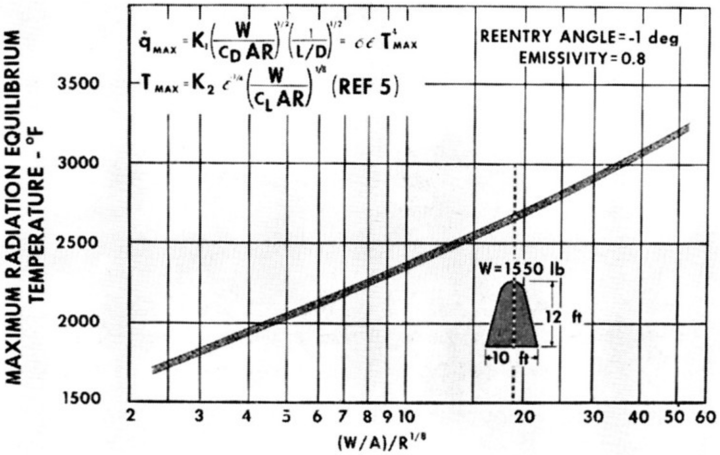


FIG. 10 — Maximum re-entry temperature vs. wing loading and nose radius parameter for L/D of 0·2 to 0·6

they can be packaged for stowage in the cabin and for ejection. Expandable structures, however, are limited to temperatures of about 2000°F (1100°C) by the strength of their woven type materials and can only be applied to the flare of a cone behind the blunt nose where maximum surface temperatures are below 2000°F. For instance, the blunt nose cone module shown in Fig. 10 may consist of a rigid cylindrical capsule with a spherical nose protected by a ceramic or ablation material heat shield and an open expandable structure skirt. Another solution is to design for the lowest possible wing loading and a large radius, i.e. $(W/A)/R^{1/8}$ of less than 10, which is the range of inflatable type vehicles and those with large flexible wing surfaces like the paraglider.

6. ESCAPE CONCEPTS FOR RE-ENTRY VEHICLE

From the analysis of the safety and escape requirements, it was concluded that there are basically four concepts, shown in Fig. 11, which provide maximum safety throughout the mission. These concepts have been subjected to a preliminary investigation to establish feasible designs, their advantages and disadvantages and design criteria for the optimum system. A great deal of effort was concerned with the design of independent structure escape modules which satisfy the requirements of minimum weight, minimum stowage volume, an efficient re-entry configuration and minimum complexity.

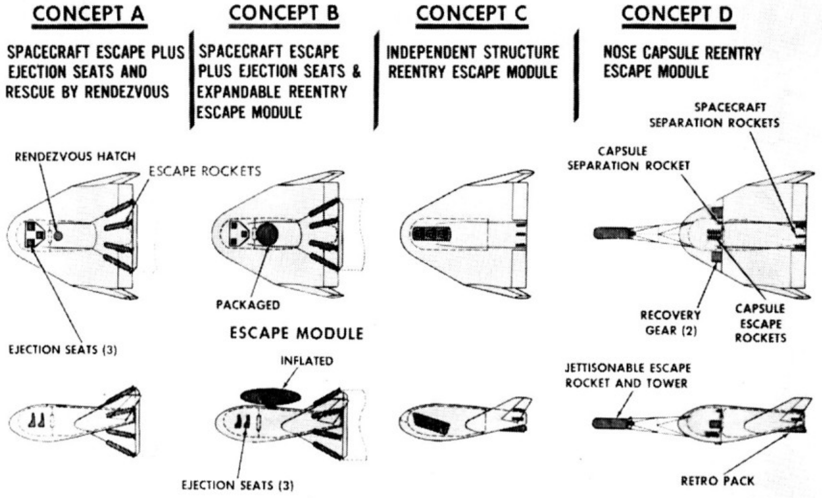


FIG. 11 — Escape concepts for re-entry spacecraft

(*A*) *Spacecraft escape plus ejection seats and rescue by rendezvous*

During orbit non-separable crew escape techniques provide temporary protection from hazardous conditions on board the spacecraft until rescue is accomplished by rendezvous with another vehicle launched from the ground or from a space station already in orbit. For escape during boost, the spacecraft is separated from the launch vehicle by means of an escape propulsion system and, during approach and landing, ejection seats are used.

