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HL-20 Concept: Design Rationale and Approach

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Design approaches for new space transportation systems strive to lower the cost per flight at affordable life-cycle costs in the 2000 plus era. Achieving efficiency in all operational activities is a major goal for all future systems. The key design drivers are adequate margins, the use of airline/aircraft approaches to certification, and ease of maintenance via subsystem accessibility. These goals have driven the design of the Rockwell HL-20 personnel launch system (PLS) concept. The entire system, both the spacecraft and support systems, has been designed for maintainability and producibility in order to minimize life-cycle costs. In these studies, the aircraft/airline approach to aircraft certification and flightworthiness was used. The vehicle and vehicle subsystems are certified one time, and regular maintenance is scheduled to ensure that flightworthiness is maintained throughout the life of the system. The resulting system-design concept described here reflects these goals through design features that facilitate operations, manufacturing, maintenance, and inspection and overhaul.

Introduction

THE National Aeronautics and Space Administration has been examining vehicle concepts to complement the Space Shuttle system to provide the crew changeout at the Space Station Freedom and possibly support other missions. The key objectives have been to provide an alternate manned access to space facilities and a more cost-effective, more operationally efficient, more reliable, and safer system for the routine transportation of groups of people to low earth orbit. This system has been referred to as the personnel launch system (PLS). The system consists of a manned spacecraft or orbiter that would be launched by an expendable booster stage.

The Langley Research Center has been developing a lifting-body configuration called the HL-20 for potential application as a PLS orbiter. This concept has been the subject of a detailed study at Langley and Rockwell, and the results of this study are presented in this journal issue in several individual articles.[1–6] This article describes an integrated approach to the design of the system whereby the entire system (spacecraft and support systems) is designed for maintainability and producibility. This system is a cultural change from the way spacecraft have been designed in the past. The master development schedule is presented to identify the timescale for development, fabrication, testing, and deployment of the system. The flight-test program is also outlined to illustrate the stepwise and confidence-building in-flight verification of the system that complements the structural analyses and ground testing.

Concept Development Philosophy

The HL-20 PLS concept is designed for enhanced producibility and maintainability. This design approach provides features that facilitate manufacturing, maintenance, and inspection and overhaul of the flight articles. The key to the overall system design is the adoption of airline/aircraft approaches to initial certification and maintenance of flightworthiness.

A wide variety of measures have been adopted to minimize the cost of operations. Some of these were adopted from the airline/aircraft operating procedures, whereas many others have been the results of past experiences in designing and developing the Shuttle orbiter and operating the Shuttle system. The Apollo system experienced significant manufacturing problems due to very limited access to the vehicle interior for outfitting. These problems were avoided in the Shuttle orbiter by providing a large "walk-through" opening in the crew module that was later mechanically sealed. They are avoided in the HL-20 design by incorporating a mechanical break at the crew module/tunnel interface.

The design was structured for lower operating costs, and therefore, the design reflects features required by operations and maintenance to minimize costs. For example, in order to reduce maintenance requirements, hydraulic systems have been eliminated, and an all-electric system is provided to take advantage of the accelerating technology of electromechanical actuators for the aerodynamic surfaces. Serial operations are avoided by eliminating toxic propellants such as nitrogen tetroxide (N2O4) and monomethyl hydrazine (MMH), and using hydrogen peroxide and JP4 for propellants in the reaction-control system (RCS) and orbit-maneuvering system (OMS).

Built-in test systems and a health-monitoring system provide a continuous history of system health and status, which enables the scheduling of maintenance actions and elimination of expensive unscheduled maintenance actions and extensive ground testing and

Table 1 Program requirements drive system design

Program requirement	PLS features
Crew safety	Pad escape system
	Crew-module integrity (water landings)
	Multiple ingress/egress hatches
	Any runway
Simple operations	Standard missions and procedures
	Crew flight-proficiency maintenance
	Common databases
	High level of autonomy
High operational utilization	Minimum turnaround time
	Use of airline maintenance procedures
	Maintenance scheduling
Low cost per flight and low life-cycle costs	Subsystems designed for minimum maintenance
	Inspectability and accessibility to subsystems
	High-reliability subsystems
	Cost-optimized build rate
Operations and support efficiency	Designed for accessibility and maintainability
	Transportability
	Built-in test
	Autonomous operations
Economically producible	Manufacturing access
	External systems installation
	Less complex weldments
	Heatshield installation/removal
Large design margins and systems robustness assure operational efficiency at minimum risk.	

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checkout. The standardization of missions into a reduced number of preplanned missions combined with a robust launch-system design reduces the requirements for extensive flight planning.

The resulting system design reflects the achievement of the operational goals through design features in the flight-vehicle concept. The system concept reflects an integrated approach to the design of the system through the use of a product development team (PDT), in which each study discipline leader is a member of the PDT. The team was chaired by the study manager who acted as a facilitator to highlight the varying needs of each team member's task area. No single area (subsystems, vehicle design, manufacturing, or operations) dominated the development, but rather all program requirements were addressed concurrently in the design activity. Actions were assigned as necessary to team members to resolve issues between technical areas (a mini-PDT). The members would report back to the full team, and in this way, the resulting design reflected the needs of the complete team in developing the total system.

The PLS system concept outlined here is more operationally efficient than current systems because of the experiences gained from years of developing and operating manned space systems and gained from airline/aircraft large-fleet-design operations. The latter experiences have been particularly beneficial because they have been the results of millions of flight hours of operation, all with the incentive of a profit-making goal. For example, the maintenance of large fleets of commercial aircraft is now a highly structured operation, in which maximum efficiency in minimizing the time that revenue-producing aircraft are kept out of passenger- or freight-carrying operation is an extremely important consideration. Achieving efficiency in all operational activities and design approaches must be major design goals for future systems.

The outputs of this design study[1,2] include comprehensive data that highlight the potentially significant benefits of following an "airline" approach to reliability, maintainability, and operations. A major issue at this time is the lack of a man-rated launch system that is equally cost-effective to operate. Indeed, the booster systems currently available will dominate the operational costs. The booster system must be cost-effective for not only the PLS concept but also all applications. These concerns are being addressed by other NASA studies in which Rockwell is participating.

