JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 30, No. 5, September–October 1993

Design for Effective Development and Prototyping of the HL-20

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A feasibility study of the HL-20 personnel launch system (PLS) concept was conducted by a team from Lockheed Advanced Development Company, Lockheed Missiles and Space Company, and Martin Marietta Astronautics Group. The team focused on creating a PLS design approach and an accelerated development plan consistent with the historical "Skunk Works" approach to rapid prototyping. Technical design, manufacturing, system testing, and operations and support elements of the predefined baseline concept were evaluated. An initial phase program, featuring a concurrent system test during design and development, leading to the orbital flight of an unmanned HL-20 prototype on a Titan III launch system, was prescribed. A second-phase development and manufacturing plan leading to system operational status was also formulated. Baseline design feature modifications were made when necessary, without compromise to performance, to satisfy the prototype development plan. Technical design details and off-the-shelf hardware candidates were also identified for several subsystems, including the launch-system interface adapter/emergency escape system. The technical feasibility of the system and applicability of the Skunk Works approach to development of the HL-20/PLS were verified.

Introduction

LOCKHEED Advanced Development Company (LADC), well known as the Skunk Works, completed under contract with NASA Langley Research Center a study of the already defined HL-20 personnel launch system (PLS). The study objective was to evaluate the potential benefits of rapid prototyping and accelerated development for the HL-20 PLS. Many times over the past 50 years, the skunk works approach has successfully brought innovative technical systems into operation in a relatively short time for significantly less cost than typical full-scale development techniques.[1] In this study, three tasks were completed: 1) technical evaluation of the HL-20 PLS with regard to concept readiness for early prototyping; 2) definition of development and operations support, and planned schedules; and 3) a cost estimate for the design, development, test, and evaluation of the system.

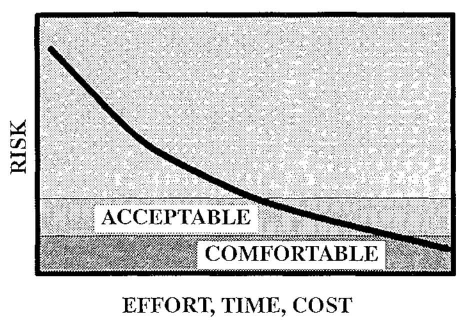

Fig. 1 Relationship between system risk level at testing milestones and program expenditures.

Received Dec. 22, 1992; revision received Feb. 4, 1993; accepted for publication Feb. 5, 1993.

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This paper focuses on the prototype design concept defined in the technical evaluation task. LADC formed a team to conduct this study and evaluate the HL-20 manned spacecraft, as well as address system-level integration issues for the PLS. Lockheed Missiles and Space Company (LMSC) undertook design of the launch-escape system (LES) and launch-vehicle interstage adapter, and Martin Marietta Astronautics Group (MMAG) evaluated its Titan III as the launch system for unmanned prototype development flights. Study results from MMAG are reported separately in this issue.[2] This paper covers design for effective development prototyping of the HL-20 and LES/adapter.

Skunk Works Approach

The Lockheed Skunk Works has demonstrated a unique ability to rapidly prototype, develop, and produce a wide range of highly advanced aircraft for the United States, including the U-2/TR-1, SR-71, and F-117A. Based on lessons learned from early programs, 14 basic operating rules for the Skunk Works were developed and written. These 14 rules have become guidelines by which all subsequent Skunk Works programs have been executed.[1] The PLS feasibility study focused on the establishment of a system development plan to capture those principles that will provide the greatest benefit to the program.

The concept of concurrent development of major systems elements and advancement to the next level of integration has proven highly successful at the Skunk Works, to accomplish goals in shorter time and for less cost. Critical to the success of this approach is early agreement by the customer and contractor on the scope of systems development concurrence. Application of this principle translates into setting goals that are focused on getting hardware off the drawing boards, through the shop and out into the field for true integrated testing as rapidly as possible. In this manner, testing will be performed at a level of risk that is acceptable, rather than comfortable, as illustrated in Fig. 1. This principle forms the basis for the Skunk Works reliance on prototyping to prove the validity of integrated flight systems early in the development phase.

The benefits gained by accelerating the analysis and test program (flying sooner) are significant. System integration and system-level issues are evaluated "up front" against real-world requirements. This leads to earlier resolution of problems and reduced program cost by putting modifications back into the design loop at an early stage. Although the risk throughout demonstration/validation may be higher, judicious risk reduction and control, through early prediction of and focus on high-risk areas, result in an overall lower-risk program and a more mature system at production go-ahead.

The end result of implementing these principles will be an overall cost savings in the development/production effort, with slightly greater up-front expenditure for the development of systems that present critical technical challenges. This up-front expenditure has traditionally been offset at the Skunk Works by prudent use of off-the-shelf technology in noncritical areas of the design. An added benefit of this approach, as illustrated in Fig. 2, are the logical "off-ramps" that occur at critical program milestones. These off-ramps provide the opportunity for program cancellation if a key enabling technology appears to be failing. Key program decisions can also be made with tangible justification.

The PLS and, in particular, the HL-20 spacecraft and adapter/LES elements are ideally suited for a Skunk Works-type program approach. Since there are relatively few new technology advancements required, the development program will focus on major system integration tasks, which will directly benefit from our integrate-and-test-sooner approach. The program also calls for a small production quantity, which is the type of program in which the Skunk Works has traditionally excelled in terms of budget and schedule performance.