(*B*) *Spacecraft escape plus ejection seats and expandable re-entry escape module*

An independent structure re-entry module, i.e. one that does not utilise primary vehicle structure, provides escape capability for the orbital phase only. Such a module is of expandable structure and is stowed in the spacecraft in the packaged condition. Alternative techniques, such as spacecraft escape and ejection seats, are used for the atmospheric and other phases of the mission. The best configuration was found to be an expandable disc module which is stowed in the spacecraft wall. For escape, the module is inflated around a hatch towards the outside of the spacecraft, occupied by the crew and separated for re-entry and return to earth. This concept will be described later in more detail.

(*C*) *Independent structure re-entry escape module*

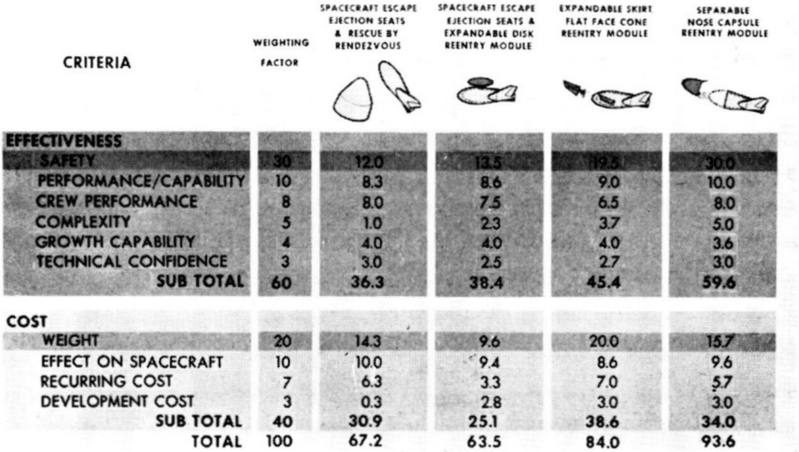
An independent structure module consisting of a minimum size rigid capsule and an expandable re-entry structure is installed in the spacecraft and is used for escape in all phases of the mission. The module is ejected in its minimum cross-section configuration and the expandable structure is deployed to provide a stable aerodynamic configuration both for re-entry and high dynamic pressure flight. The configuration which best meets the requirements of this concept is a canted cylinder capsule and an expandable skirt which can be deployed quickly to modify the cylinder into a flat face cone. The rigid capsule has a removable cover which is stowed away during the orbital phase. During the ascent to orbit and return to earth phases of the mission, the three men are installed in tandem in the assembled module ready for ejection.

(*D*) *Nose capsule re-entry escape module*

This concept is a separable crew compartment re-entry module of the nose type providing escape capability for all phases of the mission. The module utilises the nose structure of the spacecraft including re-entry heat protection system and the command compartment with flight instruments and equipment. The nose capsule is provided with booms or flaps which are stowed in the aftbody of the spacecraft and which are extended to a preselected fixed position after separation to provide trim and stability for re-entry and high dynamic pressure flight.

7. EVALUATION AND SELECTION OF OPTIMUM CONCEPT

For the selection of the optimum system, each concept was examined with respect to two sets of criteria, one concerned with escape system effectiveness and the other with cost. Fig. 12 shows overall ratings of the four concepts for the 200 nautical mile orbit mission. These were derived by first determining the relative performance of each concept with respect to each criterion and then applying weighting factors according to the degree of importance of each criterion.