The basic program has the principal objectives of achieving high levels of operational efficiency at affordable life-cycle costs while maintaining high operational utilization and crew safety. These goals (Table 1) have driven the design of the Rockwell PLS concept. The system-design concept reflects these goals through design features that have been incorporated. These features facilitate operations, as well as manufacturing, maintenance, inspection, and overhaul (Table 2).

System Features

Design for Manufacturing and Operations

The most obvious feature that enhances operational and manufacturing efficiency is the easy accessibility for manufacturing and performing ground turnaround maintenance. The subsystems are installed outside of the pressurized crew module under removable panels wherever possible. This feature provides two major benefits: 1) It greatly enhances accessibility for maintenance during turnaround while minimizing opportunities for incurring collateral damage (Fig. 1) and 2) it provides for greater efficiency in manufacturing since more installers can work at the same time. This lesson was learned from the Apollo program (and noted earlier) in which the single very small hatch and cramped interior severely restricted access to subsystems.

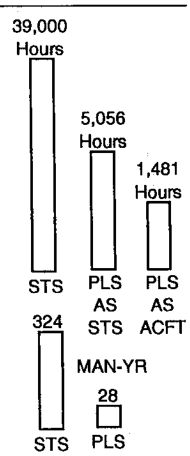
A portion of the HL-20 upper surface is made up of removable external heatshield panels. These panels are removed for access and reinstalled when maintenance is complete. The very critical seals for these panels will benefit from extensive seal research being performed for the national aerospace plane (NASP) program. The Shuttle, which provides flight experience for this design, has numerous doors and seals. Access to the aft compartment is provided by folding the fins about diagonal axes along the upper body inboard of the fins. One-*g* hinges are provided that are powered externally. Access to the crew compartment during maintenance operations is primarily through a tunnel extending to the upper hatch (the pad ingress/egress port) from a clean room in the maintenance facility as shown in Fig. 1.

The flight vehicle is made up of a number of major component parts, and each part may be manufactured offsite and mated during the final assembly process (Fig. 2). The crew module is standard 2219 aluminum made from sheets rolled in one direction (no compound surfaces with the exception of the windshield area) and welded. Internal manufacturing access is provided at the aft tunnel interface. This feature was adopted from the Shuttle orbiter crew-module manufacturing process to ease assembly and installation of internal systems. The crew module is the primary structure of the vehicle. Outboard frames carry airloads from the external surfaces to the module and provide support for subsystem installation and the landing gear.

The lower heatshield concept has a legacy extending back to the composites for advanced space transportation systems (CASTS)[4] program sponsored by Langley during 1982–83. In that program, Rockwell designed and fabricated a graphite-polyimide composite Shuttle orbiter body flap with tiles directly bonded to the material (no strain isolation panel) and tested[3,4] the design in simulated thermal and acoustic environments. The present graphite-polyimide heatshield is manufactured in a simi-

Table 2 Why HL-20 operations are more efficient

Design features	Operations benefit
Small/simple	Fewer parts count Design and maintenance
Electromechanical actuators	No hydraulics Reduced maintenance
Nontoxic propellants	Parallel launch operations
Built-in test and health-monitoring	Scheduled maintenance
Accessability	Parallel maintenance operations Reduced man-hours for turnaround
Small, certified turnaround crew	Economic utilization of skills
Design for operations	Reduced logistics support
Robust system design	Flexible operations at minimum risk
Standardized missions and procedures	Reduced flight planning Simple flight operations
Safe abort modes	Crew survivability for all credible situations



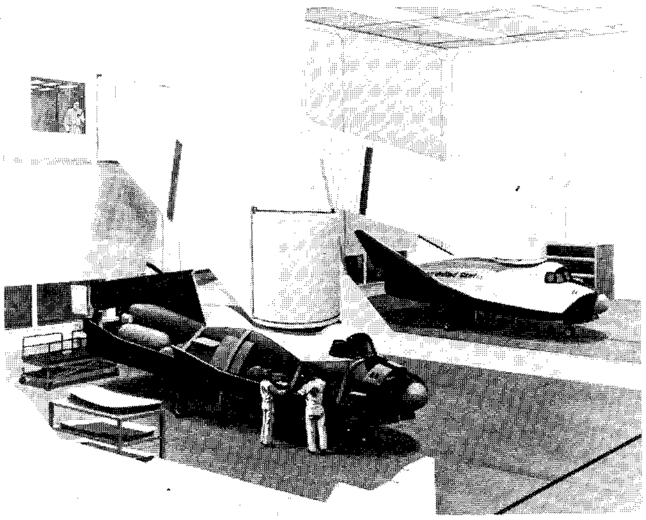


Fig. 1 Accessability during manufacturing and maintenance is provided by removable hatches.

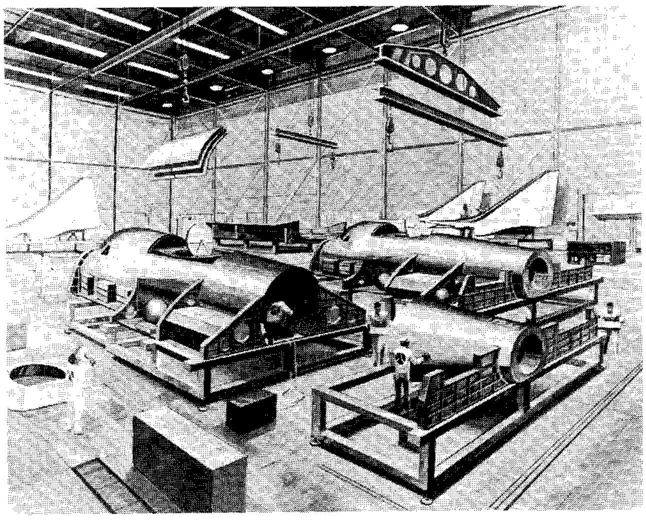


Fig. 2 Manufacturing processes have influenced system design.

lar manner. An alternate could be an all advanced carbon-carbon heatshield similar to the Shuttle orbiter nosecap and wing leading edges. The heatshield is attached to the carry-through frames by a series of thermal standoffs and is one of the last steps in the assembly process.

