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DESIGN AND ECONOMIC ASPECTS OF REUSABLE
LAUNCH VEHICLES AND CONSIDERATIONS FOR FUTURE SYSTEMS

By H. S. Becker
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NASA-GEORGE C. MARSHALL SPACE FLIGHT CENTER

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By

H. S. Becker

ADVANCED SYSTEMS OFFICE
RESEARCH AND DEVELOPMENT OPERATIONS

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ABSTRACT

The building of launch vehicles that can be used over and over again has been studied extensively for the past 10 years. Recovery and reuse of total vehicle systems has been investigated, as well as reuse of portions of a particular system. The engineering feasibility of being able to fabricate launch vehicles embodying reusable system concepts, and employing either lifting or ballistic return to Earth, has been generally accepted. Considerable uncertainty, however, exists in estimates of the number of flights, or uses, which might be available for new systems of this nature. In other words, what is the market potential for this initially more expensive type of system? This economic aspect, as well as design and specific cost features, are the subject of this paper. Additional thoughts are presented related to whether or not, in our past and current evaluations, we employ comparison methods that properly relate to systems design characteristics. Questions are raised regarding the possibility of our having improperly employed techniques evolved from our ballistic missile background to aircraft type reusable or simplified crude expendable systems, and whether these systems could conceivably employ a different and simplified program approach to development and operations as a result of their basic engineering design features and/or flight modes.

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DESIGN AND ECONOMIC ASPECTS OF REUSABLE LAUNCH VEHICLES AND CONSIDERATIONS FOR FUTURE SYSTEMS

SUMMARY

The building of launch vehicles that can be used over and over again has been studied extensively for the past 10 years. Recovery and reuse of total vehicle systems has been investigated, as well as reuse of portions of a particular system. The engineering feasibility of being able to fabricate launch vehicles embodying reusable system concepts, and employing either lifting or ballistic return to Earth, has been generally accepted. Considerable uncertainty, however, exists in estimates of the number of flights, or uses, which might be available for new systems of this nature. In other words, what is the market potential for this initially more expensive type of system? This economic aspect, as well as design and specific cost features, are the subject of this paper. Additional thoughts are presented related to whether or not, in our past and current evaluations, we employ comparison methods that properly relate to systems design characteristics. Questions are raised regarding the possibility of our having improperly employed techniques evolved from our ballistic missile background to aircraft type reusable or simplified crude expendable systems, and whether these systems could conceivably employ a different and simplified program approach to development and operations as a result of their basic engineering design features and/or flight modes.

INTRODUCTION

Debate on Reuse

For the last several years, elements of our government and industry have participated in a growing debate over the technical and engineering feasibility and potential need for reusable launch vehicles. The subject of building launch vehicles that can be used over and over again to transport men and/or equipment into and out of Earth orbit is not new, and has in fact been studied diligently for essentially a decade. These studies have been sponsored by both government and industry and have spanned a broad spectrum

of concepts. Concepts studied have included methods of returning elements of the launch vehicle to the surface of Earth by flying them in (1) an aircraft fashion, as shown in Figure 1, or (2) in a ballistic manner similar to the way we have recovered our Mercury and Gemini manned space capsules and the manner in which Apollo will return from the moon. Various types of propulsion have been considered including rocket and airbreathing concepts and systems employing nuclear propulsion. Recovery and reuse of the total vehicle system has been investigated, as has been the reuse of only portions of the system. The latter include schemes which would expend various items of the vehicle — varying from complete stages to subelements of a stage such as the propellant tanks. One can immediately ask why this interest in trying to make launch vehicles like airplanes, or returnable space capsules, when we already have means of getting into orbit that have cost our nation a considerable amount in both dollars and time; means that are represented by investments in large and costly ground facilities (including manufacturing and launch complexes) and communications and operations centers around the world. The primary argument for reusability stems, of course, from the intuitive feeling that it should be less expensive to reuse hardware than to throw it away, especially when it has been costly both to develop and manufacture.

If reuse is obviously so cost attractive then why doesn't our nation move ahead with development of a reusable launch vehicle system? In order for a reusable vehicle development program to be acceptable, one of the first orders of business has to be the general acceptance of engineering and technical feasibility. It appears that this hurdle has essentially been passed. The engineering feasibility of being able to build various types of reusable systems, either employing lifting or ballistic return to Earth, has generally been accepted. Certain disagreements do exist in proposed "best" design approaches, and there are remaining questions about exact, detailed operational cost characteristics. It does appear, however, that there is acceptance on the part of the industrial community that a system could be engineered and built, and a summary of the highlights of the technical aspects of these systems is discussed below. The largest uncertainty exists in the number of flights, or uses, which might be available for new systems of this nature. That is, what is the market potential? Reusable systems have been estimated to require very large development funds, typically billions of dollars. In order to adequately amortize, or write off, these large development costs, many flights are required. It is uncertainty in the ability to predict the market that appears to be the largest single deterrent to development of any reusable launch vehicle concept. To add further to the dilemma, our nation's space endeavors are in competition for dollars with other segments of our national efforts. In order to attempt to circumvent this problem, consideration has been given to system

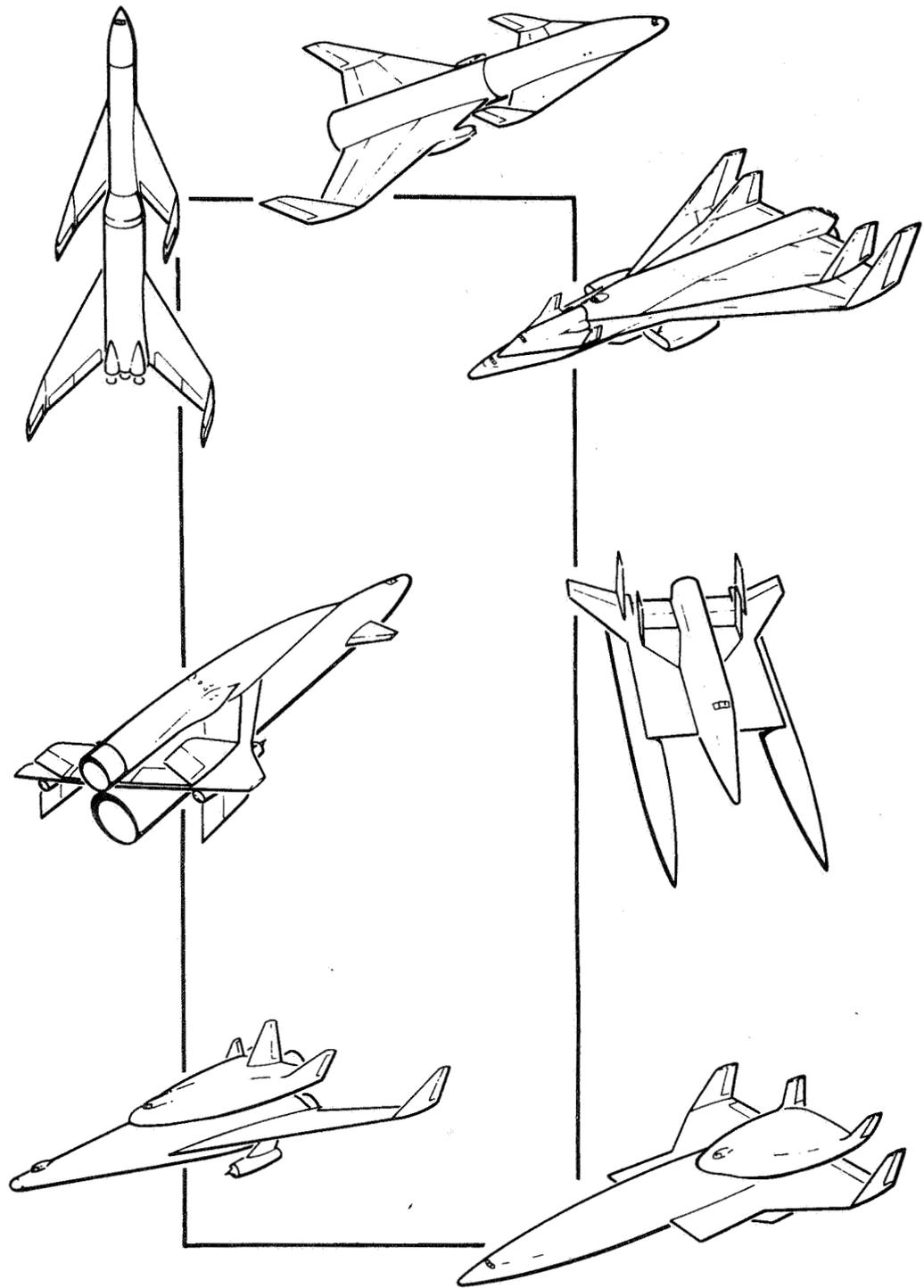


FIGURE 1. AIRCRAFT-TYPE REUSABLE LAUNCH VEHICLE CONCEPTS

development approaches that would evolve a reusable system by developing, or bringing into operational use, various parts of the system in an incremental fashion. It is not clear, as will later be seen, that even these approaches are financially attractive. In summary, it appears that the market demand is uncertain and the dollars to develop the market are scarce.

Let us now step back and consider how we got to the point where we currently stand in our nation's ability to deliver men and equipment into and out of Earth orbit and trace in greater detail the characteristics, both engineering and economic, of reusable launch vehicles in order to better understand the debate which is currently under way.

How We Got Where We Are

Just prior to the advent of the space age with the launching of Sputnik I in October of 1957, our nation's military were developing vehicles that had the potential of delivering mass into Earth orbit. These vehicles, shown in Figure 2, were the ballistic missiles under development by the United States Air Force and Army. With the advent of Sputnik I, it was decided — after the initial Vanguard launch attempts — to modify and employ an existing military vehicle to launch our nation's first satellite. (The Vanguard was specifically designed and developed for the International Geophysical Year activities based upon national policy which directed the use of nonmilitary vehicles for our first orbital space flight efforts.) The first United States satellite was the Explorer I, launched with a modified Army Redstone missile. Since that time, vehicles having this ballistic missile inheritance have been employed for all of our nation's space endeavors of both a manned and unmanned nature. As shown in Figure 3, the capability to place larger payloads into Earth orbit has steadily increased with time, although still employing this basic ballistic missile technology. By that we mean that the vehicles developed (1) employ rocket engines for propulsion in all stages, (2) are launched vertically, and (3) upon completion of their mission, that is after all propellant is consumed and a given velocity is imparted to a certain mass, the vehicles are expended — typically to be destroyed in the atmosphere or impact in the ocean. However, if it were not for this ballistic missile capability, in both technology and availability of operational hardware, our nation never could have moved into the space age as it did. How then do these ballistic-missile derived concepts relate to reusable launch vehicles, which is our primary topic of discussion here. That is, what are the genetics of launch vehicles, or aerospace transportation systems?