Finally, current budget constraints on all advanced defense and space-exploration programs will require that each acquisition dollar be spent wisely and efficiently. The Skunk Works approach offers that option.

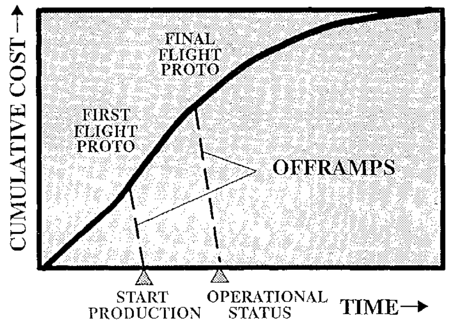

Fig. 2 Off-ramp opportunities at critical PLS program milestones.

Feasibility Evaluation

Groundrules

The following principal groundrules defined the starting point for the technical evaluation of the HL-20 PLS: 1) a NASA-defined HL-20 configuration that was for an eight-man (six passengers and two crew) configuration; 2) design reference mission 1, a 72-h Space Station crew rotation mission; 3) launch and return from the Kennedy Space Center with a 50 × 100 n.mi. orbital insertion and 1100 ft/s on-orbit Delta V budget; 4) the fleet was to be sized to support, over a 20-year operational span, four launches per year employing reusable spacecraft; 5) the configuration was to retain the outer mold line of the aerodynamic shape developed by NASA[4]; 6) the vehicle was to have full mission-abort capability during ascent; and 7) the configuration was to use expendable launch vehicles, given as the Titan III for the unmanned prototype and the proposed national launch system (NLS) core stage for the operational system. Lockheed was given the design concept for the HL-20 spacecraft and LES, developed under a previous Rockwell International effort, which was performed under a different set of objectives and groundrules.[5] LADC reviewed the baseline design to assess the applicability of rapid prototyping. Design decisions from the Rockwell study, if we assume a conventional development process, were largely compatible with the accelerated-development rapid prototyping challenge. However, in several important areas, the baseline design was found to use either technologies or fabrication processes not sufficiently mature to meet an accelerated timetable.

Vehicle Concept

The HL-20 reusable spacecraft forms the core of the PLS concept. The subsystems and consumables provisions are designed for a 72-h mission including launch, orbital maneuvering, docking with Space Station Freedom (SSF), crew transfer, reentry, and landing. Since the HL-20 spacecraft is not designed to carry large payloads, it is significantly smaller than the Shuttle Orbiter vehicle. The vehicle is vertically launched and returns via horizontal landing. By virtue of its lifting-body design, a reentry crossrange capability of up to 1000 n.mi. is achieved. It is a self-contained taxi/payload vehicle that is designed to safely return deconditioned astronauts from orbit using a piloted or automated landing approach. The HL-20 will interact with the SSF through piloted or automatic rendezvous and docking. It is designed to be independent of SSF while docked so as not to drain the orbiting station of critical power or consumable resources. Special circumstances, such as unanticipated mission extensions, may be accommodated through SSF interface design features for power-system recharge and consumables replenishment on an as-needed basis. Crew provisions are tailored to prevent adverse biophysical effects during reentry, as the crew will be returning from a nominal 3- to 6-month stay in orbit. Crew seats recline to alleviate vertical gravity effects, and the deconditioned crew can be removed horizontally through the aft HL-20 hatch.

The core HL-20 structure, as defined by the baseline design, consists of a cylindrical, pressurized crew cabin shell with ring-frame stiffeners and longerons. Lateral frames extend from the pressurized shell and provide a mounting structure for the attachment of the lower heatshield, subsystem components, outer skins, and fins. The control surfaces consist of elevons extending from the trailing edges of the fins, a top centerline-mounted all-flying rudder, and upper and lower body flaps. Subsystem components rest in bays external to the pressurized cabin. This arrangement allows easy access to critical components and significantly reduces maintenance requirements. The baseline vehicle design was driven in large part by accessibility considerations, with the overall goal of achieving "airline comparable" turnaround times. Subsystem architecture and reliability goals are also consistent with rapid vehicle turnaround.

Evaluation Methodology

To support rapid prototyping, all elements of the system including software must be sufficiently mature at startup so that an aggressive schedule can be maintained without risk of delays while technical stragglers also mature. For the HL-20, this means using subsystems flown on manned or unmanned spacecraft or manned aircraft that meet the physical and operational requirements or have been extensively tested in an appropriate environment. Manufacturing and assembly methods must meet an equivalent standard of readiness. Structural and thermal protection system choices must use materials currently available in sufficient quantities for the prototype and test articles. Processes involved in manufacture must use facilities and equipment that are available and accessible within the projected timeframe of the prototype development schedule.