A groundrule that drove the vehicle sizing was the requirement that the vehicle fit into the Shuttle orbiter payload bay and carry two pilots and 8–10 station crew members. By providing a wing-folding mechanism, the HL-20 fits into the payload bay while supplying sufficient internal volume for eight passengers in addition to the flight crew. The folding-fin feature and size restriction also facilitates transport of the HL-20 inside C-5A and C-17 aircraft. The folding mechanism can be powered on orbit by integral motors and on the ground by an external drive. The fins are designed to be folded in a 1-g environment without additional support.

The development of the PLS lifting-body-vehicle concept has benefited from the combined experience of Rockwell and subcontractor study participants. With the broad objectives of operational efficiency, low life-cycle costs, and crew safety, features have been provided that include the following: accessibility for maintenance; easy access for installation of subsystems during manufacturing; simple welds on conventional material; crew ingress and egress hatches that accommodate deconditioned Space Station Freedom (SSF) personnel; transportability in aircraft and the Shuttle orbiter; and subsystems enhancing the ability for efficient maintenance operations and turnaround (Fig. 3).

Space Station Docking Provisions

Two methods exist for final docking to the Space Station node: 1) berthing by use of the SSF remote manipulator arm for the final movement to the node while the spacecraft is inactive, and 2) docking whereby the spacecraft is controlled by the crew and provides all maneuvering functions. The docking concept has been selected for the HL-20 baseline because finer attitude and movement control using the vernier RCS thrusters is possible; this concept relieves the SSF crew from additional tasks. In case there is a failure on the SSF, the ability to perform a hard docking externally could be required. Provisions for an SSF arm-grapple fixture will also be made so berthing can be performed.

In the docking scenario, the vehicle is maneuvered and controlled by a pilot located in the aft tunnel using viewports in the access hatch for targeting and visual control. The conical interface adapter must remain on-orbit with the station to accommodate the PLS. No resources are required from the station but such items as power can be utilized, if available, to recharge or extend the life of the spacecraft batteries. Separation is accomplished in reverse sequence.

Crew Accommodations

Crew members returning from the Space Station are expected to have been in space at zero-g for up to six months. In these cases, the returning crew could be deconditioned to the point that would require removal from the PLS in a near horizontal position, keeping heart and head in a level plane to avoid adverse reaction to the 1-g Earth environment. The design of the HL-20 PLS accommodates this requirement. The aft hatch, used for docking with the Station, is the primary egress hatch during ground operations for removing deconditioned SSF crew members. These crew members are assisted onto a pallet from their seated position (the seats are sharply reclined for entry and landing) and placed on gurneys for transport to a crew recovery facility until they regain their ability to stand upright in the Earth's gravity. HL-20 flight crew members are expected to be able to exit unassisted.

Operations and Support

Major portions of the design focused on a support package that covers reliability/maintainability, ground operations, flight operations, and supportability (logistics). The primary goal was an oper-

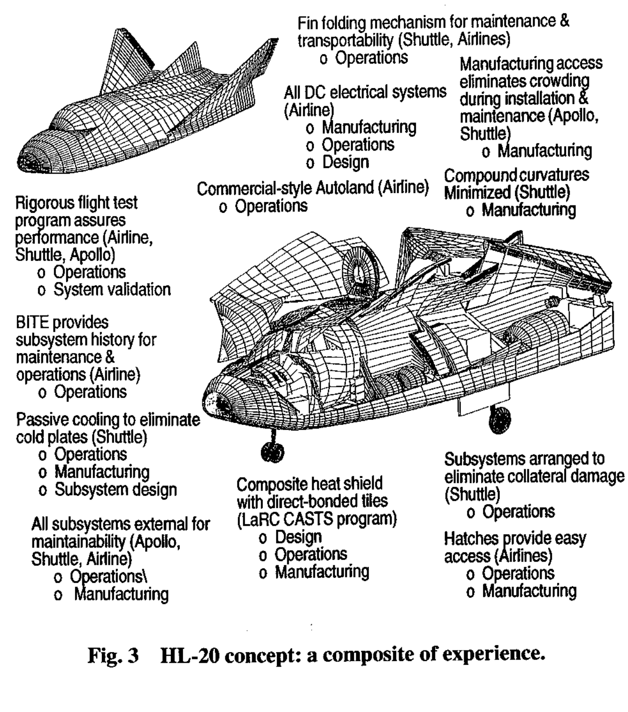


Fig. 3 HL-20 concept: a composite of experience.

ations concept that was affordable and minimized safety and cost risks. An operations database was developed which substantiates each of the support estimates for HL-20 and provides traceability back to the original source for all data.

The HL-20 uses an entirely different and simplified approach to ground operations than is currently used in the space program. Experience gained from manned space operations was combined with the airline approach to operations to provide an optimal approach in the PDT environment. The goal ensures that maintenance requirements were properly treated in the vehicle-design layout and that the fabrication process was addressed early in the design process. This approach avoided the "old" process of designing a vehicle concept and then trying to determine how to build and maintain it; all these factors add up to an expensive manufacturing and operational concept.

By using on-board and ground automated monitoring systems plus state-of-the-art software and hardware components, the HL-20 can be processed with a minimal amount of personnel and resources. The current Shuttle approach amounts to decertification after each flight. The HL-20 approach is to perform only the required maintenance indicated by the monitoring system, similar to airlines where recertification is required only of repaired systems. The use of airframe and powerplant (A&P) mechanics for HL-20 processing will reduce overall costs. This cost reduction is accomplished by maintaining a small work force of personnel trained to perform tasks on multiple HL-20 systems (i.e., maximizing the use of crosstrained personnel to perform multiple tasks). The principal aspects of the operations and support development are described in Ref. 5.

The Air Transport Association (ATA) (see Ref. 6) has developed a systematic numbering and titling approach (ATA 100) that is used to provide a common means to identify inspection and maintenance procedures. These concepts were applied to the HL-20 servicing functions. Since the HL-20 is a spacecraft, the additional required procedures that must be developed should be in accordance with the commercial ATA 100 procedures to better realize cost-saving attributes.