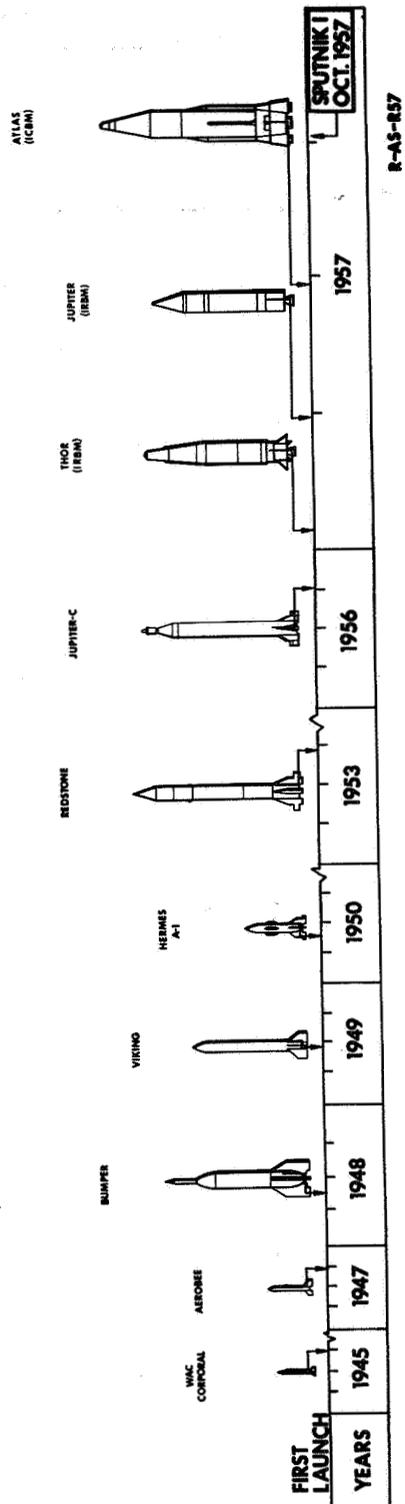
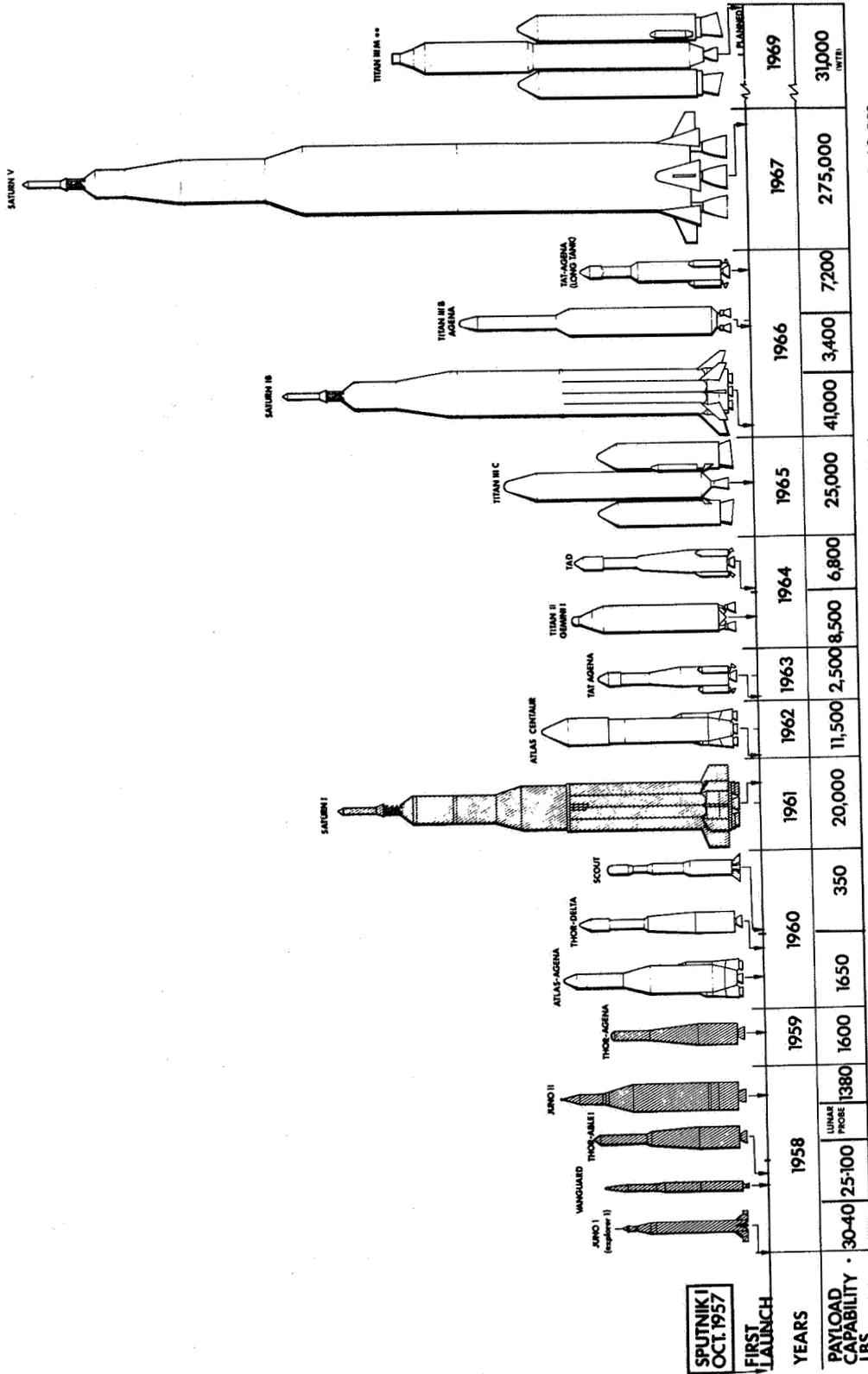


FIGURE 2. PRE-SPACE VEHICLES



R-AS-R58

• 100 N.M. CIRCULAR ORBIT (EASTERN TEST RANGE)
 ** UNDER DEVELOPMENT - FIRST LAUNCH DATE ESTIMATED

§ RETIRED FROM INVENTORY
 WTR - WESTERN TEST RANGE

FIGURE 3. SPACE LAUNCH VEHICLES

SYSTEM CHARACTERISTICS

Launch Vehicle System Genetics

Schematically shown in Figure 4 are the combinations representing possible transportation system concepts. On the left are systems which the United States employed when it first entered the space age and which are still used for the bulk of our space launches. Progressing to the right are combinations of launch vehicle and spacecraft (or payloads) employing varying degrees of recoverability with the vehicle on the right representing single-stage-to-orbit concepts. The ability to attain a vertical takeoff single-stage-to-orbit rocket vehicle employing ballistic recovery of all the hardware appears within the reach of technology currently in existence, and certainly for capabilities forecasted into the 1975-85 decade. It should be noted here, however, that this flight mode typically results in a very low ratio of payload to vehicle weight. It is most useful in the Saturn V class (shown in Figure 3) or Post-Saturn class, that is, several hundred thousand pounds or more of payload to Earth orbit. Concepts other than this, that is, vehicles which would have aerodynamic or aircraft type (1) launch and (2) return to Earth flight modes require propulsion and/or structures and materials breakthroughs in order to attain a single-stage-to-orbit capability. The need for vehicles of very large payload capability is quite limited, and for this, and the technology breakthrough requirements for the aircraft type flight modes, the bulk of the highly reusable concepts considered to date, and further treated in this article, employ multiple stages and aerodynamic (or lifting) flight.

Shown in Figure 4 are systems concepts which are in existence, under development, or have been under study for several years. In addition it can be seen that various technology areas associated with structures and materials, propulsion, aerodynamics, etc., and under investigation by our nation for several years, have applications to recoverable concepts as shown. It is the fact that this wealth of data exists, as noted earlier, which has convinced the industrial community of the general engineering and technological feasibility of reusable vehicles.

It should be noted, at this point, that the concepts shown in Figure 4 are not meant to imply that increased desirability exists by going from the expendable systems on the left to the highly reusable systems on the right. It has been recognized that a continuum of alternatives exists in systems

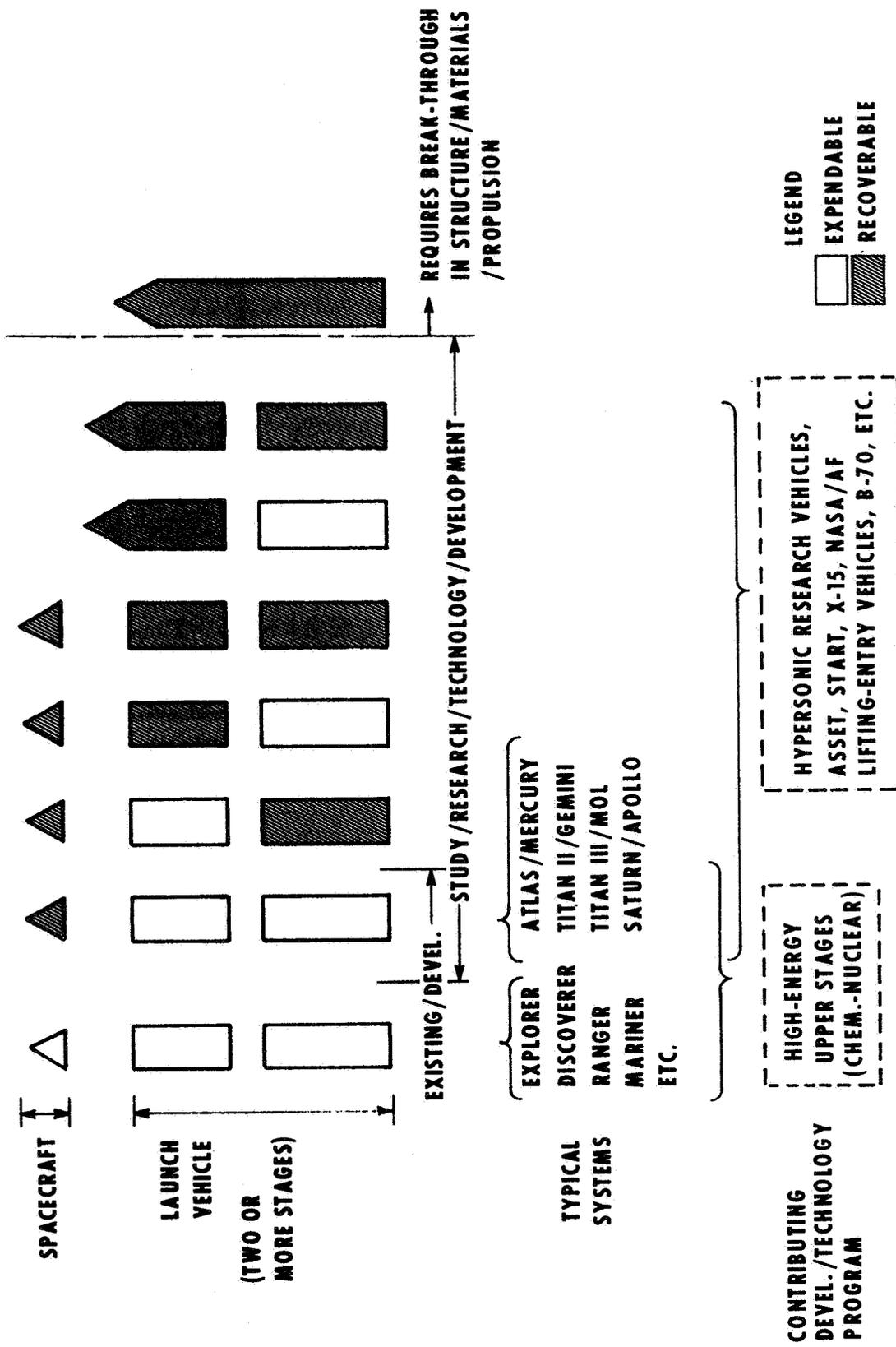


FIGURE 4. AEROSPACE TRANSPORTATION SYSTEMS GENETICS

concepts. And study of this continuum, including utilization of varying degrees of reusability and expendability, has been undertaken to assess the desirability of reuse. This may be viewed in a more graphic manner in Figure 5 which pictorially presents concepts in existence or under study. This figure also indicates the dilemma in choosing the most fruitful path to follow into the future because of the multitude of evolutionary paths available.

As mentioned earlier, the need for reusable systems has been presumed to rest with the potential high traffic rate requirement to carry men and/or equipment/cargo into and out of Earth orbit. This is based primarily on space station logistics which appears to be the class of mission beginning to materialize over the horizon in the decade of the 1970's. As shown in Figure 5, a family of "real world" vehicles exists as represented by the first middle arrow. These vehicles are those previously discussed which evolved from our ballistic missiles and range in size up to the large Saturn and Titan class vehicles which became operational in the middle part of the 1960's. All other concepts represent study vehicles based upon system design and technological investigations. The potential for continuation of the path following on from those vehicles currently in the inventory represents the fact that, if sufficient payload weight lifting capability is not available, the vehicles we currently have can be uprated by various alternatives. These include (1) adding large solid propellant motors to the vehicles (in a manner similar to that accomplished by taking the basic Titan II ballistic missile and adding solid motors to provide the Titan III capability) or (2) using new stages with existing stages — such as the employment of a large solid propellant motor or pressure fed liquid stages with existing high energy upper stages from the Saturn family of vehicles. Consideration has also been given to use of certain stages of the large Saturn V launch vehicle (e. g. , the first and third stage) to provide payload capabilities reduced from the Saturn V but greater than the existing Titan III or Saturn IB.

The concepts on the evolutionary path on the left of the figure represent various aircraft-type approaches employing rocket and airbreathing propulsion and differing flight modes (e. g. , vertical and horizontal takeoff) which have been considered.

The vehicle concept on the right represents an alternative under investigation by various government and industry sources at this time, but one that is highly speculative and for which data are not currently available to adequately compare it with other alternatives. If we step back and investigate the engineering and design features of our current launch vehicles, we find that they are rather sophisticated devices; that is, their design compares quite closely with the way structures and subsystems are designed and

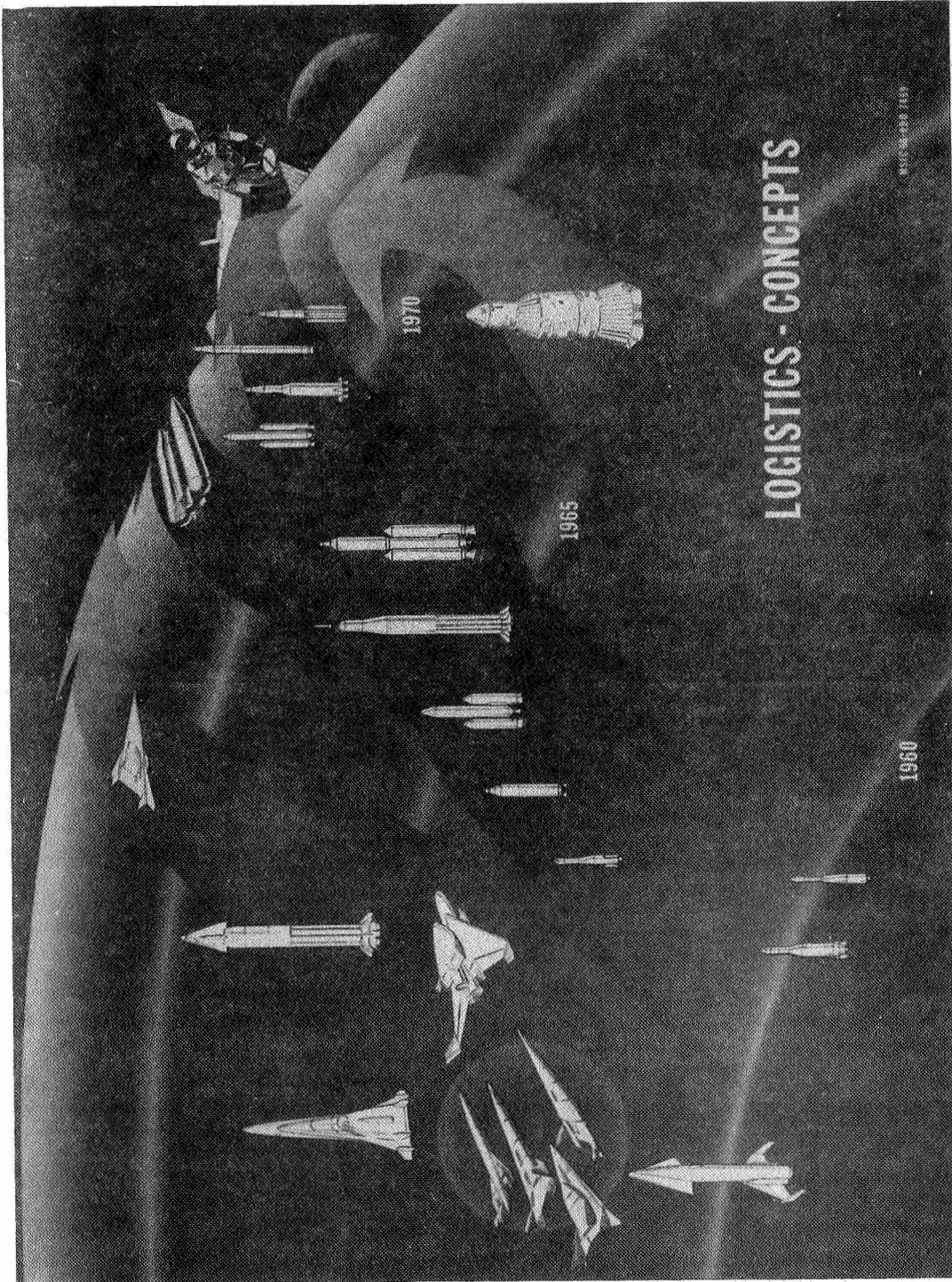


FIGURE 5. LOGISTICS CONCEPTS

fabricated for high performance aircraft, although they do not fly like aircraft and are expended, or thrown away, after their use. This new concept under investigation represents a vehicle that conceivably could be fabricated on the basis of very "crude" or simplified techniques thereby possibly providing extremely low development and operational costs.