LADC engineering made a thorough evaluation of the technical merits of the baseline HL-20 vehicle using the information provided by NASA Langley at the beginning of the feasibility study. Initially, specialists in aerodynamics, subsystems, structures, producibility, and manufacturing disciplines evaluated the design to identify areas where development stumbling blocks in the baseline approach might be encountered. Engineers were also tasked with determining areas where design details were insufficient to make a clear feasibility assessment. In those areas where configuration details were insufficient to establish technical feasibility, conceptual design approaches were created in order to "round out" the vehicle design concept. When design approaches incompatible with the Skunk Works development plan were found, alternative approaches were defined. No major roadblocks were encountered in developing design concepts for HL-20 subsystems. Based on these results, it was concluded that the vehicle design and operating concept are feasible. The entire technical feasibility assessment process was performed within a framework of minimizing potential development risks and identifying existing hardware that could be used on the HL-20 with little or no modification. Technical specialists from several major spacecraft subsystem design companies were invited to participate with LADC engineers in establishing realistic design approaches and cost estimates. The team examined the NASA baseline design from the perspective of establishing a rapid prototyping plan for HL-20. Three types of outcomes resulted from this assessment. The first class of results represent design by exception, whereby baseline design concepts were replaced by alternative approaches that were determined to be more compatible with an accelerated skunk works prototyping program. This group is the major focus of this paper. Four examples of design by exception were identified in the study: 1) heatshield and fin substructures were changed from monolithic graphite/polyimide to titanium; 2) the propellants/propulsion system design approach was changed from a multimode GN_2, JP-4/H_2O_2 concept to a single-mode MMH/N_2O_4 system; 3) the cooling loop and CO_2 removal system of the environmental control and life support system (ECLSS) were modified to include ammonia boiling and lithium hydroxide canisters, respectively; 4) the interstage adapter launch-escape system was changed by reducing the six solid-rocket motors to four and adding a blow-down gas hydraulic thrust-vector control system.

In the second type of outcome, baseline validations, alternative approaches were evaluated in tradeoff studies, and the baseline choice was selected. The thermal protection system and primary electrical power generation represent such systems. Electric-power trade study results are discussed in primary electrical power section. The third type of outcome, subsystem availability, resulted from evaluation of the avionics, flight controls, landing gear, and emergency recovery subsystems. In these cases, the baseline subsystem approaches were judged to be compatible with our accelerated development schedule. To verify this, specific subsystem hardware candidates that met HL-20 requirements were identified to insure that mature systems would be available during the development program. Minor system design changes were also made when necessary. In this sense, the baseline subsystem designs were validated. Results of subsystem architecture refinement and hardware candidate component surveys for the avionics core processing, navigation, actuators, and landing-gear subsystems are discussed later in this paper.

Alternative Design Approaches

Heatshield

The development of an alternative heatshield design approach was a key element of the technical feasibility assessment. LADC structural design, producability, manufacturing, stress, materials, and antenna design engineers all participated in developing design concepts that would satisfy the requirements imposed by the various functions of the heatshield. Engineers from Rohr Industries also contributed to the heatshield evaluation effort.

Preliminary evaluation of the baseline monolithic graphite/polyimide heatshield design centered on development of methods for fastening the heatshield substructure to the lateral frames. It was determined early on that the metal-to-composite interface design, with its requirements for ease of removal and maintenance, would be a significant developmental challenge. Producability concerns with the single-piece composite design were also raised. Lockheed's experience with the graphite/polyimide advanced-synthetic aperture radar radome for the SR-71 reconnaissance aircraft showed the difficulty of manufacturing large, high-temperature composite structures to the tolerances demanded of designs such as the HL-20 heatshield. The rejection rate of radome structures during that program, which were manufactured by a leading composite materials development company, exceeded 60%. Complex tooling methods are also required for the fabrication of large composite structures, particularly those with compound curvature, such as the HL-20 heatshield. No curing facility of sufficient size could be found for this 30×22 ft component. Of further concern is the indeterminate process development required to assure uniform heating and removal of volatiles from the interior of the part. The baseline thermal protection system approach for the HL-20 was to use HTP-6 (Shuttle-type tiles) directly bonded to the graphite/polyimide substructure with room-temperature vulcanizing 560. This approach supposedly precluded the requirement for strain isolation pads, as used on the Shuttle, due to the greater thermal strain compatibility of ceramics to composites. The ceramic-to-metal strain isolation pads are a significant maintenance burden on the Shuttle program. Antenna compatibility was also considered. Multiple apertures will be required on the vehicle, many of which must be located on the bottom of the spacecraft. These metallic devices will be imbedded into the heatshield substructure. For a composite structure, this will pose further integration and fastening challenges and will require cutouts, which inevitably lead to laminate debonding. For the reasons just stated, the development of a monolithic composite heatshield substructure was determined to pose too great a risk for the HL-20, particularly in the context of a Skunk Works approach to vehicle development. Since LADC has extensive experience in the use of advanced, high-temperature metals in flight weight applications, concepts for the heatshield using a titanium substructure were evaluated.