The ATA 100 is an existing national asset and a fundamental resource in the PLS program. ATA 100 was developed and has been continuously improved by airline operators over the past several decades. The approach is imposed on every new airliner and provides commonality that permits an A&P technician to navigate efficiently through operation and maintenance documentation for any vehicle. This commonality of documentation has permitted airlines to pool their resources through the ATA to focus efforts on the continuing development of a single technical data specification. An even more important result of commonality, combined with universal acceptance, is that it permits contractors, subcontractors, vendors, suppliers, and operators to efficiently communicate technical data. Commonality is very significant since operations cannot be efficient without the efficient communication of technical data. Since efficient operations are a prerequisite to airline profitability, airline operators not only voluntarily comply with the specification, they also contribute the efforts of their top maintenance professionals to support the continued improvement of ATA 100. As a result, ATA 100 now embodies the highest level of operations expertise in the world. In addition to airline operators, airline accessory and component suppliers are accustomed to working with ATA 100 and know how to satisfy its requirements.

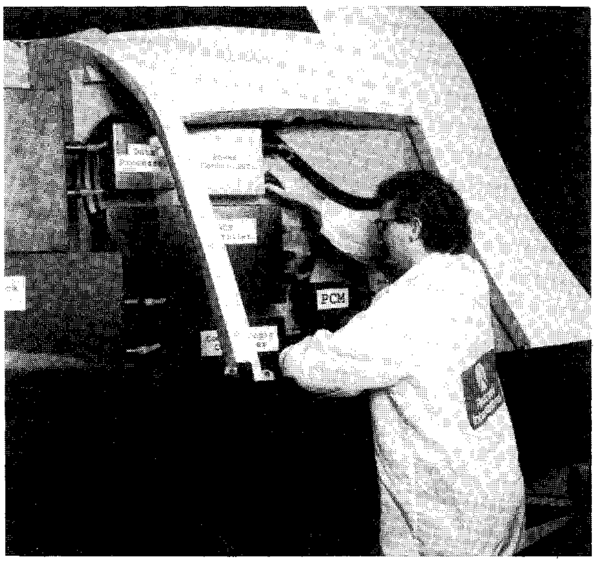


Fig. 4 Removable panels provide access to service bays.

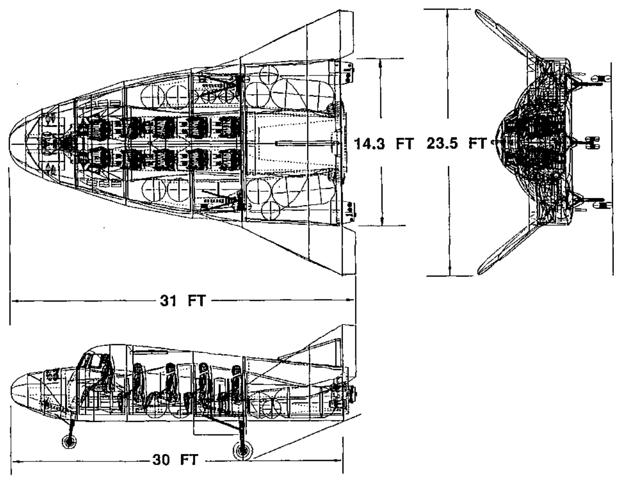


Fig. 5 HL-20 general arrangement.

Hardware Design Process

The HL-20 subsystem design supports the requirements and objectives of the manufacturing and system operations functions. Traditional spacecraft design criteria, such as weight and performance, do not have the same relative importance on the PLS program as do low life-cycle cost, ease of manufacture, and minimized ground operations requirements.

The PDT process focused on the cost-effective design of PLS subsystems. For example, easy access to avionics components was required in order to avoid interference with other servicing activities that could delay the vehicle processing during turnaround operations and incur additional costs. The avionics elements were located outside the main cabin area in an external accessible service bay (see Fig. 4). This approach is used almost universally in commercial and military aircraft where time and cost are particularly important and will also expedite the manufacturing process by allowing simultaneous operations inside and around the vehicle during assembly and checkout. Thus, the subsystem concepts selection departs from current spacecraft design practice in some cases in order to achieve the desired subsystem characteristics.

Figure 5 presents the general arrangement of the HL-20 vehicle. The locations of the major subsystem components are shown along with the significant dimensional data for the vehicle. The internal arrangement of the subsystem components and personnel integrates the requirements of subsystem function, structural load-path efficiency, and allowable center-of-mass range.

The sources of mass properties data ranged from exact data available for off-the-shelf components to approximations developed from historical parametric relationships based on physical characterizations like component area or volume, or on such performance capabilities as power output or input (Ref. 7). The placement of the subsystems within the HL-20 vehicle is done so as to achieve the required center-of-mass location of 53–56% of vehicle body length at both the full and residual consumables conditions (see Ref. 2 for full details).

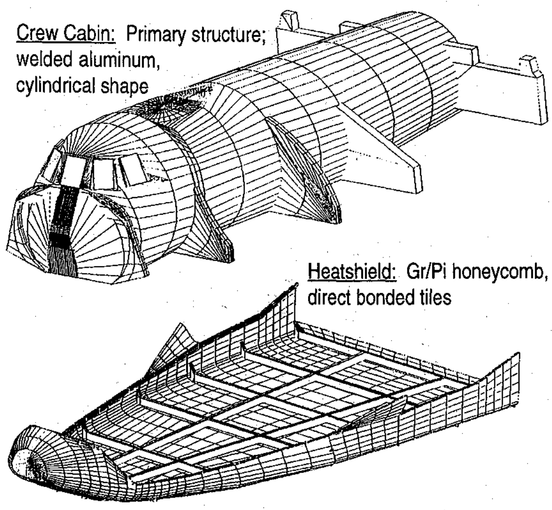


Fig. 6 Primary structures: crew module and heatshield.