The final path is an attempt to bridge the gap between low cost expendable concepts and reusable, sophisticated aircraft designs. The design shown employs expendable propellant tanks with a center rocket vehicle that would return to Earth via an aircraft or lifting flight mode.

Evaluation of these schemes is made difficult by the proliferation of concepts and alternative evolutionary paths and also because the various systems and their associated flight modes result in differing vehicle characteristics and technological features. Let us now consider some of the major differences between these reusable concepts.

Flight Modes and Environments

In designing any launch vehicle, or Earth-to-orbit transportation system, various energy relationships must be satisfied. A change in velocity and in the direction and position of this velocity (velocity vector) must occur during boost, or launch, of the vehicle. The change starts at the surface of Earth and ends in orbit. The converse, of course, exists on the return flight going from orbit to the surface of the Earth. These relationships are shown in the following equations which represent the change in velocity and flight path angle, respectively.

$$dV = \pm \int g \frac{T}{W} \cos \alpha dt \mp \int \dot{g} \frac{D}{W} dt \mp \int g \sin \gamma dt$$

$$d\gamma = \pm \int \frac{g}{V} \frac{T}{W} \sin \alpha dt \mp \int \frac{g}{V} \frac{L}{W} dt \mp \int \frac{g}{V} \cos \gamma dt$$

The plus or minus in the equations show whether velocity is being added during launch to orbit or whether velocity is being dissipated during the return phase.

The items, or factors involved, that the designer must contend with are (1) those that he can perturb or affect in his design process, and (2) the overall environment in which the vehicle flies. The former of these are those factors, such as propulsion, aerodynamics, and structure and materials capabilities, that the designer has freedom to vary, and the latter are Earth's gravitational field, its rotation, and the fact that it has an atmosphere through which the vehicle must fly. The degrees of freedom available to the designer include those items he can manipulate regarding design and technology available to him and the degree to which he "uses" the environment.

In treating the portion of the trip from the Earth's surface to orbital conditions, energy must be added or built into the system. Energy, of course, is provided with propulsive capabilities as shown in Table I. Energy is dissipated or lost (1) in overcoming the Earth's gravitational pull, (2) to atmospheric drag, and (3) in providing miscellaneous requirements (i. e. , the manner in which the trajectory is flown, guidance and control system tolerances and reserves left in the vehicle for uncertainties, etc.). All of these consume portions of the energy and must be appropriately accounted for in system design. A major difference in drag and gravity losses exists between those systems which employ (1) minimum aerodynamic flight modes and high engine thrust weight ratio characteristics (i. e. , rocket powered vehicles) and (2) aerodynamic or aircraft type flight modes such as employed by concepts using airbreathing propulsion systems. The former spend a major portion of their trajectory in a near vertical flight path utilizing their high engine thrust to weight ratio capability to accelerate and exit Earth's atmosphere quite rapidly. This flight mode minimizes drag losses but incurs relatively high gravity losses because the vehicle is traveling essentially vertically for a long period and has to be supported by the thrust of the engine to overcome Earth's gravity. Airbreathing systems provide high engine efficiency (that is, low fuel consumption per pound of engine thrust developed) but also have a low engine thrust per unit weight of engine system when compared to rocket vehicles. Systems employing airbreathing propulsion also experience greater drag losses than rockets because the vehicle flight profile dictates that they fly in the atmosphere where drag losses are incurred. The airbreathing vehicles do, however, employ aerodynamic lift to minimize gravity losses which rocket vehicles overcome propulsively. These differences are shown in Figure 6.

Other aspects of the velocity requirements relate to the possibility of utilizing the component of Earth's rotation, which is a function of the launch latitude and the direction of launch (launch azimuth) which results from the orbit to which the vehicle is going. In summary, the velocity parameters shown

TABLE I. VELOCITY RELATIONSHIPS

Energy Potential	Velocity Parameter
Propulsive	$I_{sp} g \log \frac{W_O}{W_S + W_{PL}}$
Loss Factors	
Gravity	$\int g \sin \gamma dt$
Drag	$\int \frac{D}{L} \left(1 - \frac{V^2}{V_0^2}\right) \cos \gamma g dt$
Misc Maneuv & Steering	f (Flt Profile, G&C Sys, Reserves)
Other	
Earth Rotation	$\pm f$ (Launch Latitude & Azimuth)

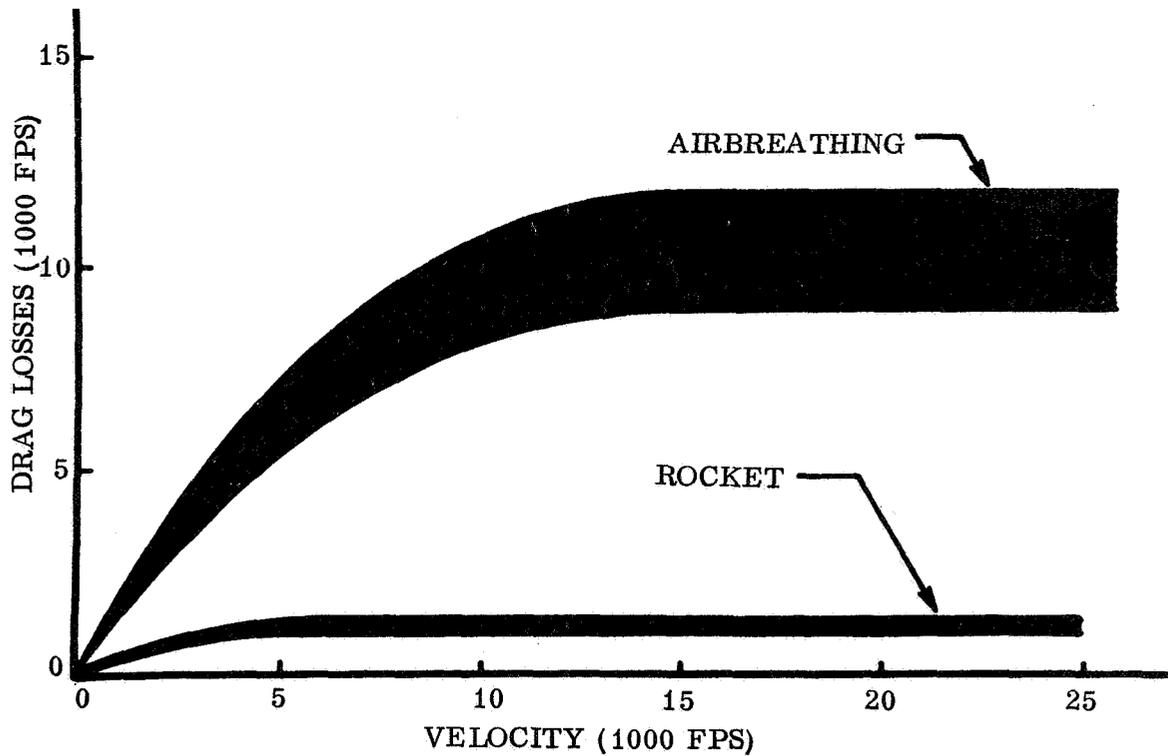


FIGURE 6. DRAG LOSSES OF REUSABLE LAUNCH VEHICLES

represent, as a simplified statement, the boost system cause and effects as they exist in nature. They do indicate, however, how the engineering degrees of freedom previously described relate to the design and performance of the system.

Vehicle Design Characteristics

The choice of these two extremes (i. e., the difference in using rocket propelled vehicles or airbreathing vehicles as described above) results in the vehicles being subjected to a rather different environment during their flight into and return from Earth orbit. As noted above, the rocket propelled vehicle typically exits the atmosphere in a rather rapid fashion and is subjected to relatively low external temperatures from air friction, and the airbreathing vehicle experiences much higher temperatures as shown in Figure 7. This difference in environment determines the type of materials and designs that

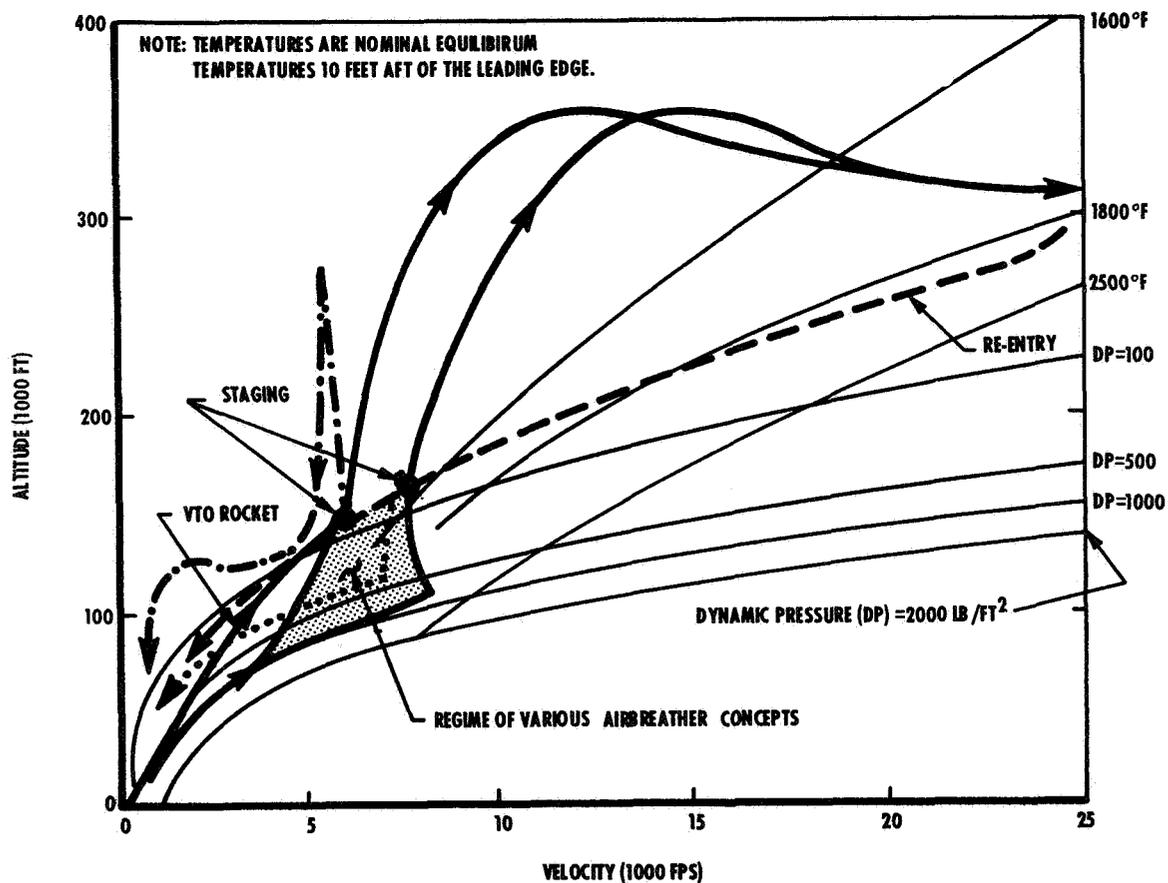


FIGURE 7. FLIGHT ENVIRONMENT

must be employed on various portions of the vehicles. Rocket propelled vehicles have a temperature distributions over the first stage, as noted from Figures 7, and 8 such that super alloys can typically be employed. Airbreathing systems, however, experience severe temperatures and pressures with resulting design complexities and weight penalties. These differences manifest themselves in ultimate designs, as shown in Figures 9 and 10, which depict representative rocket and airbreathing first stages which have been studied during the past several year. Upper stages (all rocket propelled) with either rocket or airbreathing first stages generally experience the same entry environment, and refractories, such as Columbian alloys, or ablation cooled replaceable heat shields, are necessitated, as shown in Figure 11.