Several concepts for a titanium-based heatshield substructure and tile thermal protection system were developed. A segmented substructure design was adopted and honeycomb, built-up skin, stiffened skin, and superplastically formed panel concepts were investigated. Thermal protection options evaluated for each approach included mechanically fastened metallic multiweight insulation panels and ceramic tiles (HTP-6) that are directly bonded to the substructure with room-temperature vulcanizing 560. Previous work performed by Lockheed during development of the Shuttle orbiter heatshield

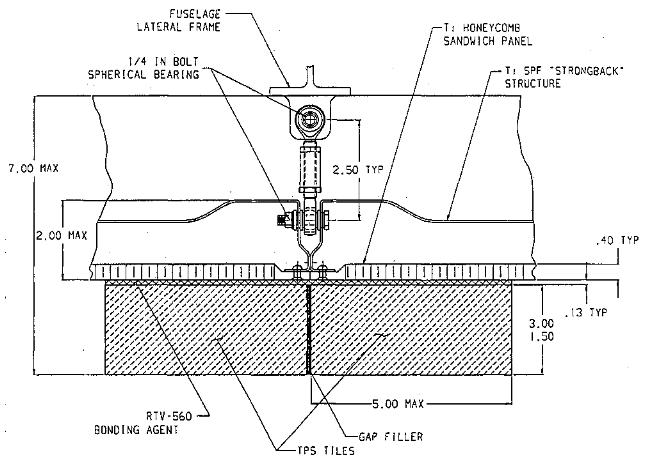

Fig. 3 Heatshield TPS bondline design and mechanical attachment concept.

showed that it is quite feasible to direct-bond ceramic tiles to titanium for cyclic, elevated temperature applications despite the inherent thermal strain incompatibility of the two materials. The difference in the thermal expansion rate is compensated for by the elasticity of the bonding material, which itself has a coefficient of thermal expansion much greater than either the HTP tile or metallic substrate. Thus, the bondline design, not the materials selection, is the critical design parameter for this concept. LADC materials and processes engineers determined that a direct HTP tile-to-titanium bond, using room-temperature vulcanizing 560 with an embedded fiberglass cloth for volatiles out-gassing, would be a suitable design approach for the HL-20. This design will enable LADC to capitalize on well-developed titanium and thermal protection system manufacturing technologies resulting in reduced risk. Antenna aperture integration will also be simplified. In addition, the metallic heatshield substructure provides more options for the development of a heatshield-to-frame attachment concept. This is a critical interface that must allow the heatshield to expand and move relative to the remaining structure, while providing a simple means for removing the heatshield during vehicle assembly, inspection, and maintenance. Figure 3 shows a notional heatshield-to-frame attachment concept and the TPS-heatshield bondline design.

Propulsion

Propulsion system evaluation focused on the selection of propellants, system configuration and modes, and the number of engines and thrusters. The baseline orbital maneuvering system (OMS) consisted of four engines burning a JP-4/H_2O_2 mixture, whereas the reaction-control system (RCS) utilized the H_2O_2 in a monopropellant mode. Vernier thrust was provided by a separate gaseous nitrogen (GN_2) system. Selection of this configuration was driven by ground processing considerations, at penalties in weight and volume.

LADC engineers revisited the propulsion systems' trade studies and compared system weight and volume requirements for the baseline-preferred approach to hydrazine monopropellant and MMH/N_2O_4 systems. The results showed that, for the given 1100 ft/s velocity change (Delta V) requirement for the HL-20, the MMH/N_2O_4 mixture resulted in a small-volume penalty (10 ft^3) but a substantial weight savings (600 lb). This is due to the difference in specific impulse between the two fuel/oxidizer mixtures. The hydrazine monopropellant option did not show any benefit in terms of volume and weight. The baseline trade studies alluded to the relatively safe handling of the JP-4/H_2O_2 combination, when compared to hypergolics, as being a desirable feature. Although the toxicity/performance tradeoff is important, the corrosiveness of H_2O_2 will also pose special handling requirements and storage limitations. In addition, much experience has been gained with hypergolic propellants through their routine use on the Shuttle orbiter and numerous satellites. Hazard controls for these fluids are well understood, and there are many off-the-shelf engines that use MMH. For these reasons, LADC recommended that MMH/N_2O_4 be used for the main HL-20 propulsion system due to the performance and weight advantages, hardware availability, and extensive experience from which to draw.

Propulsion engineering also reexamined the modes for providing OMS, RCS, and vernier thrust. The baseline configuration used JP-4/H_2O_2 for OMS and H_2O_2 as a monopropellant for the RCS system. This mode for RCS simplified the engine design at a weight penalty of 200 lb. Vernier thrust was provided by GN_2 thrusters for SSF proximity operations. The LADC system utilizes a bipropellant mode for each of the OMS, RCS, and vernier systems and retains the cold gas system to pressurize and purge the system lines. The GN_2 may also be used for vernier thrust if required for close proximity operations, although the Shuttle orbiter will employ hypergolic fuels for vernier control. Similar SSF approach procedures could be developed for both the HL-20 and Shuttle to prevent contamination of station during close-proximity operations. Adaptation of this approach to propulsion system design in the HL-20 results in a noniterated weight savings of approximately 390 lb relative to the baseline.

Thruster subsystem reliability issues, which were a factor in the baseline trades, must be evaluated further. The LADC configuration incorporates similar propellant types for all three subsystems that may enhance reliability. The enhanced reliability of proven, off-the-shelf MMH/N_2O_4 engines may well offset the increased complexity of the propellant plumbing system when compared to the baseline approach. Soliciting the assistance of propulsion system vendors, LADC engineers performed a survey of qualified, off-the-shelf rocket engine candidates with thrust levels that match HL-20 requirements. Most of the engines surveyed, with thrust levels meeting HL-20 requirements, are designed to operate with MMH/N_2O_4 propellants. A wide range of candidate engines exist. The estimated thrust levels and number of engines required for the three subsystems are as follows: OMS, two 600-lb thrust engines *or* four 300-lb thrust engines; primary RCS, 26 100-lb thrust engines; vernier, 16 5-lb thrust engines.