CRITERIA	WEIGHTING FACTOR	SPACECRAFT ESCAPE EJECTION SEATS & RESCUE BY RENDEZVOUS	SPACECRAFT ESCAPE EJECTION SEATS & EXPANDABLE DISK REENTRY MODULE	EXPANDABLE SKIRT FLAT FACE CONE REENTRY MODULE	SEPARABLE NOSE CAPSULE REENTRY MODULE
EFFECTIVENESS					
SAFETY	30	12.0	13.5	19.5	30.0
PERFORMANCE/CAPABILITY	10	8.3	8.6	9.0	10.0
CREW PERFORMANCE	8	8.0	7.5	6.5	8.0
COMPLEXITY	5	1.0	2.3	3.7	5.0
GROWTH CAPABILITY	4	4.0	4.0	4.0	3.6
TECHNICAL CONFIDENCE	3	3.0	2.5	2.7	3.0
SUB TOTAL	**60**	**36.3**	**38.4**	**45.4**	**59.6**
COST					
WEIGHT	20	14.3	9.6	20.0	15.7
EFFECT ON SPACECRAFT	10	10.0	9.4	8.6	9.6
RECURRING COST	7	6.3	3.3	7.0	5.7
DEVELOPMENT COST	3	0.3	2.8	3.0	3.0
SUB TOTAL	**40**	**30.9**	**25.1**	**38.6**	**34.0**
TOTAL	**100**	**67.2**	**63.5**	**84.0**	**93.6**

FIG. 12 — Rating of escape concepts for re-entry spacecraft. 200 n.m. orbit, 28 day mission, three-man crew

The nose capsule re-entry module is the most effective escape concept for the re-entry spacecraft and has the highest rating. With respect to cost it rates second, being penalised by the subsystem weight required for a large capsule which is inherited from the spacecraft.

The independent structure re-entry module concepts offer no major advantages and many disadvantages when applied to the re-entry spacecraft. The expandable skirt flat face cone module concept has the lowest weight and recurring cost, but is complex and rates last with respect to crew performance and effect on spacecraft. The expandable disc re-entry module has the lowest overall rating although its effectiveness is higher than that of the rescue concept. The main disadvantages, large weight, low safety and high complexity stem from employing alternate techniques to provide escape for all phases of the mission. However, considering escape from orbit alone, this concept rates high in safety, is less complex and of light weight while its effect on spacecraft configuration is small. These advantages suggest this concept to be suitable for space station application.

The rescue concept has the lowest score in effectiveness but rates high in technical confidence, growth capability and effect on spacecraft. The main disadvantages, low safety, low capability and high complexity, stem from employing alternate escape techniques, from the launch and rendezvous operations, and from the slow reaction time. Moreover, the development cost of a new rescue vehicle system being exceptionally high makes this concept economically unfeasible. This fact could not be shown clearly in Fig. 12 because of the small weight given to this criterion. The overall rating shown is, however, applicable to a concept using a logistics/rescue vehicle of existing design such as a modified Apollo.

Figure 13 shows estimated mission safety data for the re-entry spacecraft and the 200 nautical mile orbit mission as compared with similar safety data for various present-day vehicles. It can be seen that the spacecraft with no escape system would have 6570 fatal accidents in 100,000 missions as compared with 10 to 20 for current military aircraft. The safest concept is the nose capsule re-entry module with 75 fatal accidents. Spacecraft escape plus ejection seats and rescue by rendezvous rates last in safety with 190 fatal accidents.