The first stage rocket configuration employs "today's" technology liquid oxygen and kerosene and is a winged body type of configuration. The basic air frame tankage consists of semimonocoque construction for the propellant tanks without the necessity of employing a vapor barrier insulation typically needed for airbreathing vehicles which employ the deep cryogenic liquid hydrogen as the stage propellant. Also, the upper stage of this configuration does not have to be buried within the mold lines of the first stage because of the large thrust-weight ratio available with rocket propulsion and the resulting small influence of drag on overall vehicle system performance, as was shown in Figure 6. Thus, the rocket stage is essentially a large X-15 or rocket plane.

Typical airbreathing vehicles, on the other hand, are represented by Figure 10. The first stage of these systems is generally a combination lifting and winged body. This design results from a combination of the requirement to minimize drag by burying the second stage within the first stage and by considering the weight and balance of the overall vehicle with the second stage, and for the first stage alone because of its flight in Earth's atmosphere and resulting aerodynamic considerations. The hydrogen fuel tanks are located along the leading edge of the lifting body and are circular in section. The second stage is mounted in the triangular opening behind the fuel tanks. The propulsion system including the inlets — and turboramjet engines in this concept — is located under the aft portion of the body section. Flyback to the launch facility is performed with the main propulsion engines.

Because of the employment of liquid hydrogen propellant for the airbreather, the tankage requires appropriate insulation in order to prevent the operational problems associated with cryo-pumping and boil-off. As a result of the necessity to bury the second stage essentially within the mold lines of the first stage, the first stage is structurally complicated because of the split tankage arrangement. Also shown are typical design aspects related to the air induction system