Thrust requirement estimates are based on those defined in the baseline report, which used scaled-down vehicle mass properties from the Shuttle Orbiter as sizing requirements. Reevaluation of vehicle inertias and maneuver parameters may result in modified requirements.

Environmental Control and Life Support System

LADC engineers focused on the crew environment and subsystem equipment survivability implications of the environmental control and life support system (ECLSS). ECLSS subsystem vendors with spacecraft design experience participated in the feasibility assessment. Preliminary evaluation of the baseline system revealed three potential development and operation problems for which alternative approaches were established. First, the baseline water boiler cooling loop might suffer from performance deficiencies due to the high boiling temperature of water at atmospheric pressures. This deficiency would manifest itself during times of peak cooling requirements, particularly during reentry when external heating rates are high and heat-generating subsystems are operating at the peak of their duty cycles. An ammonia (NH_3) boiler secondary loop was added to the LADC system design to enhance cooling performance during transient heat spikes. Second, the baseline regenerable CO_2 removal system may pose an avoidable development and integration risk. Although the CO_2 system is attractive from a maintenance standpoint, the removable combination lithium hydroxide (LiOH) canister and charcoal filter approach offer a proven, effective means of purifying cabin air. In addition, newer LiOH systems offer longer operating life between replacement. The short-duration missions and SSF interface will also reduce the requirements for the number of canisters and their replacement cycle. LADC will utilize the LiOH approach and monitor the development of the CO_2 system as it progresses. A third area of concern raised by LADC engineers during the evaluation was the passive conduction cooling approach for the subsystems, particularly the baseline avionics. The conductive heat flow to the cold wall through the avionics box fasteners was determined to be insufficient to dissipate the heat loads that LADC avionics and power system engineers have estimated. These estimates are higher than those defined in the reference. Methods for increasing the conductive heat-transfer area and enhancing cooling system effectiveness will be evaluated in future studies.

Interstage Adapter/Launch Escape System (Adapter/LES)

The primary structural, thermal, and electrical interface between the HL-20 spacecraft and launch vehicle is provided by the combined adapter/LES shown in Fig. 4. This element

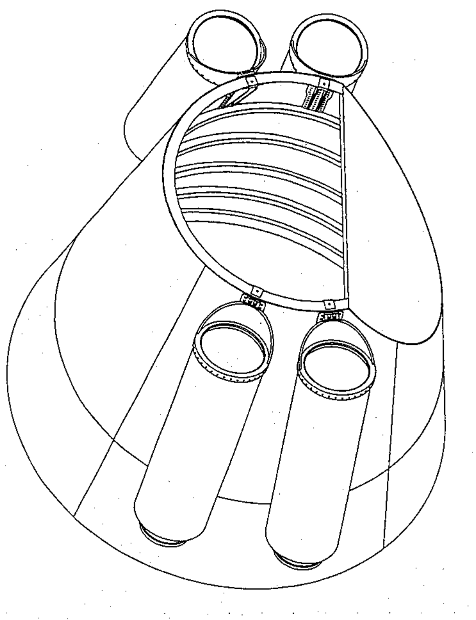

Fig. 4 Interstate adapter/launch-escape system.

of the PLS provides the critical transference of flight loads and an emergency escape capability to the HL-20 crew throughout the ascent trajectory. LMSC structural design, aero-thermal, stress, propulsion, and manufacturing engineers contributed to this conceptual design, which satisfies the system requirements. The adapter/LES is comprised of an aluminum, two-piece structure (upper and lower), with four solid-rocket motors (SRMs) mounted externally to the upper segment. The solid-rocket motors provide sufficient thrust to accelerate the combined HL-20 (at launch weight) and upper adapter structure at 8 *g* away from the launch booster. Nominally, the adapter/LES separates pyrotechnically from the HL-20 at the forward interface upon orbital insertion. In an emergency abort, the adapter/LES separates at the interface between the upper and lower segments simultaneously igniting the SRMs to accelerate the HL-20 away from the booster. After SRM burnout, the forward pyrotechnic interface separates the remaining structure from the vehicle. The structure is sized by bending loads imposed during normal ascent and has sufficient strength to compensate for dynamic overpressure loads resulting from a critical booster failure. The interstage structure is a conventional, ring-stiffened aluminum monocoque with six stub longerons to transfer loads to the HL-20. Every effort will be made to keep the design as "clean" as possible, with minimum part count, to simplify manufacturing and assembly and minimize cost. The propulsion system consists of four solid-rocket motors with HTPB-type propellant and redundant cold-gas-blowdown thrust-vector control systems. While the motors are a custom design, the technology was borrowed from the Trident ballistic missile upperstage and is mature. The proposed gas-hydraulic blow-down thrust-vector control system, ignitors, and separation ordnance will consist of off-the-shelf components.