The fuselage structure includes the crew cabin/primary structure, extension frames that support the lower heatshield, subsystem bays, and lower heatshield structure (Fig. 6). The crew cabin is based on a 76-in.-diameter cylinder that is an efficient pressure vessel shape.[8] The heatshield employs a direct-bond thermal protection system (TPS) tile concept that was investigated with a prototype demonstration in the CASTS program. Directly bonding the tiles to a graphite-polyimide honeycomb structure with a similar coefficient of thermal expansion yields weight savings of up to 30% compared to the present STS orbiter technique. Cost savings accrue from fewer manufacturing processes (including the elimination of the strain isolation pad) and larger tile sizes.

Pressure Vessel/Crew Cabin Design

The HL-20 structural arrangement incorporates features that support the low operations and manufacturing costs. The design process begins with the different disciplines listing the desired characteristics of the structure. Disciplines often have divergent desires, but the objective of the design function is to accomplish the best compromise possible in achieving the overall PLS program goals. Some of these disciplines are as follows: Operations—"inside-out" vehicle (easy access), nonstructural doors, easily inspectable primary structure, and rugged structure (no GSE protection); manufacturing—flat or single-degree-of-curvature structure, minimize parts count and subassemblies, minimize materials requiring hand labor, and specify conventional materials and joints; and structure—simple shapes with few cutouts and advanced, high-performance materials.

The required airline level of subsystem access in a vehicle as small as the HL-20 is challenging if standard spacecraft structural arrangements are adopted. Maintainability approaches are usually defined at a lower level of design such as a particular access door design, line replaceable unit rack, or quick disconnect. An accessible, maintainable design in the overall vehicle concept, not just at the detail level, is required to achieve believable levels of access at the vehicle level.

Airlines perform major maintenance on an aircraft by first removing all access panels to completely reveal the subsystems. The selected HL-20 structural concept allows the same level of access to facilitate airlinelike servicing during turnaround operations (Fig. 4). Because the vehicle structure is necessarily associated with nearly every other subsystem, the fundamental design approach affects the installation, operation, and maintainability of every other system. Since the level of subsystem access was so important to the outcome of the efficient operations and low-cost goals of the PLS program, the crew cabin design was given the highest priority as the primary structural element of the vehicle. Several structural concepts were considered. One structural option that was considered is a *near-moldline conformal pressure shell* that is both primary structure and the crew cabin. In this concept, the subsystems reside within the pressurized portion of the shell, and access to these systems is available only from the inside, which suggests maintenance complexity and interference as well as concealment by seats, passenger stowage provisions, and nonstructural interior panels. The broad, flat lower structure (conforming to the lower moldline) is susceptible to extreme deformation when pressurized. This effect can be reduced by using vertical tension ties installed across the vehicle interior, but these ties further restrict access to subsystems. Nonpressurized cutouts in the shell would be required for the landing gear and the propulsion system involving complicated bulkheads. These and other subsystem penetrations would result in weight penalties. Another structural approach is to employ a *non-load-carrying conformal pressure vessel inside the outer load-carrying structure*. The principal advantage of the floating structure is that it is easier to thermally isolate than the load-carrying concept just discussed. This design has the same access-through-primary structure concerns as the former. In addition, this concept reduces the amount of volume usability by having this extra structural element.

Rather than inherit the weight, volume, and access problems associated with the conformal configurations, a *cylindrical crew cabin* design was finally selected that combines the functions of primary load-carrying structure and pressure vessel into a single element. The operations issues that are created by having most of the subsystems located within the body are avoided by having the pressurized compartment sized only to meet the crew space requirements and then locating the subsystems outside in easily accessible service bays. In this way, penetrations through primary structure are largely avoided. This concept also provides the thermal advantage of a floating cabin structure (one with few heat shorts) with a separate, airload-carrying heatshield suspended from the vehicle primary structure.

A three-dimensional NASTRAN finite-element model of the selected HL-20 concept was formulated[8] with a representative stiffness for both in-plane and out-of-plane behavior. The modeling and results are discussed in Ref. 8.

Suspended Heatshield Design

The structural concept for the suspended lower heatshield is a 1/2-in.-thick graphite/polyimide honeycomb that is stiffened with upstanding honeycomb frames and longerons located to coincide with the heatshield attachments to the pressure vessel. This concept is one of many that could be employed on the HL-20 suspended heatshield structure. The following discussion addresses two of these alternates and compares the performance and manufacturing characteristics of each relative to the composite honeycomb.

A *skin-stringer heatshield* option was considered because of a concern over the bondline strength of the graphite-polyimide facesheets and the honeycomb core due to the high operational temperature of the materials and lack of experience with the graphite-polyimide honeycomb design. This concept consists of a thick graphite-polyimide lay-up for the lower tile bonding surface with a number of stiffeners to achieve the required resistance to deflection. Since the heatshield design is driven by high stiffness requirements (to keep the tiles from breaking loose), the thick composite lay-up must be substantial to produce the same resistance to bending as the more efficient reference honeycomb. Specifically, the lay-up must be about 0.39 in. thick to match the 1/2-in.-thick honeycomb. This value translates to a 300% increase in total heatshield weight with the same number and location of stiffeners as the reference. Because this large thickness raises concerns over the creation of voids in the lay-up, a reduced thickness on the order of 0.09 in. was also considered. This dimension, however, means that substantially more stiffeners would be needed (at every 18 rather than 68 in.) to meet overall stiffness requirements. Since the tooling for the stiffeners of either concept requires the design and fabrication of separate tooling elements to support the upright stiffeners, the thinner version needs about 60 times as many tooling pieces. With the increase in the number of stiffeners, this heatshield would have roughly 20 times the number of inside bays or pockets as the reference for installation of hand-bagged internal insulation packages. The added weight, increased part count, and much larger insulation installation costs of the thinner skin-stringer design lead to the contention that the reference honeycomb design is preferred from both manufacturing costs and performance considerations.