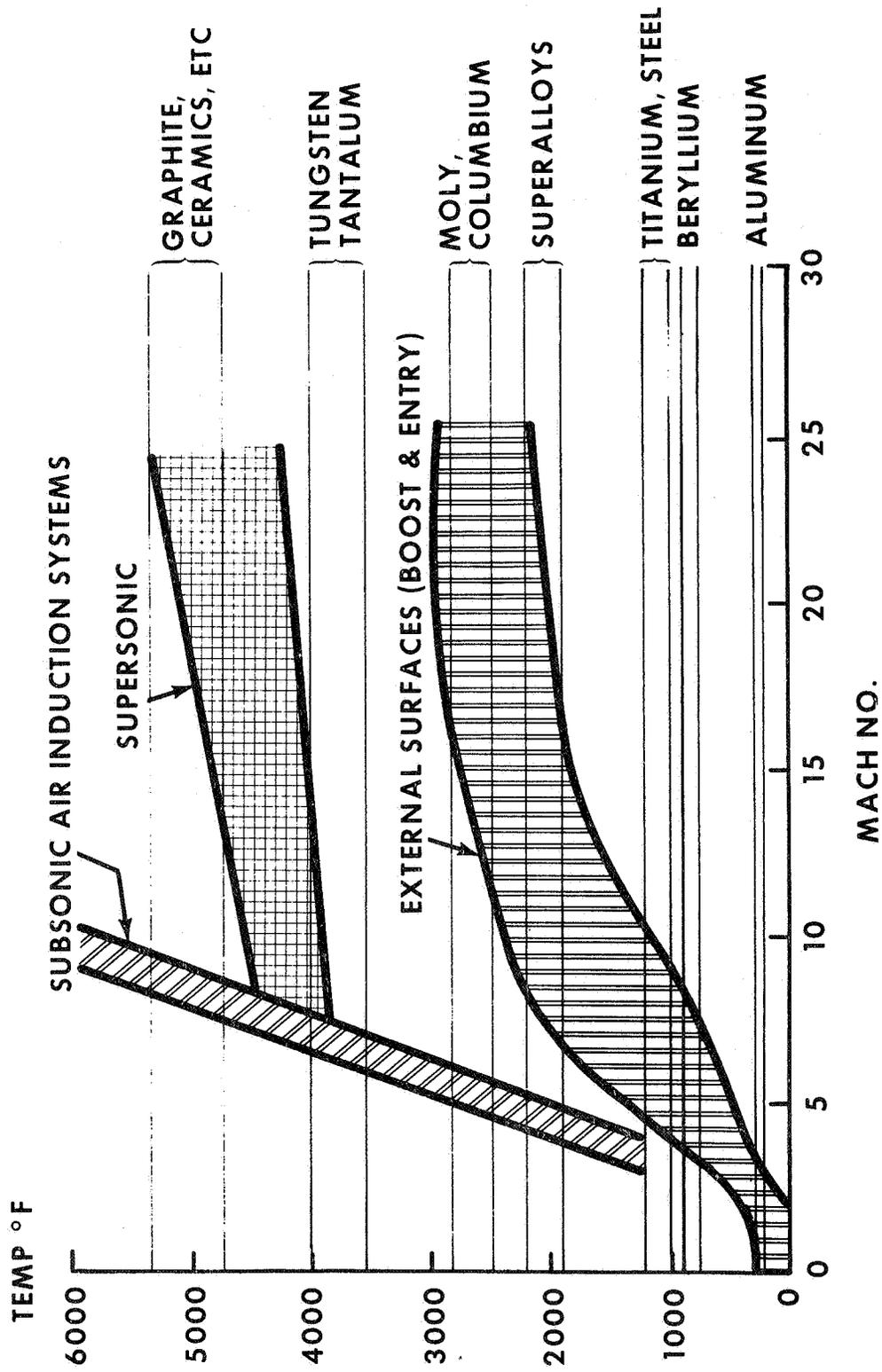


FIGURE 8. HEAT PROTECTION REQUIREMENTS

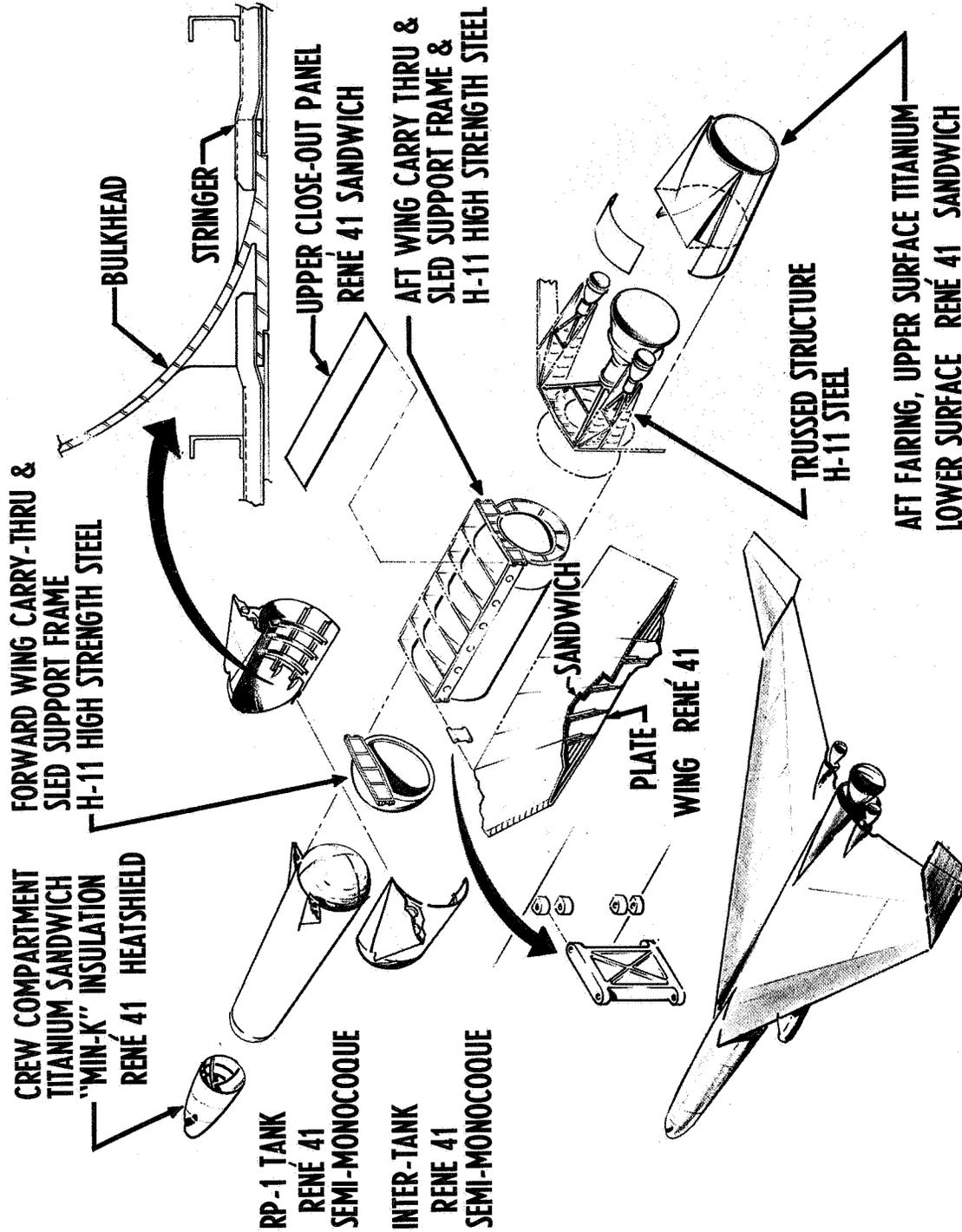


FIGURE 9. STAGE I STRUCTURAL DESIGN - TYPICAL ROCKET VEHICLE

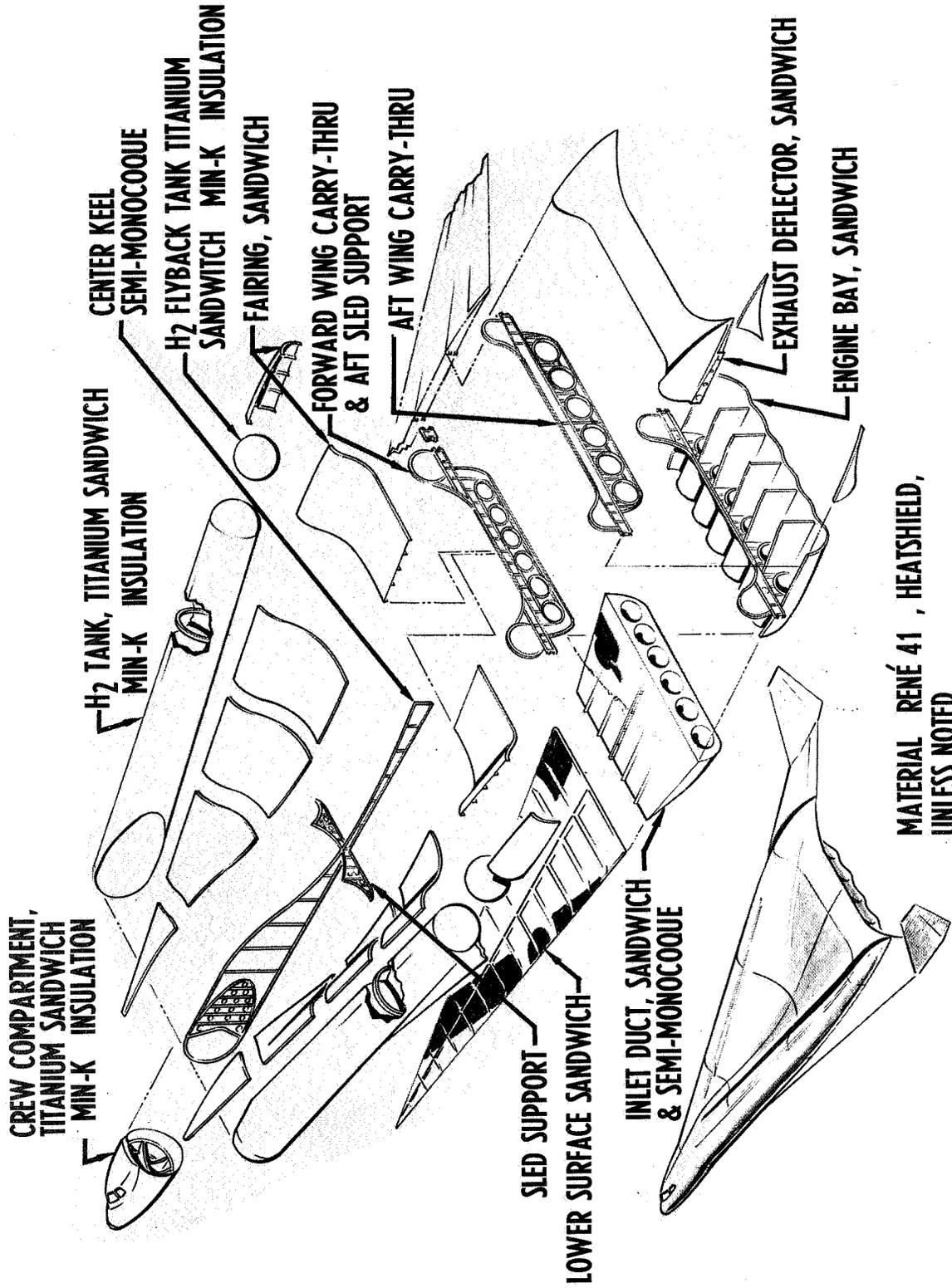


FIGURE 10. STAGE I STRUCTURAL DESIGN - TYPICAL AIRBREATHING VEHICLES

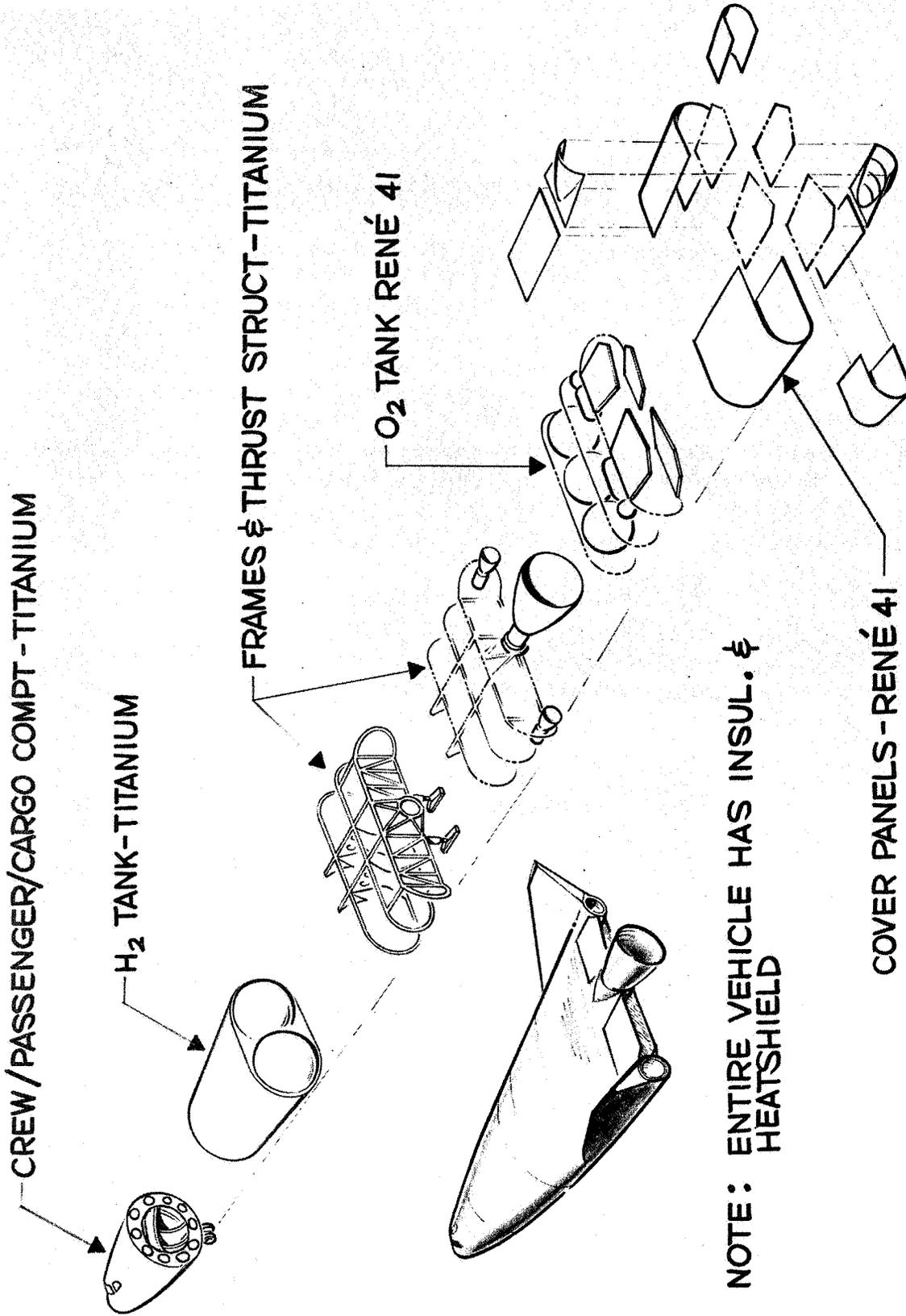


FIGURE 11. STAGE II STRUCTURAL DESIGN

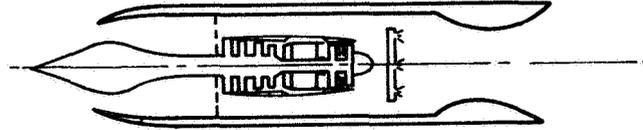
and installed engine system. The structure of the inlet ducts for this type of airbreathing stage is the only portion of the vehicle system that requires primary design for creep because it experiences high loads and high temperatures simultaneously, as shown in Figure 8.

Upper stages, for either vehicles using rocket or airbreathing first stages, are quite similar, and a representative configuration is shown in Figure 11. A lifting body configuration is shown employing an advanced propulsion system — in this case, a high chamber pressure oxygen-hydrogen rocket engine. The structural features result from the external environmental conditions, as previously described.

As a result of these differences in environment and design complexity, airbreathing propelled vehicles have been generally estimated to require an empty weight of approximately 20 to 25 percent more than rocket vehicles, including weight of the upper stages, to perform the same mission. It appears that the higher specific impulse (low consumption of fuel per pound of thrust) is offset by the lower bulk density and lower thrust to weight ratio characteristics of airbreathing vehicles resulting in greater hardware empty weight as noted. It further appears that the airframe design, as shown, is somewhat more complex and, therefore, affects development and operational maintenance and refurbishment. These items all influence total system costs, resulting in approximately 20 to 25 percent higher total program costs (including development and operation) estimated for airbreathing vehicles. Based on these predictions, airbreathing vehicles have generally been estimated to be of less economic attractiveness than rocket propelled vehicles, and further discussion and comparisons will be made on the basis of the type of rocket configurations discussed to this point.

It should be noted, however, that a more speculative type of airbreathing propulsion system has been considered which could have high potential attractiveness. The vehicle described above employed a turboramjet engine which is a concept that consists of a propulsion cycle utilizing combustion gas to drive turbines which, in turn, drive air compressors as shown in Figure 12. Addition of suitable by-pass capabilities provides the ability to

TURBORAMJET



SCRAMJET

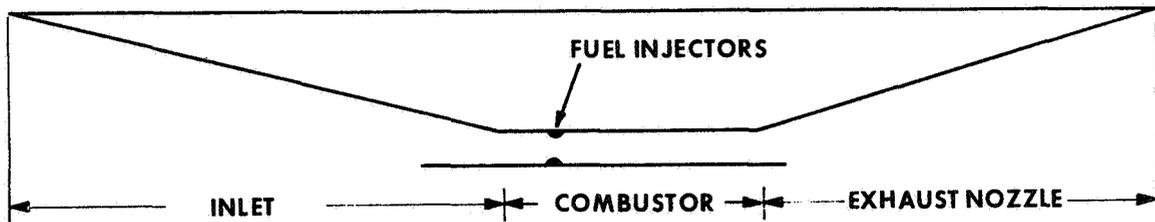


FIGURE 12. AIRBREATHING ENGINE CONCEPTS

operate in a ramjet flight mode, thereby resulting in the designation of "turboramjet." The scheme is generally to operate the turbo-machinery up to a speed at which sufficient compression is generated by the inlet to make operation of the ramjet mode advantageous. Operation of the turbo-machinery is discontinued entirely at a velocity that imposes overly severe design limits on these components or at which the operation in the ramjet mode alone is more efficient. Combustion of the fuel with the air occurs at velocities which are subsonic. The other concept referred to above would combust fuel with the air at supersonic stream velocities thereby precluding the need for large complex air induction systems. This concept is referred to as the Supersonic Combustion Ramjet or SCRAMJET and is shown schematically in Figure 12. It appears that basic combustion feasibility has been demonstrated for the SCRAMJET, and it remains to obtain a suitable integrated vehicle and engine

system design and to better predict performance parameters in order to adequately evaluate this concept. It should be noted that the SCRAMJET is a concept which actually results in the engine system being an integral part of the airframe. This is different from classical airbreathing engine systems such as the turboramjet in which the engine and air induction system can be considered essentially separable from the airframe for certain evaluation and design purposes. Aspects related to attainable SCRAMJET performance and cost, considering overall flight vehicle cooling, lifetime, and reliability, must be included and realistic vehicle system design data obtained in order to evaluate this concept in a commensurate fashion with the more conventional airbreathing configurations. The SCRAMJET, however, cannot be excluded as a potential contender, and ultimate decisions will depend upon results of technology and design studies which will occur over the next decade.

Operational Considerations

At this point, one might well step back and ask why reusable vehicles have to fly like airplanes. Can't, as noted earlier, multistage configurations be designed for ballistic entry rather than lifting or aerodynamic flight modes? The ballistic flight recovery mode has, in fact, been considered over the years in conjunction with the aerodynamic or lifting flight modes. Typically, in ballistic entry, vehicles would be decelerated with large flaps or dive-brakes to a speed suitable for deployment of parachutes which would be employed, possibly in conjunction with rockets, to further reduce the velocity so the stage is not destroyed upon impact. Configurations studied to date have flight trajectories such that impact would occur in the ocean. A concept employing this type of scheme to recover the first stage of the Saturn V launch vehicle is shown in Figure 13. This concept has also been considered for stages of the Titan III and smaller Saturn vehicles. It has generally been estimated that the number of reuses, or lifetime, for this approach is much reduced from that for aircraft type vehicles. These reductions result from the fact that the flight environment and the types of designs employed result in vehicle lifetimes being reduced because of fatigue and also because of the reliability associated boost and recovery operations. Investigations have also included refurbishment and repair required after recovery from the ocean. These considerations, in addition to the weight penalties — added to the vehicles which were designed under criteria applied to expendable ballistic rocket stages for which weight is a major factor — have indicated their lesser attractiveness. Various activities are, however, continuing on these concepts to further reduce uncertainties, and current efforts are mostly in the



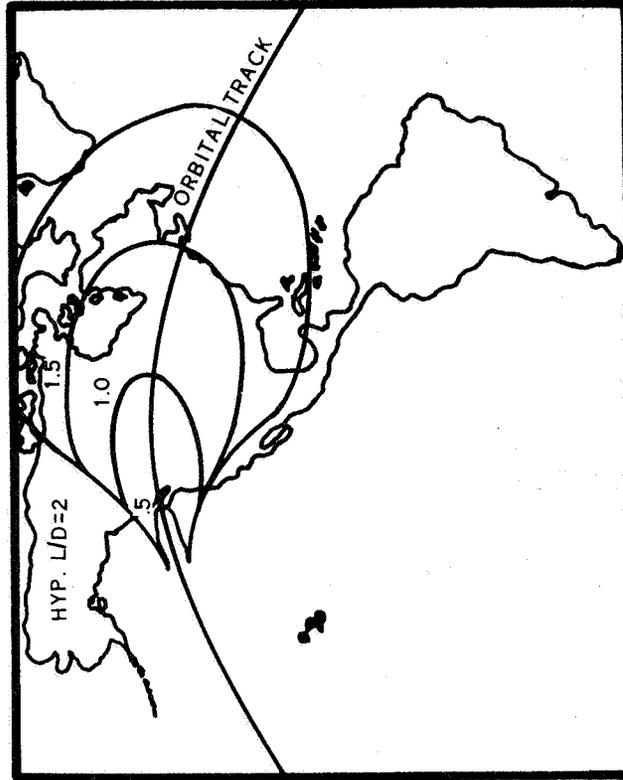
FIGURE 13. BALLISTIC RECOVERY CONCEPT

area of research and technology. It should be noted here that the concept shown is an adaptation to a stage initially designed to be expendable. Ballistic recovery concepts have been incorporated in "new designs," but primarily for very large vehicles, as discussed earlier.

Once the aircraft type of flight mode is established, it is then necessary to determine how much aerodynamic efficiency, e. g. , lift to drag ratio (L/D), is required. For first stages, the vehicle typically reenters the atmosphere and decelerates at a point several hundred miles downrange from the point of launch, thereby necessitating flyback to the launch site or some other suitable location. The design tradeoff typically is the same as that for airplanes in which weight penalties associated with providing suitable aerodynamic lift to drag ratios are traded off with the penalties to provide propulsion, including the need to incorporate tankage to encapsulate return propellant. Rocket stages considered have typically employed turbojet or turbofan engines located under the wings or along the fuselage as seen in Figures 1 and 9. These vehicles have generally been designed to have subsonic lift to drag ratios ranging from four to six depending on the flight angle of attack — typically, 5 to 10 degrees. As a result, these stages have aerodynamic and handling characteristics quite similar to today's large commercial turbojet aircraft during flyback and landing.