YEAR	CLASS OF VEHICLE	FATAL ACCIDENTS PER 100,000 FLIGHTS	SURVIVAL PROBABILITY
1965	PUBLIC AIR TRANSPORT	1	0.99999
	MILITARY AIRCRAFT	10 to 20	> 0.9998
	X - 15	500 to 700	> 0.9930
1975 ★	SPACECRAFT, NO ESCAPE SYSTEM	6570	0.9343
	SPACECRAFT ESCAPE PLUS EJECTION SEATS AND RESCUE BY RENDEZVOUS	190	0.9981
	SPACECRAFT ESCAPE PLUS EJECTION SEATS & EXPANDABLE REENTRY ESCAPE MODULE	165	0.9983
	INDEPENDANT STRUCTURE REENTRY ESCAPE MODULE	120	0.9988
	NOSE CAPSULE REENTRY ESCAPE MODULE	75	0.9993

★200 NAUTICAL MILE ORBIT

FIG. 13 — Safety data of various types of vehicle

8. SPACE STATIONS

Figure 14 shows three representative configurations of space stations that may be operating between 1970 and 1980. The single module is a non-rotating station and may have a crew of 4 to 6 men. The other two stations may have a crew of 15 or more, a radius of 75 ft, and rotate at 4 r.p.m. to provide 0·4 *g* artificial gravity. Each of these stations would be launched by a single launch vehicle with the large ones being folded during launch and unfolded automatically in space. Space stations will operate in conjunction with a logistics support system which will involve a number of vehicles that would rendezvous with the stations at scheduled intervals for resupply, maintenance, crew rotation etc. Economic considerations suggest that the resupply vehicles should have the capability to carry 5 to 10 passengers and 6500 lb cargo and be able to rendezvous with more than one station per mission. A modified Apollo/Saturn V configuration is suggested for up to 5 passengers and a lifting re-entry type vehicle with a recoverable launch vehicle for up to 10 passengers.

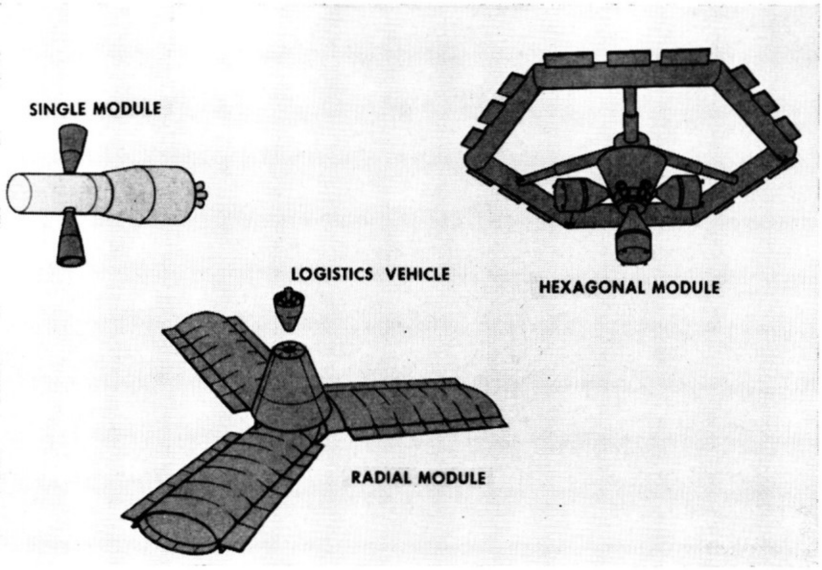


FIG. 14 — Space station configurations

9. ESCAPE CONCEPTS FOR SPACE STATIONS

Space stations would require a separable escape system to provide protection against such emergencies as explosion, fire, orbit decay, severe instability, life support failure and subsystem failures. The time available for action varies from less than 5 seconds for explosion to several hours for orbit decay. Emergency onset and lethality times are critical due to the long egress time (more than 60 sec) that is inherent with a large size of crew and station configuration.

There are three separable escape concepts for space stations.

1. Escape in a logistics vehicle docked at the space station.
2. Escape in a non-re-entry module and rescue by rendezvous with a logistics/rescue vehicle launched from earth or another space station.
3. Escape in a re-entry module.

