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HUMAN FACTORS TECHNOLOGY REQUIREMENTS IN SPACE SHUTTLE DEVELOPMENT

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BioTechnology, Inc.

Falls Church, Virginia
Los Altos, California

for

Headquarters
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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FOREWORD AND ACKNOWLEDGMENTS

This report was prepared for Headquarters, National Aeronautics and Space Administration, with Walton L. Jones, M.D., Deputy Director, NASA Office of Life Sciences, and Joseph N. Pecoraro, Director, Bioenvironmental Systems Division, serving jointly as Project Monitor. The purpose of the study was to identify human factors problems related to space shuttle operations, particularly those requiring advances in human factors technology in order to achieve effective solutions. In collecting information for this project, a number of individuals and facilities were visited. In all instances, project staff members were accorded the full measure of hospitality and given all possible assistance. A note of thanks is due to individuals at the following facilities for their helpfulness and cooperation:

Headquarters, National Aeronautics and Space Administration
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NASA Flight Research Center
Edwards, California

NASA Langley Research Center
Hampton, Virginia

North American Rockwell Corporation
Downey, California

McDonnell Douglas Astronautics Company
St. Louis, Missouri

Lockheed Missiles and Space Company
Sunnyvale, California

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CHAPTER I

INTRODUCTION

The next major event in the United States national space program will be the space shuttle system, which should rank in importance with the Mercury, Gemini, and Apollo spacecraft as a vehicle for furthering the exploration of space. The space shuttle will provide complete logistics support for an orbiting space station and will be used to ferry personnel, consumables, scientific equipment, construction materials, and fuel to the satellite. The space shuttle will possess a number of very distinct advantages over earlier spacecraft. Economy will be an important feature since the shuttle will be essentially completely reusable. Contributing to economy will be greatly reduced ground support and checkout equipment. Another advantage rests with the rapid recycle time for the shuttle. Extensive prelaunch preparations will not be required. Therefore, a single shuttle will be able to make a number of orbital trips during a given year.

The capability for launch into orbital flight, rendezvous and docking with other spacecraft, reentry into the earth's atmosphere, and landing as a conventional aircraft makes the space shuttle a unique vehicle. It will be distinctly hybrid in character, possessing many of the characteristics of spacecraft while retaining much of the flavor of an aircraft. As such, this vehicle places man in a new operating environment and will present new demands on his capabilities.

If a new aerospace system such as the space shuttle is to perform as designed, man must operate successfully as an element within the system. It is imperative, therefore, that one understand the man-machine interfaces in the system, the problems posed by each, and the technology (including physiological, psychological, and behavioral) which must be developed to provide for the proper support of man and the fullest utilization of his operational capabilities. To achieve this understanding, a careful analysis must be made of the system and the human factors problems which it poses. It then becomes possible to address these problems during the design and development process and to achieve optimum solutions. If human factors problems are recognized and solved as the system design emerges, it will not be necessary to resort later to extensive personnel training or to expensive retrofits in order to overcome deficiencies in the man-machine interface.

This report summarizes human factors problem areas related to the operation of the space shuttle system. The problems discussed are those which it is felt will require advances in human factors technology in order to achieve effective solutions. The identification of problems resulted from (1) an analysis of proposed space shuttle design and planned missions, dealing in large measure with contractor Phase A reports, (2) a review of the adequacy of existing human factors technology, and (3) statements by industry and Government personnel (obtained through personal interviews and documents) indicating that certain features of planned space shuttle activities involve potentially serious human factors problems.

In completing the requirements of this project, the specific task assignments were:

1. To survey planning information relating to the development of a space shuttle system and prepare a comprehensive description, giving particular attention to personnel responsibilities and activities.

2. To prepare a summary statement concerning the proposed role of human operators in the system, dealing particularly with the man-machine interface.

3. To define potential human factors problem areas related to supporting the human operator and to insuring optimum performance on his part,

emphasizing those for which current human factors technology is believed to be inadequate.

4. To prepare recommendations for appropriate actions on the part of NASA to resolve man-machine interface problems during the design and development stage of the space shuttle system.