Considerations regarding the aerodynamic requirements for upper stages or orbital entry vehicles imply rather different considerations. On one end of the continuum is the potential need to provide the ability to land at various sites when returning from orbit. This ability to obtain a large footprint is obtained during flight immediately subsequent to entry from orbit and occurs at hypersonic speeds. The lateral range, or ability to provide this footprint capability, is related to the hypersonic aerodynamic efficiency of the vehicles and, to a lesser degree, the entry angle of the vehicle. As mentioned earlier, the general need for reusable vehicles appears to result from the need to provide the ability to take men and/or equipment into and out of Earth orbit for space station resupply. In this regard, the missions are highly predictable — that is, the orbital conditions of the space station are well known. Space station missions under consideration include returning from orbital altitudes ranging from approximately 200 to 300 nautical miles and orbital inclinations ranging from approximately 30 to 50 degrees. Figure 14 shows the landing capability when returning from orbit from these conditions. As seen, relatively low hypersonic L/D appears adequate and, in fact, capabilities associated with ballistic or semiballistic entry devices appear adequate. Further, it is rather well known that, as the aerodynamic efficiency is increased, the volumetric efficiency of the vehicle is generally degraded,

50° INCLINATION



30° INCLINATION

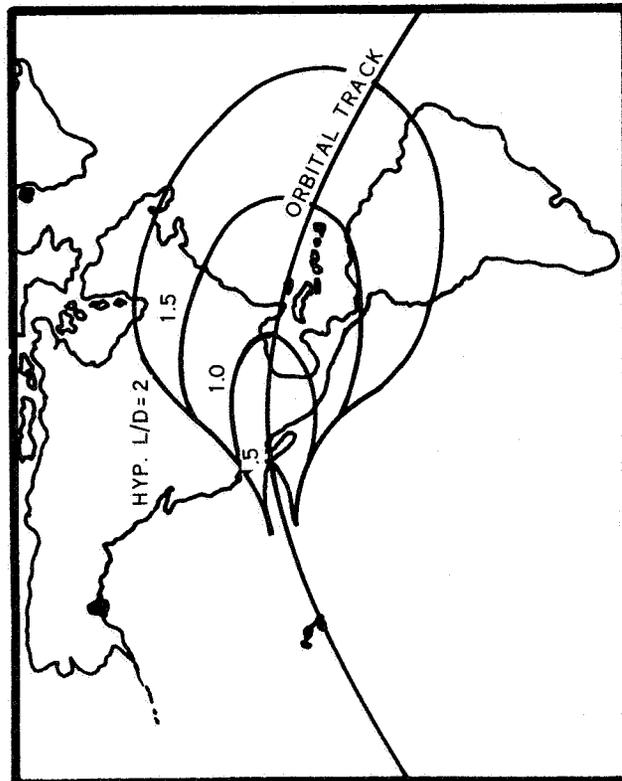


FIGURE 14. LANDING FOOTPRINT

that is, more surface area is required to provide the aerodynamic lifting capability with less volume available in the vehicle to return cargo and/or passengers as shown in Figure 15. It should be mentioned, however, that greater hypersonic L/D than attainable with ballistic or conical shapes has been investigated in order to account for potential operational uncertainties including higher maneuver capability which might result from still speculative military missions and study and technology work is continuing in this area.

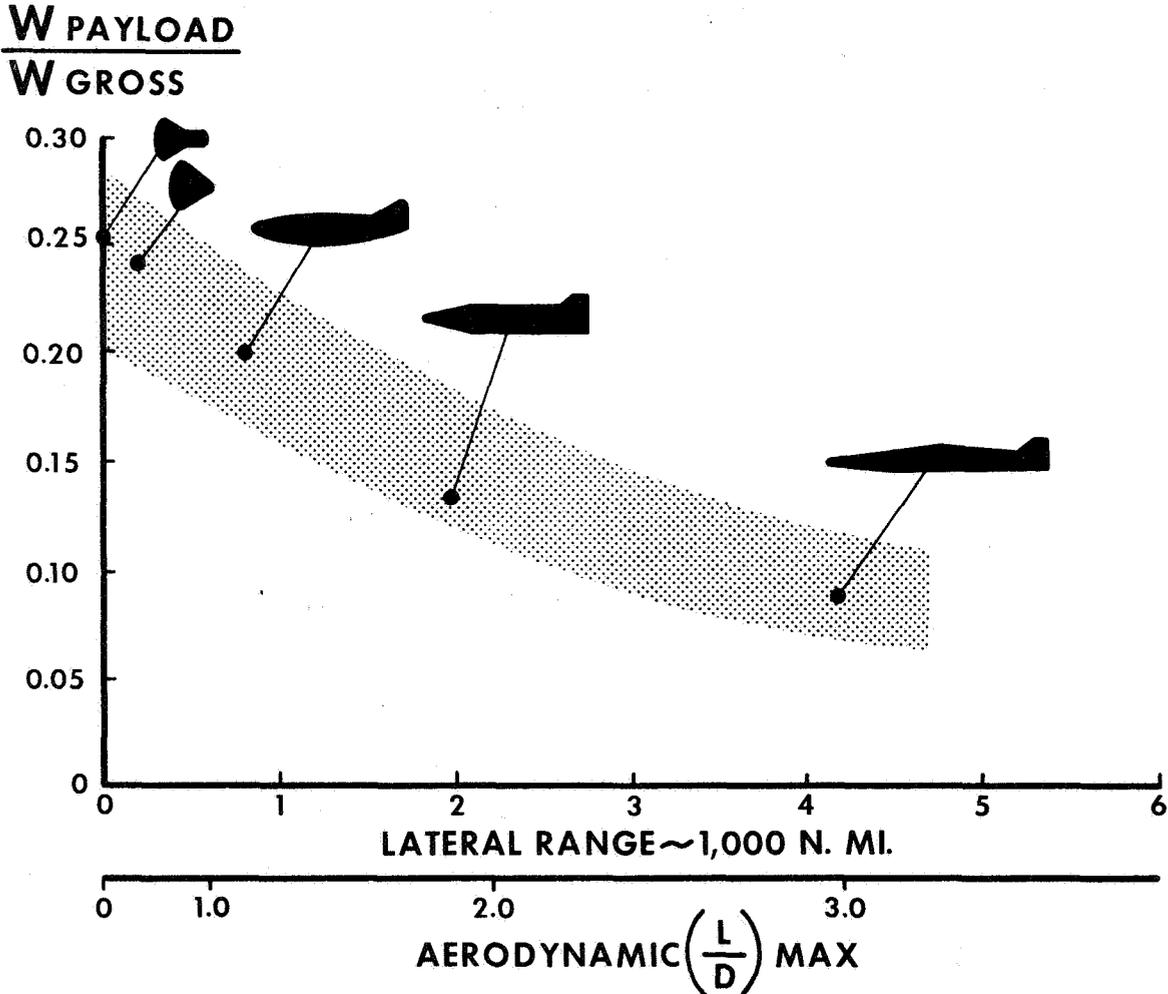


FIGURE 15. PAYLOAD TRADE-OFFS

At the other end of the aerodynamic continuum, are the considerations of landing capabilities of the vehicles — that is, what type of aerodynamic characteristics result at the conditions just prior to landing in order for a

pilot to adequately and safely land this type of vehicle. It is generally accepted that a minimum landing requirement, especially if the vehicles land without propulsion (i. e., deadstick) exists at a subsonic L/D of approximately 3.5 to 4. Once the two ends of the continuum are determined — that is, hypersonic L/D needed for footprint and subsonic L/D needed for final touchdown and landing, the problem becomes relatively well-bounded because a fixed external shape provides certain hypersonic and subsonic aerodynamic capabilities as shown in Figure 16.

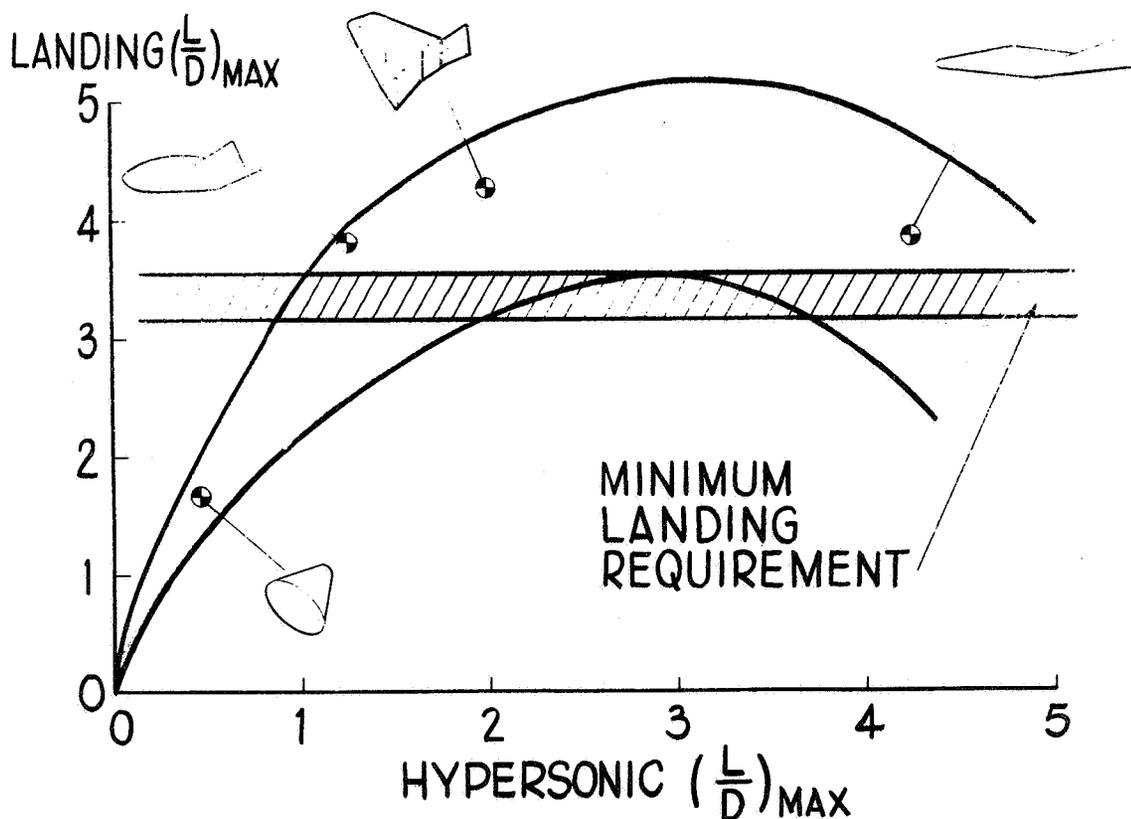


FIGURE 16. AERODYNAMIC RELATIONSHIPS

Vehicles with very high hypersonic L/D generally have low subsonic L/D's and poor landing qualities. At the other end of the spectrum are the low hypersonic L/D ballistic type vehicles having little or no horizontal landing capability. This occurs because the configuration characteristics which primarily establish the vehicle L/D are characteristically quite different in the subsonic and hypersonic flight regimes. In subsonic flight, high aspect

ratios are desirable to increase lifting efficiency and hence L/D. However, to increase hypersonic L/D low aspect ratios (high fineness bodies) are desirable because of the negligible influence of aspect ratio on lift coefficient and the large pressure drag from bluntness associated with high aspect ratio surfaces and/or bodies which must have a relatively large radius of curvature in the stagnation regions to preclude excessive temperatures or heat protection system weight penalties. For reasonable flight altitudes, viscous effects do not contribute significantly to the hypersonic drag of reentry configurations with hypersonic L/D_{\max} less than 1.5. Also base drag is insignificant over virtually the entire hypersonic L/D range. Subsonically, these two contributions represent approximately 50 percent of the total drag at L/D_{\max} .

The relationship among these aerodynamic considerations is illustrated in Figure 16. Low hypersonic L/D configurations characterized by Apollo and Gemini shapes are inefficient lifting shapes and have large base areas which result in very high subsonic base drag; consequently, they have low subsonic L/D's. At hypersonic L/D's of approximately 1.0, typical configurations such as the HL-10, M-2, and SV-5 have potential capability for horizontal landing provided the base area is properly reduced to decrease base drag. These configurations give subsonic L/D's of about 4.0 which is acceptable for landing according to pilot evaluations. However, as the hypersonic L/D increases, the configurations tend to become finer, and the subsonic lift curve slope decreases, resulting in reduced subsonic L/D's.

The restriction relative to low aspect ratios for the high hypersonic L/D configurations could be relaxed and higher subsonic L/D's achieved with these configurations if materials capable of operating at extremely high temperatures were developed. The high subsonic and hypersonic L/D's could then be achieved by employing configurations having high aspect ratios and sharp leading edges (small radius of curvature bodies).