The non-re-entry escape concept appears to offer no advantages when compared to the docked logistics vehicle escape concept(6). The re-entry module escape concept merits consideration only if it can be launched as an integral part of the space station without significantly affecting the launch configuration, and if it can be developed at a lower cost than that of modification, production, refurbishment and operation of an existing spacecraft, such as the Apollo, for a logistics vehicle. The economic and operational advantages of such a re-entry module concept increase with the number of stations in orbit. A specific design of an escape concept for space stations which exhibits these and other advantages is the expandable disc re-entry module proposed here.

10. THE EXPANDABLE DISC RE-ENTRY MODULE ESCAPE CONCEPT

A one-man configuration of an expandable disc module is shown in Fig. 15 and a three-man configuration in Fig. 16. The module consists of a rigid entry section and an expandable shell structure. The rigid section forms one end of the cabin and contains the entry hatch with a window, flight equipment mounted on the hatch and a parachute stowed around the hatch. Retrorockets as well as inflation and foaming equipment are mounted on the rigid section so that they can be jettisoned. The expandable structure is inflated to a lenticular cross-section disc re-entry vehicle, 15 ft in diameter and a curvature radius to body diameter of 1·2. A torus forms the rim of the disc, two spherical surfaces, the sides, and a conical surface between the two sides, the crew compartment. The material is a nickel–chromium alloy metal fabric woven