Interstage adapter/LES development is to be addressed by a crossfunctional product development team. That is, in addition to such traditional elements as systems engineering, design engineering, and systems analysis, other disciplines, such as test engineering, manufacturing engineering, system safety, and product assurance, will be active from program inception. The intent is to drive requirements and design trades necessary for safety, producability, and low life-cycle cost "up front," rather than in subsequent stages of the product life cycle. Production planning will proceed in parallel with design. Hard tooling will be used throughout to minimize or eliminate retooling in the transition from development to production. Some retooling may be needed to add the after-skirt extension required for NLS launches. Safety demands that the first flight unit be, essentially, a production prototype. An attributes-testing philosophy, rather than the traditional component-test approach, will be incorporated to support the aggressive PLS schedule and provide the reliability necessary for an abort escape system. This comprehensive development test program will culminate in a full-up system static firing and LES "pop-up" test.

Primary Electrical Power

The HL-20 will be an all-electric spacecraft that relies solely on stored energy. Trade studies were performed in the baseline (Ref. 5) study, during which the selection of rechargeable silver-zinc batteries was made as the preferred energy-storage device for the HL-20. LADC engineers determined that the number of batteries recommended for the baseline was insufficient. The peak-power estimate, required for flight-control systems during reentry, increased from 10.7 kW for the baseline to 21 kW. This revised LADC estimate resulted from the determination of more realistic actuator power requirements. However, the battery depth of discharge is limited to 80%, leading to a design margin requirement of at least 20%. A further allowance is required for redundancy and safety. The addition of a single baseline-sized silver-zinc battery pack to compensate for the higher-power estimates would result in a 360-lb (noniterated) weight penalty. Other concerns raised in regard to the baseline battery system included their maximum shelf life of 180 days, hydrogen out-gassing, and the improbability of recharging from SSF due to procedural complexity.

LADC engineers evaluated two design alternatives to address the energy-storage issue. The first alternative evolved from a revisit of the primary power-system trade study discussed in the baseline report.[5] In particular, the feasibility of using the lithium thionyl chloride system ($LiSOCl_2$), identified as the "reference" energy-storage device in that report, was investigated. The $LiSOCl_2$ batteries were found to have excellent power-to-weight ratios and higher discharge rates than AgZn batteries. They have a proven record of performance in space and marine applications; the use of these batteries on the HL-20 was estimated to save 870 lb (noniterated) relative to the baseline silver-zinc system. Discussions between LADC engineers and battery-system vendors also resulted in the determination that the safety issues with the $LiSOCl_2$ system discerned during the baseline trade study could be mitigated through proper design and handling techniques. In addition, out-gassing by $LiSOCl_2$ batteries is not an issue, whereas out-gassing of the silver-zinc system is a significant concern. Finally, derivative $LiSOCl_2$ off-the-shelf hardware is available. On the negative side, the $LiSOCl_2$ batteries were determined to be very expensive from an operational standpoint, since they are not rechargeable and must be replaced after each use. Their cost is further increased by the fact that they are expensive to manufacture. The use of the $LiSOCl_2$ system on the HL-20 was estimated to produce a recurring cost of $0.25 million/flight/lb of weight saved relative to the baseline silver-zinc system. This penalty would be unacceptable for the HL-20 PLS program. The second alternative resulted from an available silver-zinc battery pack configuration with a higher power density than that identified for the baseline HL-20 battery system. The battery pack configuration design had the capacity to meet the revised HL-20 peak-power demands estimated by LADC power-system engineers, and this design was adopted as the preferred approach for the HL-20. The selected system consists of 14 battery packs (as compared to 8 in the baseline design), with a total installed weight of 2695 lb. This represents a weight savings of 85 lb (noniterated) relative to the baseline system, and the system has sufficient energy, power, and redundancy to meet the revised HL-20 requirements. The hydrogen out-gassing will be controlled through battery bay thermal control, overboard venting, and neutralization.

Vehicle Hardware Identification

Core Processing Module

Much of the effort performed by LADC avionics engineers consisted of developing conceptual subsystem architectures that improved on the detail provided in the baseline study.[5] Subsystem vendors were then invited to discuss HL-20 avionics subsystem development, to provide their expertise and identify potential off-the-shelf candidate modules for the vehicle. They also supplied rough-order-magnitude costs for existing and modified hardware. A candidate core-processing module for tying together the avionics subsystems was identified in the study. This processor is well suited to be the backbone of the HL-20 avionics suite and interfaces with the adapter/LES control and launch-vehicle status-monitoring systems. The processor is modularly designed for fault-tolerant space application and provides the needed redundancy for safe PLS operation.

Guidance and Control

The study focus for the guidance and control system was redundancy, accuracy, reliability, and autoland capability. Evaluation of subsystem architecture alternatives led to the definition of a triple-redundant ring-laser gyro inertial navigation system and to a triple-embedded global positioning system combination as the preferred approach. The predicted mean time between failure for the system is 4000 h, with a correspondingly low life-cycle cost. The system provides autoland capability with flight-proven software and a dual-radar altimeter approach for redundancy.

Navigation

The conceptual HL-20 navigation system links together the global positioning system, inertial navigation system, radar altimeter, and dedicated autoland functions through the core processors. The vehicle-monitoring system will support the navigation-system function. The navigation component of the guidance and control system architecture will be developed around a combined inertial navigation system/global positioning system module.