An *isogrid heatshield* option alternative resulted from the desire to install tiles on carrier plates for subsequent fastener attachment to the nodes of the isogrid. Open isogrid also suggests the possibility of subsystem access. However, the ideal isogrid size for the loads on the heatshield is too small to provide a practical level of access. This isogrid concept is assumed to be produced by machining a thick aluminum plate, although a few concepts for making the isogrid structure from composite materials have been put forth. Isogrid is competitive with or superior to other structural concepts when the loading is complex and especially when substantial torsional loads are applied. However, since the heatshield is not the primary structure in the reference configuration, only bending, small-shear, and no torsional loads are imposed. Thus, the isogrid is not loaded to its full potential and is therefore less efficient than more simply machined shapes like a waffle pattern. Because the aluminum material has a lower service-temperature limit (350°F) than the reference graphite-polyimide (500°F), the amount of TPS would increase correspondingly. Essentially, the same conclusion is reached with the isogrid option as with the skin-stringer heatshield design: The added weight, increased machining cost, and much larger insulation-installation costs of the isogrid design lead to the contention that the reference honeycomb design is preferred from both manufacturing costs and performance considerations.

Thermal Protection System

The flight environment used to size the TPS materials is based on the HL-20 vehicle reentering with a maximum *L/D* of 1.3. The reference trajectory parameters and resulting thermal environment are presented in detail in Ref. 9. The TPS sizing methodology is derived from the Space Shuttle program. Twenty-four one-dimensional thermal math models (TMM) were constructed to simulate TPS and structure temperature response due to the reentry heating. The TMMs were analyzed using the Rockwell multidimensional heat conduction computer program, XF0031.

These analyses showed that the flight-vehicle design has no major TPS technical concerns. The TPS materials available today are adequate to protect the vehicle structure from the temperatures of the proposed entry trajectory. Most of the materials specified for the HL-20 have been certified for 100 missions by the Space Shuttle program, although newer high-thermal-performance (HTP) tile materials (such as HTP-6) and graphite-polyimide honeycomb structural materials will require a test program to obtain certifiable thermal performance data.

Avionics Thermal Control Analysis

This analysis was undertaken to verify the feasibility of the avionics installation approach and to understand the thermal performance of representative avionic system components in the HL-20 installation environment. As noted previously, the avionics systems are placed in service bays outside of the crew module and protected by the heatshield structure and access panels. An operational goal of the PLS program is to eliminate the use of cold plates for avionic component cooling and to adopt a "passive" (heatsink) cooling concept for all avionics (and other heat-generating equipment to the extent possible). The historic trend of avionics components has been the general reduction in size, weight, and especially power consumption. All these items lead to significantly lower heat-rejection conditions. The HL-20 exploits these trends by using a passive concept that is similar to the one used by modern aircraft. In this application, the heatsink is provided by the crew cabin wall that is maintained at the cabin temperature of about 70°F by the environmental control and life support (ECLS) system.

Another contribution to the viability of the passive cooling approach is that the HL-20 will be operated in low-power consumption modes that are compatible with the passive concept. The heat generation of the PLS is very low during the powered-down mode that the vehicle assumes when it is docked at the Space Station. Operating the HL-20 in this fashion puts the vehicle in the simpler cooling method regime.

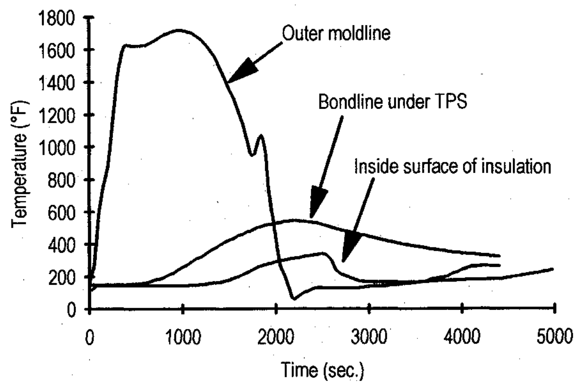


Fig. 7 Avionics bay temperature-time history.

In addition to the low-heat dissipation of modern avionics and the mission operation approach, a third factor supporting the passive concept is the higher heat-tolerance characteristics of modern avionics. Recent studies have shown that there is little steady-state temperature difference between active and passively cooled avionics configurations. Modern aircraft avionics specifications state requirements of 230°F for 30 min, which is well above the HL-20 environmental conditions determined by this analysis.

A TMM was developed for the avionics boxes. Various box packaging arrangements were considered and a combination was selected which is representative of a worst (hottest) case. This arrangement was analyzed for box temperature history and temperature distribution. The following assumptions were made in developing the model: 1) The mounting frame is at the same temperature as the vehicle structure; 2) the vehicle structure acts as a heatsink and can absorb all the thermal dissipation produced by the avionics; and 3) the avionics boxes are attached to the standard aviation equipment racks.

A time history of the avionics bay temperatures during reentry was developed and is presented in Fig. 7. The first (upper) trace gives the temperature history of the avionics bay outer moldline, peaking at about 1600°F. The center trace represents the graphite-polyimide heatshield bondline area. The third trace represents the temperature history of the inside surface of the access panel under the insulation that faces the avionics bay interior. It shows that the peak of 330°F is approached for only a few seconds before it begins to diminish.

If the avionics bay surface is assumed to be at a maximum of 350°F, the avionics components would only briefly exceed their normal permitted steady-state operating limits of 160°F. With lower initial temperatures, the avionics-box temperature achieves this limit when the mounting structure is 150°F. Conventional aircraft avionics systems regularly experience up to 200°F during adverse summer operations.

Integrated Propulsion System

The onboard HL-20 propulsion system consists of an OMS and RCS. The OMS propulsion system provides 1000 f/s of delta-V capability, with another 100 f/s for Space Station proximity operations maneuvering. The propulsion-system design emphasizes low-toxicity propellants and safe design approaches to support the ease of maintenance and rapid turnaround program objectives. The reference propulsion-system concept for the HL-20 is a hydrogen peroxide/JP4 system designed with fail-op, fail-safe reliability.