The above characteristics result from fixed geometry conditions — that is, one in which the external or aerodynamic shape of the vehicle is not changed over the entire flight regime. Because of the divergent hypersonic and subsonic aerodynamic considerations, which result in configuration compromises, the possibility of uncoupling the entry and landing modes recently has received considerable attention, as shown in Figure 17. In designing a configuration for uncoupled modes, the hypersonic configuration is selected and a variable geometry scheme is employed to give adequate landing characteristics. These concepts include the use of paraglider concepts, propulsive lift, and parachutes with retrorocket thrust for soft landing

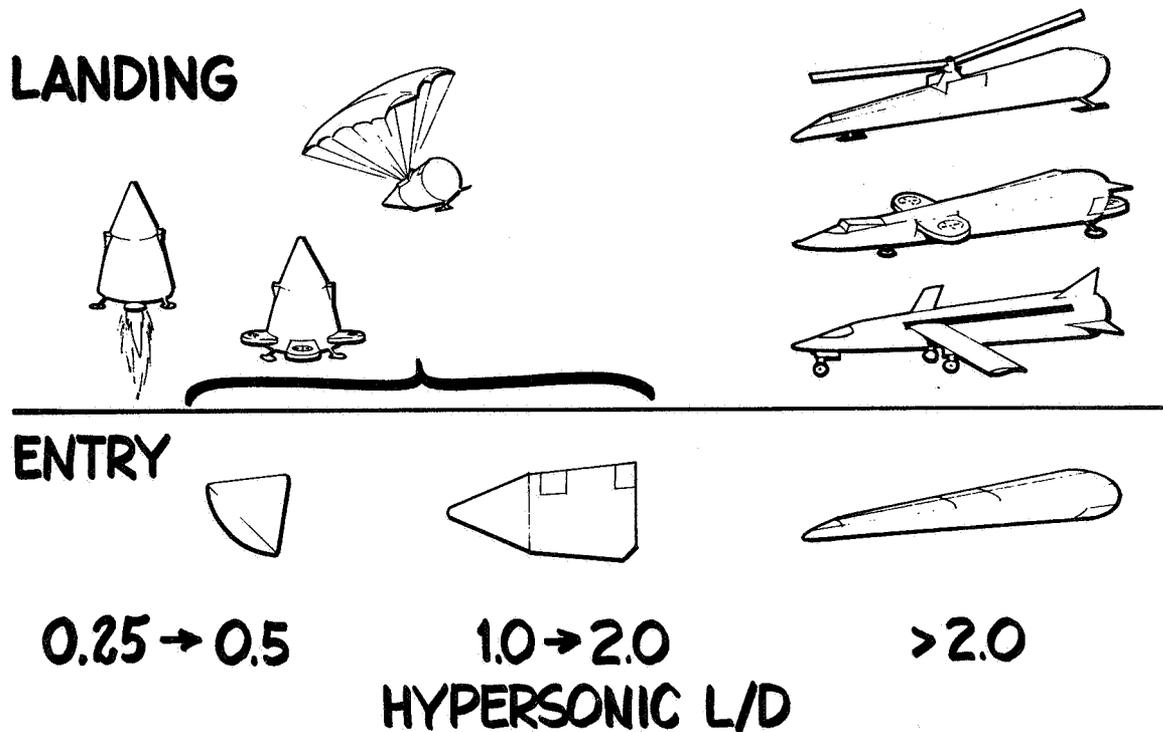


FIGURE 17. UNCOUPLED MODES

of vehicles with hypersonic L/D from 0 to 2.0. Use of stowed rotors, propulsive lift, and stowed wings for the landing of configurations with hypersonic L/D greater than 2.0 is also shown. In all cases, the landing characteristics of the configurations are as good or better than the landing characteristics of vehicles which couple the hypersonic and subsonic flight characteristics. The subsonic L/D varies from about 4.0 for the paraglider to infinite landing L/D with the stowed rotor and propulsive-lift schemes. Practical stowed-wing systems studied yield subsonic L/D's of 6 to 8. Thus it is evident that means of varying the external geometry of the vehicle are available in order to provide appropriate hypersonic maneuvering capability with volumetrically efficient devices that would otherwise have relatively poor landing capabilities. As ultimate requirements are determined a relatively broad range of alternatives exists to the designer in order to alleviate the compromises which may ultimately result from hypersonic maneuvering for footprint considerations and aerodynamic handling qualities at touchdown.

It might be worthy to mention certain additional operational considerations such as the initial launch mode — that is, should it be vertical or

horizontal. It is recognized that once it is decided to return the vehicles to Earth in an aerodynamic or lifting flight mode, the potential exists to launch or take off under this same flight condition. That is, once wings or lifting surfaces are provided, the vehicles could take off in an aircraft fashion, and if rocket propelled, could make a pull-up and then fly in a mode relatively efficient to rocket vehicles, as previously discussed. Weight penalties from the wings (lifting surfaces) incurred in horizontal takeoff, which requires that the entire weight of the vehicle be supported at takeoff and during any high load factor pull-up maneuver, offset weight savings gained by any initial acceleration along the ground — including considerations for providing ground propellant tanks and/or propulsion systems to provide ground acceleration. The ultimate weight efficiencies of horizontal and vertical take off rocket-propelled vehicles are therefore essentially equivalent. The one remaining consideration, which ultimately might have some effect on the generally accepted decision to employ the vertical takeoff flight mode, may be related to the ability to abort the vehicle in the case of an emergency. Although studies today have not indicated so, the ability to jettison propellant and then fly the vehicle under reduced power in an aircraft fashion may be somewhat better in horizontal takeoff as compared to the vertical takeoff flight modes. If a significant difference in vehicle recall capability materializes from this variation in flight mode, it could have a major impact on development requirements, thus making the selection much easier as discussed in the last section.

EVALUATION CONSIDERATIONS

Market Projections

Let us now turn to the factors which have been employed to evaluate these alternative concepts. It is worthy to note, however, that many factors influence ultimate decisions that will be made regarding the choice of expendable versus reusable systems. Mission requirements are a major determinate in this regard. These requirements include such factors as (1) how quickly vehicles must be launched (launch rate), (2) total number of launches and (3) mission profile (i. e., operational flexibility related to offset/cruise range and/or entry footprint) and they define the ability to amortize research and development and operational costs, including refurbishment, for concepts employing features of reusability. Although studies to date have not been able to quantize aspects associated with timing, the date of initiation of system development also influences system characteristics because it affects the

ability to incorporate technological growth. State of the art certainly is not static and the ability to efficiently make systems recoverable and reusable has and will continue to improve as our technological capabilities increase. We also cannot ignore the less tangible, but highly powerful stimuli and motivations related to various political, sociological and economic considerations which affect timing and approval of system developments.

In order to evaluate these systems, market and traffic rate projections have been made including the factors discussed above. Optimistic estimates of the required launches per year for the next two decades are shown in Figure 18. These projections show the representative payload, or mission requirement, for various payload classes for both military and nonmilitary space missions. It is obvious from these projections why highly reusable aircraft-type concepts have been considered in the payload regimes previously discussed. It is for the payload of space station logistics that the highest traffic rate is projected for the next two decades. As previously noted, this primarily relates to rotation of men and/or equipment into and out of low Earth orbit on a relatively routine and predictable basis. It should be noted here that the potential market predictions shown in Figure 18 are highly optimistic, resulting in a situation that would benefit any new, high development cost system — that is, the ability to amortize fixed costs is enhanced.