Electromechanical Actuators

The areas of focus for the HL-20 surface-control evaluation included actuator type, sizing, redundancy, and thermal protection. Since the HL-20 is intended to be an all-electric vehicle, the options evaluated included electrohydrostatic and electromechanical actuators. Sizing constraints were imposed because of the space available for actuator integration at the elevon and body-flap hingelines. Redundancy considerations for the actuators were driven by the control-surface configurations. Thermal environment concerns were driven by the requirement for the actuators to operate extremely close to high-temperature areas on the lower side of the heatshield and fins. Preliminary estimates of control-surface hinge moment and deflection-rate requirements for the baseline configuration were made. Control-system vendors were asked to provide hardware options for the HL-20 based on existing technologies and off-the-shelf designs. Top-level trades of packaging approach, horsepower capability, flight-control architecture, redundancy management, and reliability between electrohydrostatic actuators and electromechanical actuators were made. Although electrohydrostatic actuators offered convenient answers to the redundancy management issues, electromechanical actuators were selected as the preferred approach because they provide the packaging flexibility and development maturity required for the HL-20 program. They can also be configured to provide the desired levels of redundancy. Of those systems presented to LADC engineering by subsystem vendors, the linear fail-operate electromechanical actuator was determined to be the most promising option for applications requiring linear actuation, such as the rudder, landing gear and doors, and possibly the body flaps. For the elevons and possibly the body flaps, rotary-type electromechanical actuators will be used. A conceptual approach defined for elevon deflection is to transmit torque to the hingeline through a tube that is actuated at the fin root by an electromechanical actuator which is thermally isolated from the heated lower-fin surface. This approach may be required to prevent actuator temperatures from reaching the 400°F limit.

Landing Gear

In order to more completely define the HL-20 subsystems suite and develop accurate weight estimates, LADC engineers performed a top-level survey of existing landing gear to determine whether a suitable off-the-shelf candidate exists for the HL-20. Since the development of a new landing-gear system is typically an expensive, multiyear process, the utilization of an existing system will greatly reduce development schedule and cost. The current HL-20 aerodynamic configuration requires the capability for a "crabbed" landing approach. This will result in high side loads on the main landing gear during touchdown. Although the baseline report stated that a "fighter-type" landing-gear system would be appropriate, no specific system was mentioned. Preliminary estimates of vehicle landing weight, touchdown speed, sink speed, and geometry constraints were made during the baseline[5] and feasibility studies. The baseline approach of forward retraction of both the main and nose landing gear is compatible with LADC's configuration layout and heatshield design. Several fighter and business jet gear systems designed to HL-20 equivalent loads and speeds were identified. Of those candidates investigated, a modified F-5E gear system best matched the design strength and geometry requirements of HL-20. The original design configuration of the F-5E has the main gear mounted to a trunnion in the wing and retracting sideways and inward toward the fuselage. The nose gear retracts forward. The modified system, which was previously developed by LADC and flown on a classified aircraft, uses the F-5E main-gear components with the piston and rolling stock rotated 90 deg from their original design orientation. This modification was made to allow forward retraction of the main gear. This feature will benefit the HL-20 in two ways. First, the forward retraction capability is compatible with the HL-20 design. Second, the original main-gear structure, which is designed for high-speed braking, is now oriented to take side loads. This capability will be more significant on the HL-20 as compared to the F-5E. Fore and aft gear strength in this configuration can be increased by a side link in the original configuration, which becomes a drag link in the modified configuration. This is a simpler modification than redesigning and rebuilding the main strut to take side loads. Several F-5E are currently in service that indicate a high probability for procurement of off-the-shelf landing-gear hardware. Future studies shall focus on refinement of this approach and identifying sources for procuring landing-gear ship-sets.

HL–20:
- MANNED LIFTING BODY REENTRY
- HANDS–OFF FLIGHT CONTROL / AUTOLAND
- SEPARATE HEATSHIELD
- ELECTRIC ACTUATION
- FULL ENVELOPE ESCAPE / ABORT

A/LES:
- SRM MAN–RATING
- INITIATION / CONTROL THROUGH HL–20

TITAN III:
- VEHICLE STATUS MONITORING THROUGH HL–20
- AERODYNAMIC / STRUCTURAL LOAD COMPATIBILITY

Fig. 5 PLS technical innovation.

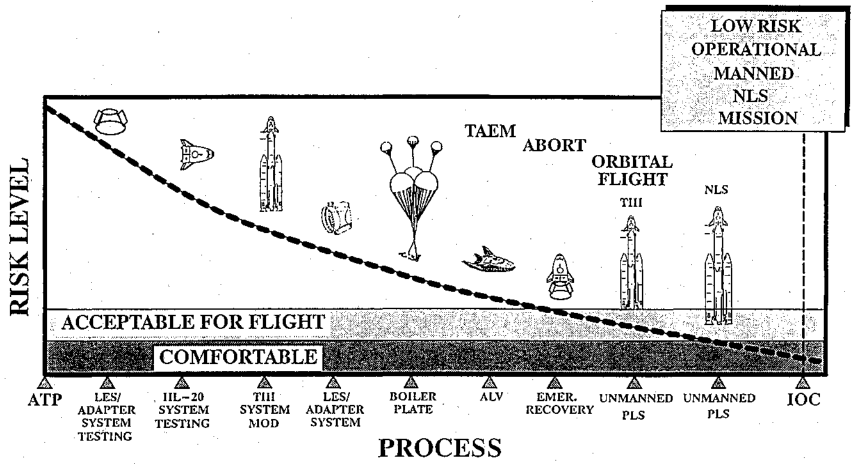

Fig. 6 PLS risk reduction and progression to operational status.