CHAPTER II

SYSTEM REQUIREMENTS AND PRELIMINARY DESIGN CONCEPTS

This section contains a brief review of the space shuttle program and outlines the system concepts used as a basis for the identification of human factors requirements. Complete and detailed specification of system performance requirements and alternative vehicle designs is beyond the scope of this presentation. Therefore, the intent of this section is to establish a frame of reference for the consideration of human support requirements by describing only those design features which will have a major influence on crew performance. Background material on the overall space transportation system goals and current development status of the space shuttle program is presented first, followed by an overview of desired system capabilities and concepts of system design and operational employment.

Space Shuttle Program Objectives

Government and industry efforts are now being directed toward increasing the economy and efficiency of future space exploration. It is both desirable and necessary to develop more cost-effective approaches; the present economic climate simply will not support the continued use of expendable booster and spacecraft hardware. Consequently, economy in space operations is now being sought through the development of a versatile, recoverable, and reusable space shuttle vehicle for transporting a varying mix of cargo and personnel to and from a low earth orbit. Operating either in support of a space station in permanent earth orbit or on special missions, this system is expected to provide critically needed additional capabilities as well as significant reductions in recurring operational costs.

The objectives and intent of the space shuttle program were concisely stated by the keynote speaker at the last annual AIAA Space Transportation meeting as follows (Mathews, 1970):

> We have defined a problem and identified a goal greatly reducing the costs of space flight operations and thereby greatly increasing the value of our return per dollar spent. . . In the sixties, this country launched nearly three hundred payloads into earth orbit or out to deeper space with a cumulative payload weight to earth orbit of nearly three and one half million pounds. Every one of the launch vehicles used was expended after its initial use and the payloads with their remote operation had no significant capability for maintenance, repair, updating or servicing except in a limited sense on the manned spacecraft. These limitations are the obvious ones to attack. . . When looked at in this light, no other program approach more solidly enhances the per dollar value and output of space flight than the development and operation of the space shuttle.

The emphasis on economy and efficiency is evident in the stated objectives of the space shuttle program, which may be summarized as follows:

- to reduce space transportation operating costs by an order of magnitude below those of current systems
- to provide a highly versatile payload capability to support a variety of space missions
- to approach a commercial airline type environment and operating concept
- to provide a versatile system which is capable of multimission and multiagency usage
- to extend the technology of manned space transportation systems.

Program Status

Requirements for a reusable space shuttle vehicle (SSV) have been under study by aerospace planners for more than a decade. The 1969 NASA Space Shuttle Task Group Report established the long range plans for the development and application of a space transportation system and identified the space shuttle as a critical element in achieving projected operational goals. The SSV is envisioned as the primary means of transportation from the earth's surface to earth orbit for the delivery and return of passengers, cargo, and scientific and special applications satellites. In addition, probes for deeper space exploration will be delivered to earth orbit by the SSV. Long term plans place the shuttle in the context of a more extensive space transportation system which includes space tug operations and a nuclear-powered shuttle for payload transfer to the moon and beyond.

Phase A vehicle configuration studies and technology requirements analyses were completed for NASA in December 1969 by four major contractors. Program planning is currently directed toward achieving an initial operational capability in the second half of 1979. In May 1970, Phase B study contracts were awarded to North American Rockwell and McDonnell Douglas for Program Definition studies outlined in the NASA Statement of Work issued in February 1970. The baseline system requirements and desired system characteristics outlined in that document provide the point of departure for the analysis of human factors issues and technology requirements.

Mission Capabilities

The basic mission of the space shuttle system is the transportation of passengers and/or cargo to and from low earth orbit. Some of the more important mission assignments for the SSV are expected to be:

1. Logistics support for a space station, including transfer of personnel, expendable supplies, and experimental equipment to orbit and from orbit.

2. Launching a variety of scientific and special application satellites, as well as retrieving and/or servicing damaged or repairable satellites in low earth orbit.

3. Transporting other vehicles and propulsive stages to support the launching of spacecraft into higher energy missions, these vehicles might include high orbit satellites and unmanned planetary probes.

4. Conducting orbital observations of up to 30 days duration.

The design reference mission defined for Phase B Program Definition studies (NASA, 1970) is a logistics resupply of a space station or a space base. The nominal operational characteristics and baseline mission capabilities which have human factors implications are summarized below.

1. A mission duration of at least 7 days and up to 30 days with the weight of additional expendables charged to payload.

2. A launch capability from a standby status within 2 hr, nominally at the next acceptable in-plane opportunity.

3. A cross range capability of approximately 200 nm (low cross range configuration) or up to 1500 nm (high cross range configuration).