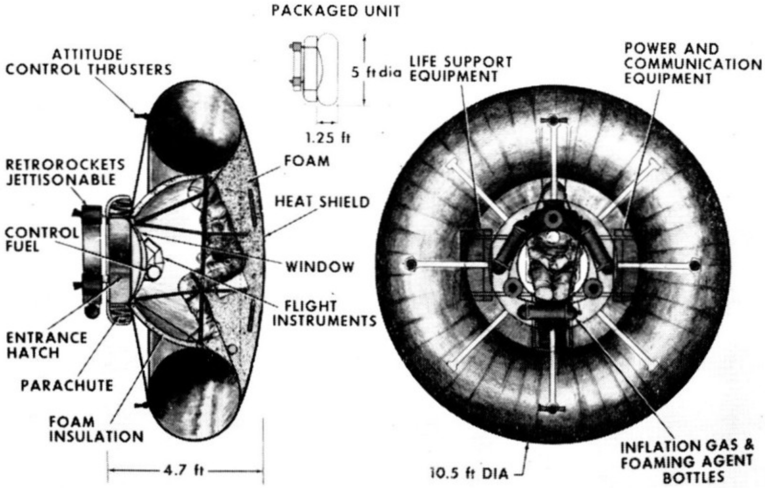


FIG. 15 — One-man expandable disc crew escape module

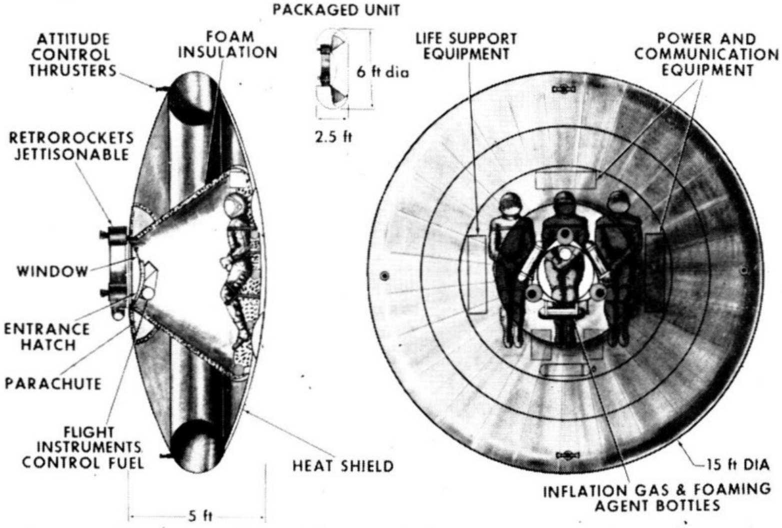


FIG. 16 — Three-man expandable disc crew escape module

from fine filaments (0·0005 inch) in the form of a textile resembling a lightweight canvas. This is impregnated with a resin compound which can provide both rigidisation by gas catalysis and impermeability. The total thickness of this material is 0·015 inch. The exterior surfaces are coated with a silicone elastomer ablative material of varying thickness for re-entry heat protection. Single wall construction is used throughout with the exception of the heat shield structure which is an integrally woven truss double wall. The crew couch, which is tailored to the body contours, and the cabin walls are foamed with a rigidising polyurethane foam providing structural support and insulation. The crew is restrained on the couch by a webbing harness. Life support, power supply and communications equipment are mounted near the heat shield to provide a satisfactory vehicle centre of gravity location. Attitude control thrusters mounted at the torus periphery provide roll, pitch and yaw control.

A three-man module can be packaged into a 6 ft diameter by 2·5 ft envelope and stowed at the wall of the space station for launch. The modules can be erected either immediately after the space station is occupied by the crew or when an emergency escape is necessary. In the former case, meteorite protection is necessary and can be provided in the form of an inflatable rigidised hangar. In the latter case, time may be a critical factor.

The module is erected by inflating first the torus and then, simultaneously, the integrally woven truss and the other compartments. A gas pressure of 10 lb/in^2 is used to maintain the integrity of the structure until rigidisation by curing of the resin is completed.

Figure 17 shows an artist's conception of escape from a space station with

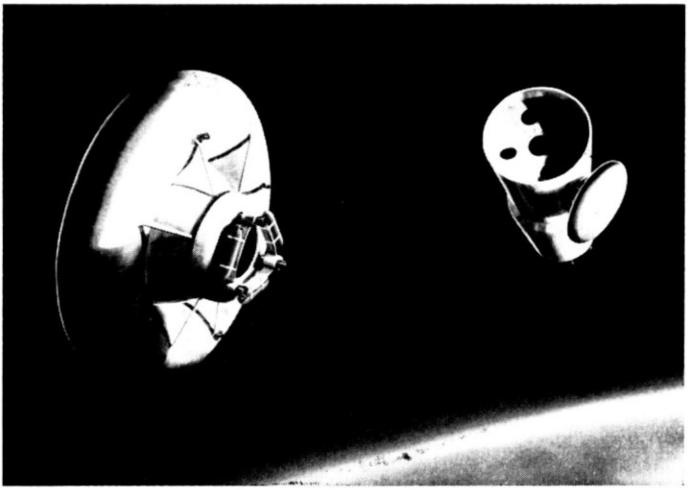


FIG. 17 — Escape from space station. Expandable re-entry disc

the expandable disc module. The escape modules are attached to the space station so that the escaping crew can enter the modules directly from the space station by opening the hatch. After activating the system, the escape modules are separated by applying thrust. The de-orbit parameters are selected for landing near a recovery base and following alignment and stabilisation the retrorockets are fired. After retrofiring, the retrorockets are jettisoned and the escape module is re-orientated for re-entry with its heat shield to the wind side. A lifting re-entry is then performed with the module trimming itself and stabilising at 60 degree angle of attack. Range control is achieved by roll modulation using reaction jet controls. At lower altitudes the module is stabilised by a drogue chute and recovery is accomplished by parachute and landing bag deployment.

Estimated weight summaries for the one and the three-man module configurations are given in Fig. 18. Preliminary estimates for a six-man module show a total weight of 3000 lb and a re-entry weight of 2800 lb.