Personnel Accommodations

The nominal PLS mission profile has personnel in the vehicle for 9 to 12 h during the ascent/rendezvous period and no more than

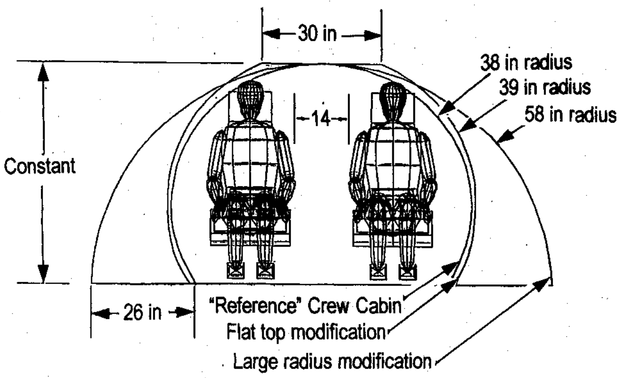


Fig. 8 Cabin wall modifications.

9 h for the return flight. These two relatively short periods permit a tolerable level of habitability for the small HL-20 vehicle.[6] Trade studies were performed to optimize the cabin volume within the manufacturing and design objectives. The total volume available to the crew in the current configuration shown in Fig. 5 is 580 ft^3. A trade study examined possible modifications to the crew cabin shape and internal layout to increase the available crew volume. In all cases, the cabin floor is flat. Alternatives were examined that 1) minimize the change to the vehicle outer moldline but increase the cabin cross-sectional area, 2) increase the seat location and aisle width, and 3) improve the cabin/tunnel transition. For each option, an assessment of the manufacturing and operations impacts was made. The pertinent factors and their relative importance when evaluating a given cabin area for habitability were determined. These criteria were used in the evaluation of the crew cabin shape options that are illustrated in Fig. 8.

Alternate Cabin Shapes

The initial crew cabin shape for the HL-20 used a constant circular radius and aisle width for most of the cabin length. There was a short conical transition between the seating areas and a constant-diameter transfer tunnel leading to the Space Station docking port. If the initial cabin inboard profile is maintained by constraining the vehicle upper-surface centerline to its original location, additional interior volume can be provided by increasing the cabin circular radius. The increase in interior volume occurs at the expense of space available for the subsystems that must reside between the cabin wall (pressure vessel) and outer moldline. Aft of the cabin midpoint, the integration of the larger cabin radius is easy to accomplish since the vehicle is increasing in width. Forward of the cabin midpoint, the vehicle outer-moldline contours will be effected.

A second approach to modifying the cabin radius involved adding a flat section to the top of the cabin and joining it to larger radii on either side. This approach added a small amount to the total cabin volume without significantly changing the cabin shape. The ring frames will include the new flat section of the cabin and cannot be produced in one piece. This would have an important impact on the manufacturing effort.

A third option added headroom and internal volume by raising the centerline vehicle contour and providing a larger cabin radius. This approach conserved the reference subsystem volume and increased the cabin area but significantly altered the original HL-20 moldline shape, which was not allowable under the study groundrules.

Seat Location and Aisle Provision

The second part of the trade study addressed the location of the passenger seats. By moving the seats outboard, a center aisle is created to allow easier passage by personnel on orbit and especially for rapid egress during an emergency. The initial structural concept for the cabin interior had the passengers seated close to the vehicle centerline to shorten the load path from the seats to the single center keel. This approach minimized the structural elements for transferring the launch and abort loads of the passengers and maximized the outboard stowage volume and headroom. However, the ability to traverse from front to rear was made more difficult. The preferred arrangement created a 14-in. center aisle by using a dual-keel structure in the center of the cabin. Headroom was reduced, especially in the aft row of passenger seats, but the habitability and rapid egress capability of the design were much improved.

Increased Transfer Tunnel Volume

This option produced the largest increase in internal volume with no change to the reference vehicle moldline. The objective of the initial design was to maximize the subsystem volume in the aft section of the vehicle since the initial monopropellant OMS/RCS concept required large tank volume. By changing to a more efficient (volumetrically) bipropellant propulsion concept, more of the aft area could be allocated to usable cabin volume. Rather than use the original cylindrical transfer tunnel, the cabin volume was increased to the full moldline depth and the transfer tunnel evenly tapered from the cabin diameter (76 in.) to the docking port diameter (44 in.). These changes increased the available cabin volume by a full 16% to the final 580 ft^3. Additional benefits of this change are the much simplified cabin shape resulting from the elimination of the short conical transition section of the initial tunnel. The concept for the preferred vehicle retains the original moldline contours and achieves higher level of habitability by incorporating a wide aisle in the cabin and the larger transfer-tunnel configuration.

Rapid Egress Capability

For on-pad emergencies that require evacuation of the HL-20 vehicle, the ability of the 10 occupants to exit the vehicle within a specified time was an issue. The limited cabin volume, close seat spacing, and small top hatch all contribute to this concern. The total exit time is driven by the bottleneck in the egress operation, which is assumed to be the 36-in.-diameter top hatch. (This assumption is made because a queue could form behind the hatch.) The opening area of the hatch is approximately 6 ft^2, and the hatch is hinged at the bottom so it swings downward to create a small platform when opened on the vertically oriented vehicle. This egress concept has been proven by a series of ingress/egress tests[10] at Langley Research Center. The Langley full-scale mockup was used in horizontal and vertical modes to test crew movement under normal and emergency conditions. All crew movement capability expectations were realized or exceeded.

Master Development Schedule

The PLS preliminary master program schedule, Fig. 9, establishes realistic and complete schedules for all the following activi-

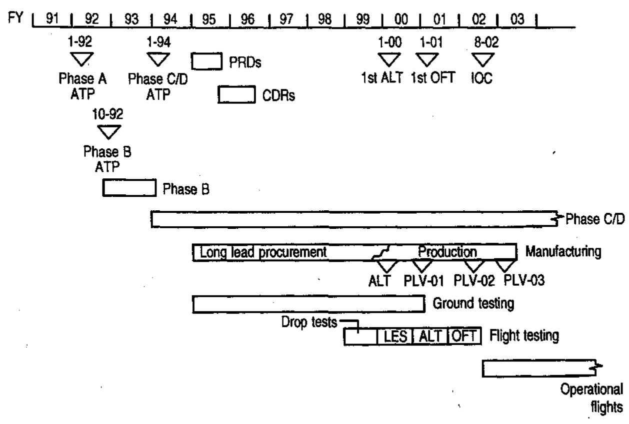


Fig. 9 Master program schedule for system development.

ties: engineering, facilities, tooling, procurement, mission operations, ground test, flight test, production, and operations support. The Master Program Schedule reflects the following groundrules: 1) All production work is based on a two-shift, five-day-week schedule, 2) all production fabrication is supported with one welding line that, in turn, supports two final assembly lines, and 3) the schedules assume that computer-aided design, computer-aided engineering, and computer-aided manufacturing processes are in place and the associated schedule benefits can be realized.