4. An automatic landing capability which will allow recovery operations under FAA Category II visibility conditions.

5. The capability to land horizontally on runways no longer than 10,000 ft.

6. Landing visibility comparable to that of high-performance aircraft.

7. A one-time, go-around capability for both booster and orbiter vehicles.

Vehicle Design Goals

The SSV must efficiently transfer large, low density payloads to orbit and back by operating as a high-performance propulsive stage, a spacecraft, a reentry vehicle, and an airplane. If the design is deficient for any of these roles, penalties will be suffered in terms of reduction of payload capacity, and restriction of mission capabilities. In addition, the design requirements adopted for the shuttle will enable the vehicle to operate without major support from the ground and provide an acceptable environment for routine passenger-carrying missions. With these missions in mind, acceleration limits have been set at 3 G's when passengers are aboard, and shirtsleeve conditions will prevail for both passenger and crew compartments.

Some of the more significant vehicle characteristics which may be expected to impact the human factor engineering effort are outlined below:

1. The specification of a two-man flight crew, with the vehicle flyable by a single crewman under emergency conditions.

2. A shirtsleeve environment for crew and passengers, but with provisions for adequate controlability in space-suited operations during the flight test program.

3. Habitability provisions on a "modular accommodations" basis, allowing a personnel complement mix from 2 + 2 to 2 + 12 while still maintaining dimensional stability of the basic cabin and compartments.

4. Provisions for redundant full mission capability; minimum-requirement, minimum-performance backup system concepts are not acceptable.

5. Booster stages designed for manned operations as well as for unmanned operating mode.

6. Design for maximum control onboard the vehicle, with minimum ground operations support.

7. Provisions for vertical and horizontal ground emergency egress, with the appropriate vehicle/ground systems interfaces.

8. Docking, cargo manipulation, and orbital body retrieval by remote manipulation and teleoperator techniques.

9. Provisions for automatic or pilot-controlled landings, with Category II capability.

10. Use of all-electronic displays and controls whereven practicable.

A number of different vehicle combinations and configurations have been considered in earlier SSV design studies, including triamese (three elements), stage-and-a-half (droppable propellant tanks), and a variety of two-stage, fully recoverable systems. Configuration trends for the booster and orbiter vehicles have ranged from fixed, straight wing concepts through clipped delta wing, lifting body, and variable geometry configurations. Until recently, a fully reusable two-stage configuration employing straight fixed wings on both the booster and orbiter stages appeared to be favored for its reentry and approach and landing characteristics. However, this configuration limits lateral ranging capabilities to approximately 230 nm, and the current trend is toward adoption of a delta-wing configuration to achieve cross range capabilities on the order of 1100 nm and increased payload.

Operational Sequence

Nominal space shuttle operations are expected to permit up to 75 launchings per year with total turn-around times fron landing to launch readiness held to less than two weeks. The basic operational employment concept shown in Figure 1 encompasses prelaunch activities (readiness preparations and checkout, transfer to launch pad, erection and mating of vehicles, etc.)