ITEM	NUMBER OF MEN	
	1	3
STRUCTURE	285	490
LIFE SUPPORT EQUIPMENT	45	90
REACTION CONTROL SYSTEM	20	40
INSTRUMENTS AND DISPLAYS	15	20
COMMUNICATION EQUIPMENT	10	10
POWER SUPPLY EQUIPMENT	25	40
SURVIVAL EQUIPMENT	50	100
LANDING BAG INFLATION EQUIPMENT	25	40
PARACHUTE SYSTEM	20	45
CREW	205	615
TOTAL WEIGHT AT REENTRY lb	700	1490
RETROROCKETS	60	85
INFLATION EQUIPMENT	100	150
FOAMING EQUIPMENT	25	40
TOTAL WEIGHT JETTISONED PRIOR TO REENTRY	185	275
TOTAL MODULE WEIGHT (NO CREW) lb	680	1150

FIG. 18 — Weight statement. Expandable disc re-entry module

The aerodynamic design is based on modification of the conical portion of a blunt-faced re-entry vehicle such as the Apollo to achieve a disc-shaped lifting re-entry vehicle. Figure 19 shows the aerodynamic coefficients as a function of the angle of attack for the three-man module configuration obtained by using modified Newtonian theory and data from ref. 7. It can be seen that a hypersonic L/D of 0·5 is obtained near $C_{L_{\max}}$ with a 60 degree angle of attack. The configuration is statically stable from an angle of attack of 35 up to 90 degrees. Trim at 60 degree angle of attack is achieved by locating the centre of gravity between 40 and 45% body length behind the leading edge(7).