Development, Testing, and Operations Approach

Software

Development of software for the PLS system will be a major schedule, cost and performance driver. There are multiple links in the data-transfer chain between all segments of the PLS architecture. Software will be required for each of these interfaces. The scope of the feasibility study did not allow for in-depth software requirements definition. Our software development philosophy was tailored and determined to be consistent with the requirements historically imposed for man-rated spacecraft systems. LADC has extensive experience in the development of software for advanced flight systems covering a wide range of operational uses. These include navigation systems for low-altitude, high-speed attack aircraft and high-altitude reconnaissance systems utilizing real-time, direct, and satellite-linked data transfer. The approach to software development for the PLS will encompass the following: 1) synthesis of the intangible man-rated attributes required of the system, including specification of a comprehensive suite of tangible critical tests; 2) implementation of a build-in quality rather than check-for-quality development philosophy; 3) an approach to software migration from a management and technical perspective with mitigation planned from ALV to unmanned prototype to manned vehicles, up front incorporating reusability for each portion migrated; 4) a tailoring of the existing Skunk Works software development process to unique HL-20 requirements with reuse/migration; 5) an extended analysis and integration portion of the process to accommodate software complicity with NASA standards; and 6) risk reduction with a follow-on study prior to demonstration/validation.

To control the schedule and cost of software development, the software migration approach will be used to insure that software developed for early stages will be directly applicable to later stages of the program. As the level of system integration and testing progresses, so too will the level of software integration proceed to support the test and evaluation effort.

Technical Innovation

The establishment of an aggressive, thorough PLS development plan that will capture the benefits of the Skunk Works approach to aerospace system prototyping and testing was a primary achievement of the feasibility study. LADC has created a framework for PLS development that encompasses the identification of key development and integration tasks, a risk-assessment approach[6] for those tasks, and establishment of off-the-shelf design solutions in noncritical areas. A testing schedule was established that focuses on proving that the design and integration solutions will work. These solutions will be developed during the phase 1 design process. LADC perceives that the development of PLS will be relatively low risk when compared to previous programs, and that the Skunk Works approach to the HL-20 PLS program will result in significant payoffs. Within the scope of the feasibility study, LADC has identified the PLS technology and integration requirements that will pose the greatest challenge. Figure 5 summarizes the major technical issues for design and operation of the HL-20 spacecraft, adapter/LES, and Titan III launch system as separate elements and an integrated system.

Demonstration and Validation

The LADC PLS development plan has two phases. The goal of phase 1 of the program (demonstration/validation) will be to demonstrate the critical technologies in a highly integrated design/test program. The program will culminate in the production, flight, and turnaround of an unmanned prototype HL-20 on a Titan III launch vehicle. The Skunk Works plan is to defer testing of the manned configuration until phase 2 (engineering and manufacturing development) after the results of the initial, unmanned orbital flight test have been evaluated.

The prototype will be developed around off-the-shelf hardware to the greatest extent possible, as a cost- and risk-reduction measure. The feasibility assessment provided LADC engineers with confidence that many subsystems which will meet HL-20 and adapter/LES design requirements are currently available. The Titan III itself is a critical off-the-shelf element of the phase 1 configuration. The orbital prototype spacecraft will fly a single, unmanned flight to low earth orbit and return at the end of the program. The spacecraft, built strictly as a flight-test vehicle, will not be refurbished to operational specifications.

Engineering Manufacturing Development

Early phase 2 activities will focus on testing the prototype vehicle in the unmanned mode and then in a refurbished, manned configuration. The manned flights will use a crew of two and be launched on a man-rated system (NLS). Envelope expansion will be performed using the manned prototype throughout phase 2 until the first flight of a fully configured, operational vehicle. Since the operational HL-20 must be designed for unpiloted flight, the PLS lends itself well to this stepwise development approach. The prototype configuration will be designed to the best possible approximation of the operational configuration. The degree of similarity between the two will be a function of the maturity of the operational vehicle design at prototype design freeze. The prototype must reflect operational vehicle design features that are critical to the performance and safety-of-flight requirements established at the outset of the program. Enabling technologies and system integration approaches must be validated during the prototype flight-test program. Otherwise, the prototype system will be useless to the objectives of program risk reduction. Figure 6 shows, in a broad sense, how the incremental stages of PLS element testing progress toward a level of risk that is acceptable at the time that the first orbital PLS flight occurs. The first orbital flight and successive flights and testing early in engineering manufacturing development will serve to reduce the risk of the PLS to a level that is comfortable enough to commence manned flight testing.

Concluding Remarks

In this study, a design approach to the HL-20 PLS has been identified that satisfies the requirements for rapid prototyping as performed at the Lockheed Skunk Works. Our reliance on testing of system-integration concepts early in the HL-20 PLS development process leads to early resolution of technical problems. This design philosophy, which encompasses judicious risk reduction and control, results in substantial program performance payoffs. The combined design and development plan created here provides an opportunity for significant cost and schedule savings relative to traditional manned space system-synthesis programs. This tailored approach is based on proven methods that have been applied successfully to several aircraft-development efforts. The PLS program provides an excellent opportunity to apply the Skunk Works approach to a major space-system development effort.

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