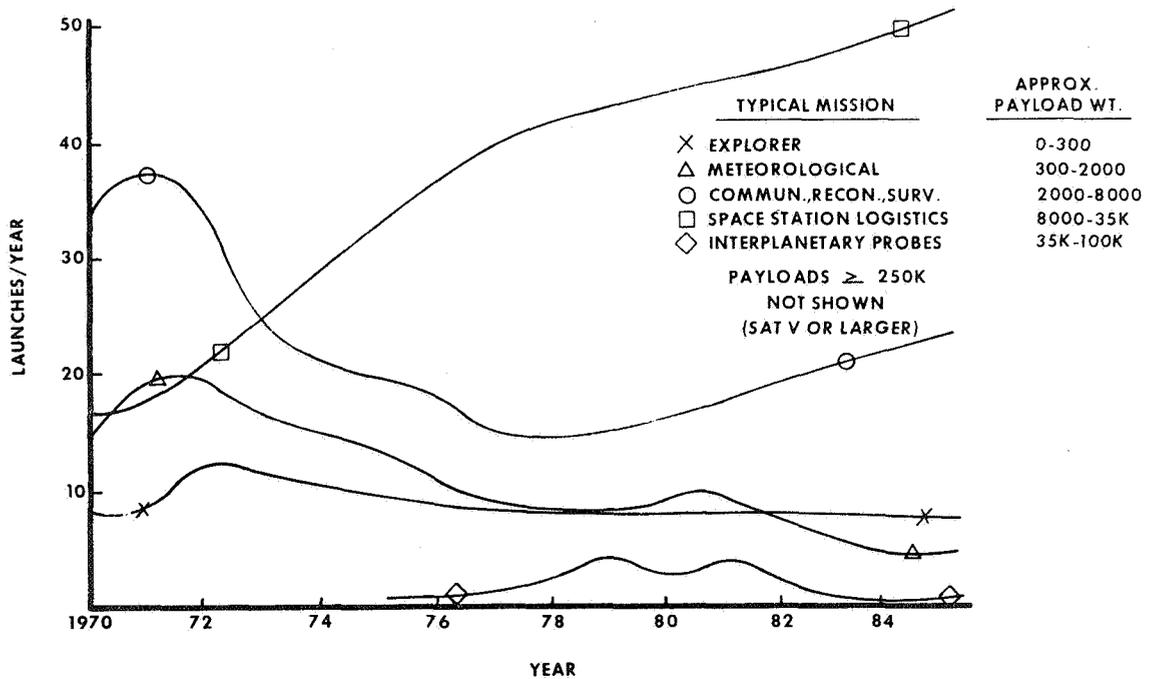


FIGURE 18. POTENTIAL MISSION REQUIREMENTS

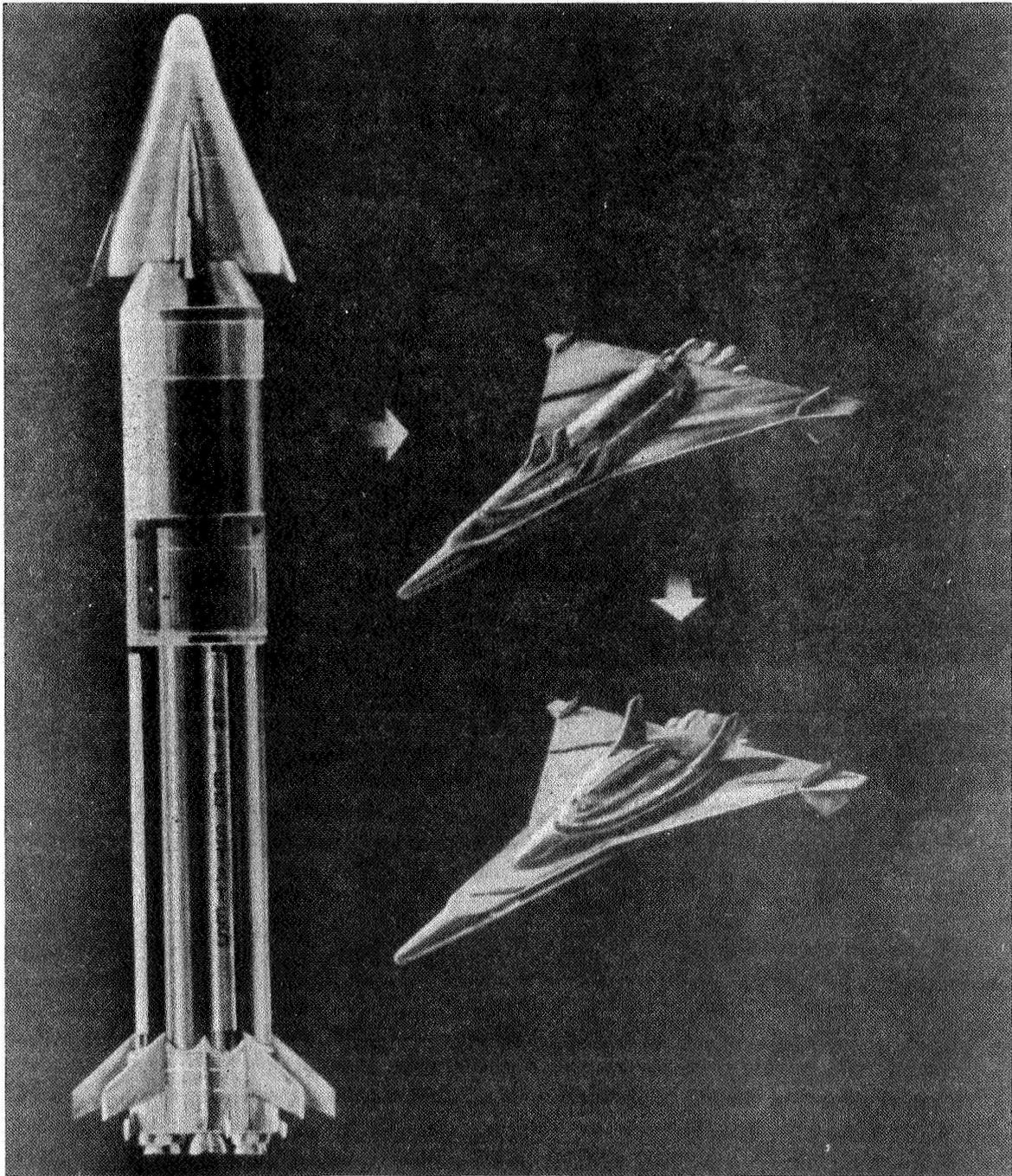


FIGURE 20. POTENTIAL INCREMENTAL DEVELOPMENT APPROACH

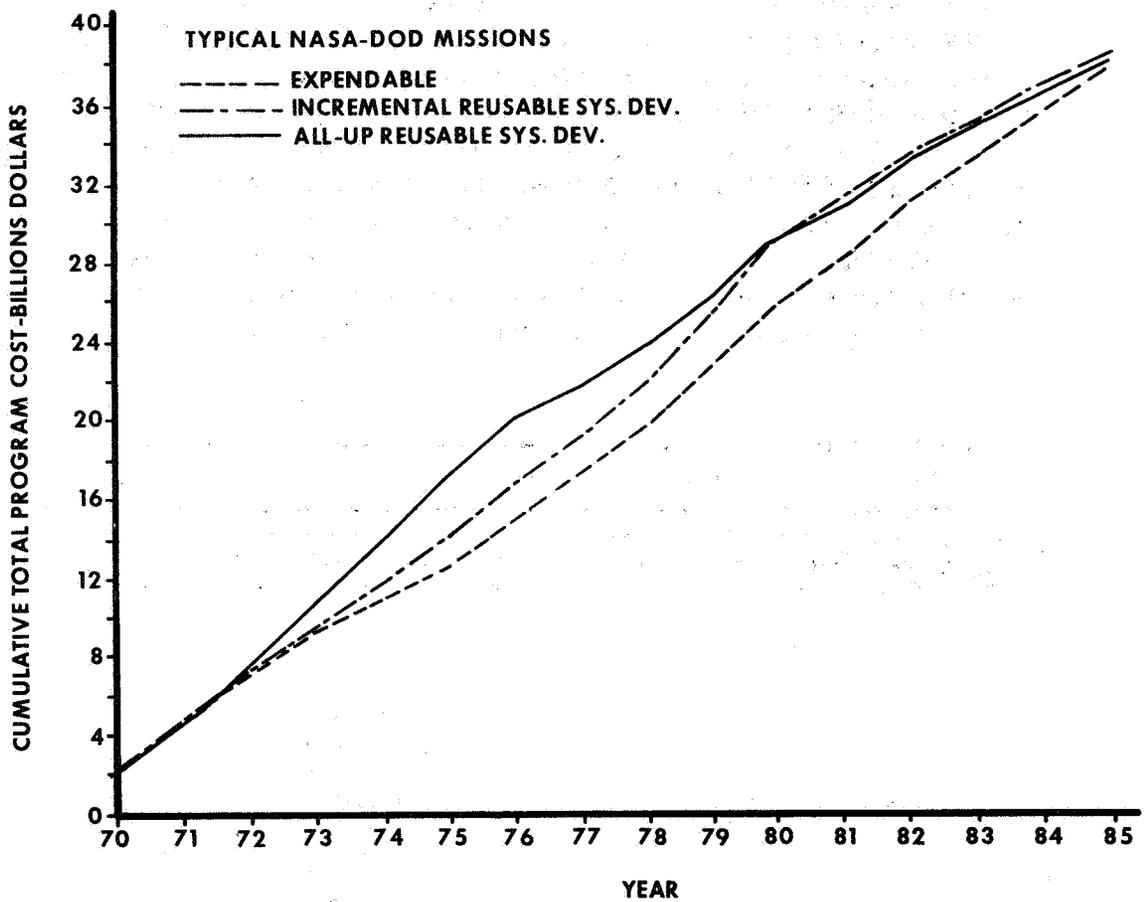


FIGURE 21. ALTERNATIVE PROGRAM COST COMPARISON

System Comparisons

It can be seen that the systems employing the expendable launch vehicles are less expensive until approximately 1985, 20 years hence. The completely reusable system becomes cost competitive with the incrementally developed system in approximately 1980, and the total program cost from there is approximately the same. Herein lies the dilemma. Cost savings are predicted but not until essentially two decades from the present. If only the first step in the incremental development program would have been used, the crossover point would have occurred at approximately 140 launches, or uses, of the

vehicle which would have occurred in 1979 and money would have been saved continuously from there to the end of the program. What is this trying to tell us? Let's look at the problem in a somewhat different fashion. Figure 22 has extracted an estimate of nonmilitary space station logistics requirements to approximately 1980 and this is felt to be a somewhat optimistic estimate — optimistic because continuous space station operations are shown commencing after the initial NASA Earth orbital Apollo Applications Program in the 1970-71 period. Also space station crew size estimates range from three to six men in the early part of the 1970's to nine to twelve men in the latter part of the decade with continuous operations taking place rather than an interrupted operation, as may be more likely the case in our actual space program efforts.

CY	72	73	74	75	76	77	78	79	1980
	EARLY / INTERIM WORKSHOP		ADVANCED WORKSHOP		LONG DURATION SPACE STATION				
CREW SIZE	3-6	6-9		9-12					
CREW ROTATION	56 DAYS	120-180 DAYS		120-180 DAYS					
AVG. LOG.* REQ'TS/YR									TOTAL LAUNCHES
3 MAN S/C	5-11	3-8		5-11					36-82
6 MAN S/C	5	1-5		3-5					22-40
9 MAN S/C	(5)	1-2		1-5					12-34

*SATURN IB OR TITAN IIM EQUIVALENT

FIGURE 22. TYPICAL NASA LOGISTIC REQUIREMENTS

Shown are the estimates of crew rotation that would exist over this period of time. The figure shows the number of launches that would be made per year and the total launches from 1972 through 1979, depending upon the spacecraft

size and crew rotation period that might ultimately be employed. It is quite evident that a major factor is the size of the device employed to carry the crew and cargo into and return from orbit — that is, the spacecraft. One can infer the same message from the previous total program cost comparison. A very significant factor relates to the size and overall efficiency of that portion of the system used to house the passengers and/or cargo. If improvement can be made in both size and cost, including implications of possible reuse, on this portion of our Earth to orbit logistics systems, it appears that maximum benefit can be incurred — certainly for the next decade or so. If, as part of obtaining this improvement, it is required that launch vehicle capabilities are needed which are greater than those of our current vehicles, increased performance can be obtained by various uprating alternatives, as previously discussed, at very modest cost. This further detracts from the ability to argue for the development of fully reusable logistics systems, especially at the low potential launch rates attainable with new, improved spacecraft as indicated in Figure 22.

FUTURE CONSIDERATIONS

Where We Stand

In summary, it appears we can say that the technical feasibility has been established for reusability. That is, much data exist on many concepts which have allowed us to agree that engineering development programs could be initiated on selected concepts which could bring into being totally reusable Earth-to-orbit logistics systems.

In order to make these systems attractive, many launches would be required to amortize the high research and development costs — especially for totally reusable systems which have been estimated to be on the order of several billions of dollars for development.

Our ability to accurately predict the market demands and operational requirements that will materialize in the next decade or so appears uncertain. However, a major determinant in the number of launches required is attributable to the characteristics (crew size, volume, weight capacity, etc.) of the personnel and cargo spacecraft which makes this portion of the system a major factor in establishing Earth-to-orbit logistics costs.

Research and development costs for any new logistics system are in competition with the funds needed to develop a market that could in turn justify or require a new logistics system. That is, dollars are currently scarce.

As discussed earlier, the evolution of our capability into the space age was based upon a ballistic missile inheritance which may have resulted in our using improper methodologies to predict the characteristics and requirements of future systems. As an example, we find that the development programs and operational requirements used for comparison of new Earth-to-orbit logistics systems seem to be based upon the types of program approaches used for ballistic missiles and expendable spacecraft. One then can ask whether or not the operating conditions of potentially new and different systems (e. g. , aircraft type approaches) are sufficiently different so that one could formulate development and operational programs in a sufficiently different way to have a major impact on cost. The tests, analyses, and documentation required for development of a ballistic expendable device result from the required high confidence level that the vehicle operate properly when committed to flight. This exists because many failures result in catastrophic failure modes. On the other end of the continuum are those vehicles which could conceivably fly like aircraft and in the event of failure could be safely returned to base. Figure 23 dramatically presents these different approaches. Shown are the number of checkout manhours, directly relatable to cost, that are typically required for expendable space launch vehicles. Also shown are the checkout manhours contributing to costs for high performance aircraft systems. (The aircraft shown here are commercial Boeing turbojet airliners.) It can be seen that, as minor failures are experienced in our ballistic expendable concepts, we increase our testing requirements rather than decrease them. This condition is directly attributable to the fact that any failures are catastrophic and in order to assure maintenance of high confidence level tests are not deleted from the program but are added. In the case of those systems which have recall capability, (i. e. , benign failure modes) as we learn and correct deficiencies, testing is reduced — thereby having a direct impact on cost.

The basic design approach also influences the types and numbers of development tests required. As an example, margins of safety in design are nothing more than ignorance factors. The more we know about the environment, material capabilities, and quality control that we experience on the production line, the more we can reduce the margins of safety applied to our designs. If we apply large margins of safety, then we are saying that the design in operational use can hardly ever, if ever, experience an environment that will place the vehicle in an operating regime outside of its capabilities. If this is the case,

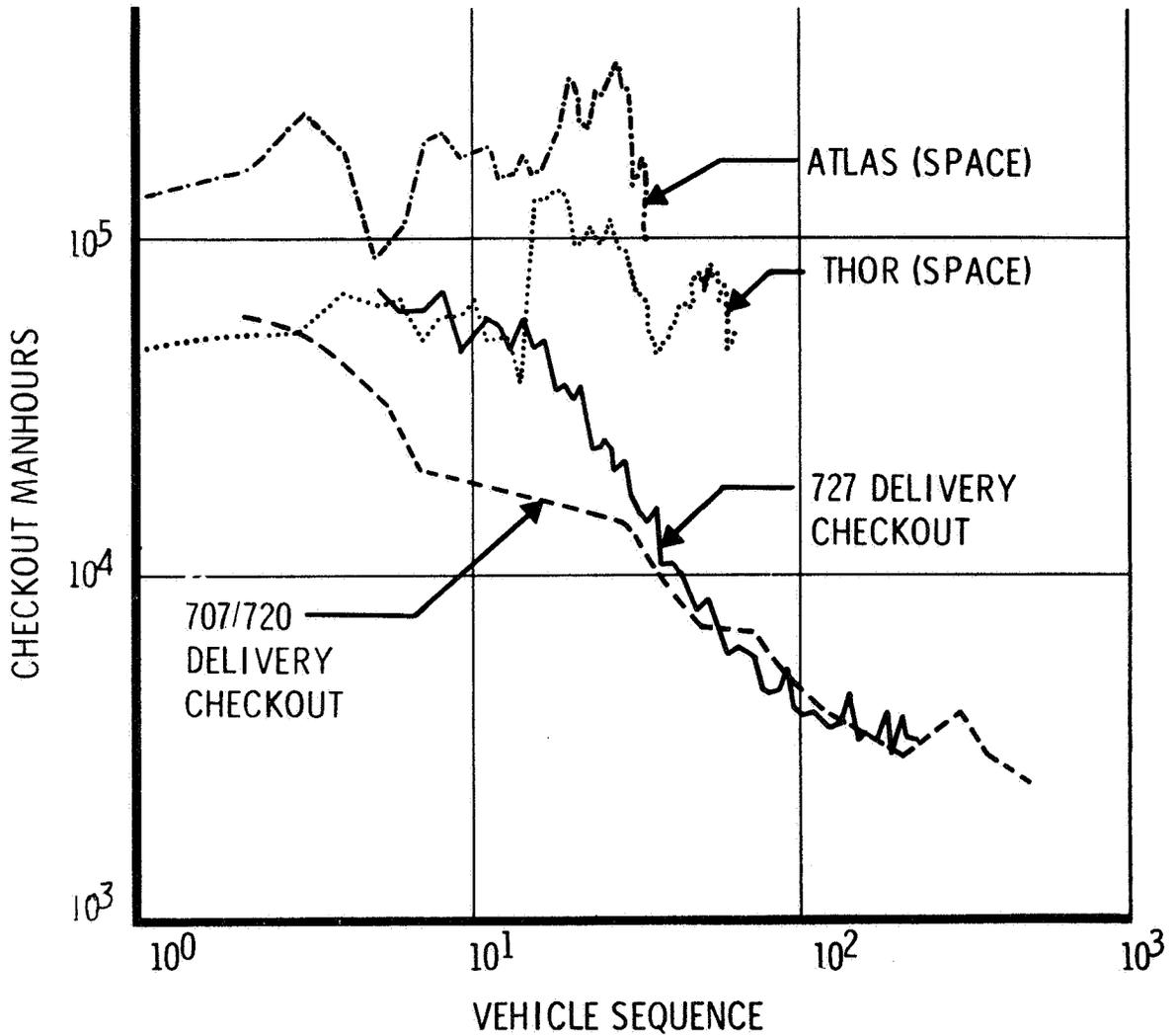


FIGURE 23. SPACE BOOSTER PRELAUNCH AND AIRCRAFT DELIVERY CHECKOUT

then also we should be able to preclude much of the engineering effort associated with analyses and test.

The two aspects having a major influence on program costs are, therefore, associated with the operational or flight modes of our vehicles and the design margins of safety we employ, as shown in Table II. Have we really explored these aspects which could lead to rather different approaches to R&D operations and program management in a manner to obtain greater insight into potentially attractive future concepts?

TABLE II. LOGISTICS SYSTEM DESIGN ALTERNATIVES

FAILURE MODE DESIGN APPROACH	CATASTROPHIC	BENIGN (VEHICLE RECALL)
CLOSE TOLERANCE	CURRENT SYSTEMS	✓ (2)
LARGE MARGINS OF SAFETY	✓ (1)	

✓ POTENTIALLY DESIRABLE APPROACH

TYPICAL EXAMPLES

- (1) SIMPLIFIED/CRUDE ("BIG DUMB BOOSTER")
- (2) AIRCRAFT TYPE REUSABLE
- POSSIBLE TO COMBINE (1) & (2); SIMPLIFIED EXPENDABLE TANKS WITH REUSABLE SPACECRAFT HAVING BOOST PROPULSION

The author thinks that much would be done along these lines that could possibly allow the ability to provide our nation a greater output for the dollar expended on our space efforts, as indicated in the above table.

What We Should Do

A major effort should be continued to develop the market — that is, funds and efforts are needed to continue the development of space program activities that will benefit our nation and ultimately lead to a logistics market.

Initiation of a major development effort on fully reusable Earth-to-orbit logistics systems is not currently warranted.

Logistics personnel and cargo spacecraft do appear to warrant cost reduction efforts including definition of operational requirements such as maneuver and landing requirements, personnel and cargo size, and degree of reuse.

While this market is being developed, and logistics systems requirements defined, it might be fruitful to examine our analytical tools and approaches used to compare future systems.

As mentioned earlier, a vehicle concept is currently under consideration which would employ a very crude and simplified, and hopefully low cost, approach to the design of expendable vehicles. Certain combinations of recoverable and expendable designs, and their associated development and operational requirements, are also under evaluation. These concepts should be evaluated in light of the above considerations.

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APPROVAL

DESIGN AND ECONOMIC ASPECTS OF REUSABLE LAUNCH VEHICLES AND CONSIDERATIONS FOR FUTURE SYSTEMS

By H. S. Becker

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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