These groundrules were selected to produce low-cost fabrication and production operations. The overall schedule was developed to minimize risk and parallel major operations as much as possible. The program objectives have placed operations and producibility as high priority elements. The key word is "access"! The best examples of this are the removable heatshield, exterior subsystem access panels, and manufacturing access opening in the crew cabin. After installing the other systems, the heatshield and access panels are installed on the cabin exterior. This process allows maximum accessibility during fabrication and assembly. The manufacturing access opening in the crew cabin provides significant benefits to the PLS program, as a similar access opening in the Space Shuttle orbiter crew module. Additional benefits can be derived through the mechanical closure/opening, if disassembly of the transfer tunnel from the crew cabin is required.

Flight-Test Program

The flight test program outlined here illustrates the stepwise and confidence-building in-flight verification of the system that complements the structural analyses and ground testing. The flight-test program is comprised of three major elements: the parachute system, HL-20 flight vehicle, and overall launch system. The parachute and emergency recovery system must be fully qualified prior to the launch of any manned flights; hence, it is a relatively long lead-time item, and because of its nature, the recovery system can be isolated for most of its testing. Approach and landing flight tests will assure and verify the low-speed handling qualities of the spacecraft, as in the Shuttle orbiter program. The orbital test program will then verify the entire launch, orbit operations, and recovery of the flight systems, as well as the ground and flight operations systems.

Parachute, Water Impact, and Launch-Escape System Tests

The qualification sequence for the PLS parachute system was obtained from the developers of the Shuttle orbiter drag chutes. The PLS parachute design is based on the Apollo design, but is resized to satisfy the PLS requirements. Five simple parachute bomb drops and 25 full three-parachute cluster tests are scheduled. The bomb drops would use a dead weight equal to one-third the PLS maximum weight. Twenty-three of the three parachute tests will be drop-tested with a full-up parachute system, motors, drogues, and parachutes. These tests will use one of four PLS boiler-plate vehicles, which will have appropriate instrumentation for the drop tests. All parachute drop tests will be made from a large-type air transport like a C-5 or C-17. Other boiler-plate vehicles will be used for qualifying the launch-escape system and water impact.

Approach and Landing Tests (ALT)

The ALT program validates the following PLS system capabilities in a controlled environment: autoland performance, landing-gear and brake performance, low-speed aerodynamic control authority, crosswind landing sensitivity, c.g. envelope sensitivity, maximum-weight vehicle performance, and final-approach energy management.

The ALT flight-test vehicle is a production flight vehicle with additional instrumentation added and nonfunctioning systems removed. It is dropped from the Dryden B-52 test aircraft. The vehicle has a unique crew cabin to interface with a pylon under the B-52 wing. A single ejection seat is installed to provide abort capability since the vehicle design can only accommodate one ejection seat due to space limitations.

The ALT flight-test profiles would include a straight-in landing with no maneuvering using autoland, light braking and little or no crosswind, maneuvering with autoland, hard braking and nominal crosswinds, maneuvering with crew (i.e., hands-on) landing, hard braking and maximum crosswinds, straight-in landing with aft c.g. and crew landing, hard braking and nominal crosswinds, and maneuvering with aft c.g. and crew landing, hard braking, and nominal cross winds.

Orbital Flight Tests (OFT)

The OFT program verifies that the system is operational by validating analytical models, including the following, which are developed to describe flight performance and environment: The OFT program also establishes crew confidence in the PLS flight-worthiness design, operations, performance, and handling quality. Each OFT flight will accomplish a number of tests in addition to collecting data to verify engineering math models. For math-model verification, four flights of data are required. Six flights are scheduled in the preliminary master program schedule, including two that are contingency flights to assure that at least four flights of data are obtained. Center-of-gravity control during the flights occurs by ballasting. Also, all launches are made into the Space Station Freedom (SSF) orbit to provide an additional abort mode during the test flights (i.e., abort to SSF). The orbital flight-test article is a production vehicle with a special data and communication system installed and six passenger seats and provisions replaced by batteries and ECLS consumables. These modifications satisfy the collection of flight-test data for the 72-h mission capability.

Conclusions

A wide variety of measures have been adopted to maximize operations efficiency. Some of these were adopted from the airline/aircraft operating procedures, whereas many others have been the results of experience in designing and developing the Shuttle orbiter and operating the Shuttle system. Rockwell's Apollo experience has also been a significant benefit.

Although the HL-20 is inherently smaller than the Shuttle orbiter, the parts count has been minimized and the parts have been simplified for easier maintenance. The hydraulic system used on the Shuttle orbiter has been eliminated, and an all-electric system proposed for moving the aerodynamic surfaces to take advantage of the maturing technology of electromechanical actuators. The small size, reduced number of parts, and system simplification reduce the maintenance requirements significantly. Serial operations have been eliminated by removing toxic propellants such as $N2O4$ and MMH. Hydrogen peroxide and JP4 have been substituted as propellants for the RCS and OMS systems.

Built-in test systems provide a continuous history of system health and status. This information greatly enhances maintenance operations by enabling the scheduling of maintenance actions and minimizing unscheduled maintenance actions that are always expensive. A fully ground-tested and flight-verified system reduces the requirements for extensive flight planning, as does flying standardized personnel-transfer missions combined with a robust launch-system design.

The PLS system concept is more operationally efficient than current systems because the experiences gained from years of the airline/aircraft large-fleet design operations have been incorporated. These experiences have been beneficial because they are the results of millions of flight hours of operations and provide an incentive for profit. Efficiency in all activities and design approaches to achieve those efficiencies must be major design goals for all new systems in the future.

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