Figure 20 shows altitude, peak heating rate, dynamic pressure and decelera-

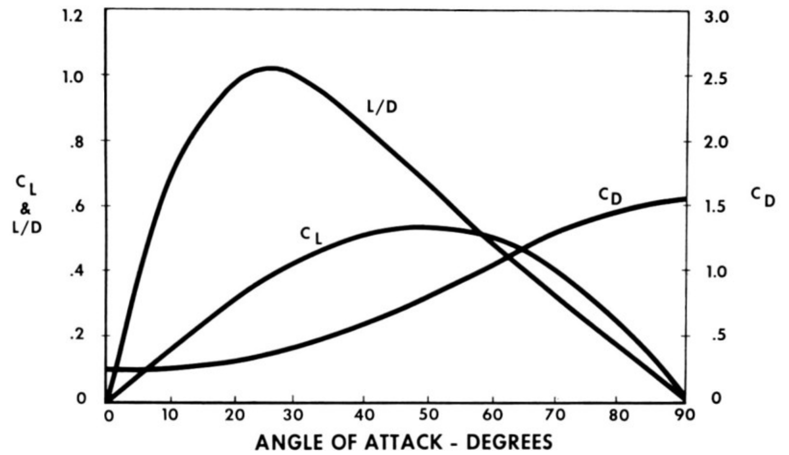


FIG. 19 — Aerodynamic characteristics of a three-man expandable lifting disc

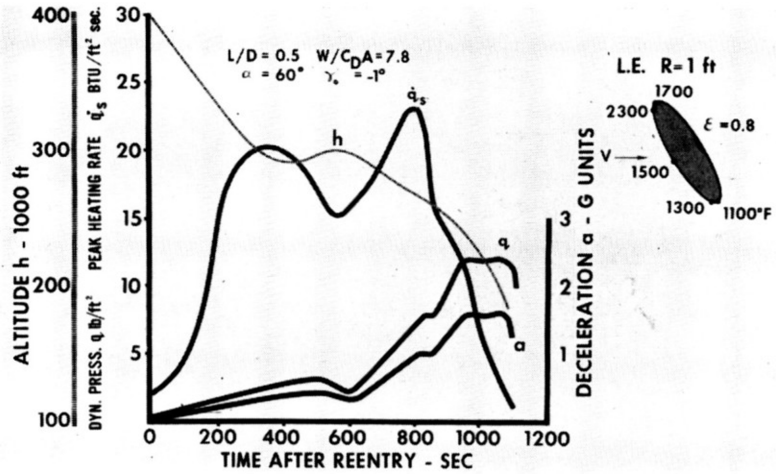


FIG. 20 — Typical re-entry histories. Three-man lifting disc

tion as a function of time for a re-entry velocity of 26,000 ft/sec at 400,000 ft altitude and an entry angle of one degree. These histories show clearly the characteristic long period oscillation of a constant angle of attack re-entry. Maximum deceleration is only 1·6 *g*, characteristic of a lifting re-entry. Surface temperatures during re-entry are relatively low due to the low wing loading, *W*/*A* of 8, the use of lift, and the large radius and spherical shape of the heat shield. The peak heating rate shown for the one foot leading edge radius reaches a high value of 20 Btu/ft^2 sec at the first pull-out at 290,000 ft altitude, then drops as the module climbs to 300,000 ft and reaches a maximum of 23 Btu/ft^2 sec at the second pull-out at 270,000 ft. Peak dynamic pressure at maximum temperature conditions is only 12 lb/ft^2. The temperature distribution over the frontal surface for an emissivity of 0·8 is also shown in the sketch included in Fig. 20. Maximum temperature at the stagnation point is 2300°F (1260°C) but at the larger portion of the surfaces is below 1800°F (980°C). Preliminary thermodynamic analysis based on a silicone rubber charing ablator with an ablation temperature of 1200°F, shows that the required ablation material thickness is 0·250 in for the hottest point at the leading edge, 0·050 in at 1½ ft on either side from the stagnation point, and near zero at the trailing edge. While the exterior char surface of the ablator reaches 2300°F, metal temperatures remain below 1200°F, which is within the operating range of metallic fabric at present under development.

11. Conclusion

In conclusion, it can be stated that for multi-crew orbital vehicles on long duration missions, a re-entry module crew escape system would be more effective and less costly than a space rescue system, even when the latter uses a logistics spacecraft. For the re-entry spacecraft the optimum solution appears to be a nose capsule re-entry module which provides escape capability for all phases of the mission. For space stations with a crew of 4 to 20 men, the expandable disc multi-crew re-entry module concept appears to be an effective escape system and one that is feasible within the current state-of-the-art of expandable structures. This concept has the advantages of using an inherently stable configuration and proven re-entry techniques, similar to Gemini or Apollo, while being lightweight, readily packaged into a small volume and easily deployed.

References

(1) Mavriplis, F., 'Investigation of Emergency Escape and Rescue Techniques for Multicrew Earth Orbital Vehicles.' USAF, Flight Dynamics Laboratory, Technical Documentary Report ASD–TDR–62–297, Oct. 1962.

(2) Mavriplis, F. *et al*, 'Investigation of Independent Structure (Space) Crew Escape Concepts,' USAF, Flight Dynamics Laboratory, Research and Technology Division, Technical Report AFFDL–TR–65–226, March 1966.

(3) Eggleston, J. M., 'Some Abort Techniques and Procedures for Manned Spacecraft.' *Aerospace Engineering*, Vol. 2, No. 11, Nov. 1962.

(4) Cohan, C. J., 'Investigation of Separable Re-entry Escape System Concepts and Separation Techniques.' *Proceedings of 2nd National Flight Safety, Survival and Personal Equipment Symposium*, Space and Flight Equipment Association, San Diego, Oct. 1964.

(5) Chapman, D. R., 'An Analysis of the Corridor and Guidance Requirements for Supercircular Entry Into Planetary Atmosphere.' NASA–TR–R–55, 1960.

(6) Burns, H. P., Covington Jr. C. H., 'Investigation to Determine Feasibility of the Non-Re-entry Module Concept for Crew Escape.' USAF, Flight Dynamics Laboratory, Aeronautical Systems Division, Technical Documentary Report ASD–TDR–63–778, Aug. 1963.

(7) Jackson Jr., C. M., Harris Jr., R. V., 'Static Longitudinal Stability and Control Characteristics at a Mach Number of 1·99 of a Lenticular Shaped Re-entry Vehicle.' NASA TN–D–514, Oct. 1960.