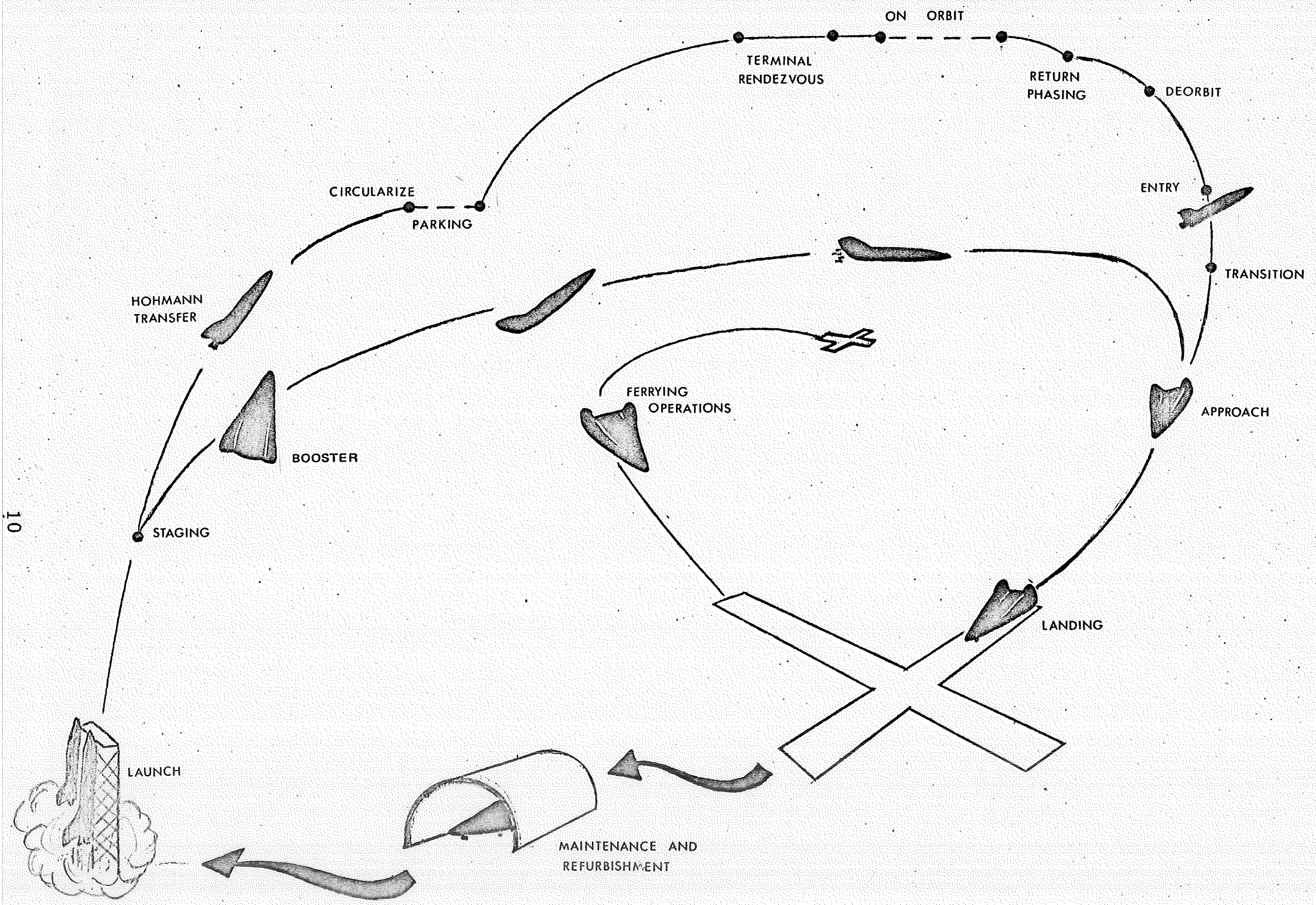


Fig. 1. Generalized SSV mission profile.

and postflight maintenance/refurbishment activities as well as the mission profile. System development efforts are aimed at minimal assembly and checkout requirements at the launch pad and the vehicle is expected to have onboard means for placing the shuttle in a safe condition quickly and easily after landing.

Liftoff and ascent are accomplished on booster vehicle power which accelerates the mated vehicles to staging velocity and altitude. At this point, separation of the booster and orbiter occurs. The booster reenters the atmosphere, decelerates to subsonic velocities, transitions to aerodynamic flight, and cruises back to land at the launch site.

After staging, the orbiter vehicle is injected first into a circular orbit and then a rendezvous orbit for space station acquisition and docking. The orbiter may remain with the space station from 7 to 30 days before separation and return phasing operations are initiated for a reentry orbit compatible with the selected landing site. An operational requirement has been established for the SSV to have a return opportunity to a primary landing site at least once every 24 hours, with more frequent intervals for the high cross range configuration.

During reentry, the orbiter vehicle will assume a high angle of attack and remain in this attitude until velocity decreases to approximately Mach 3.0 (300 ft/sec). At this point, the nose will be pushed down and the vehicle will assume a glide path of about 10° for the return to the landing site.

Current design concepts incorporate provisions for air-breathing turbojet engines which may be ignited to carry out a routine powered approach and landing, following conventional jet transport operating procedures. However, considerable weight saving could be realized if the engines and the necessary fuel reserves were eliminated in favor of power-off approach and landing operations. This possibility is being investigated. In view of the go-around requirement, the reference vehicle configuration adopted for this study will include turbojet engines for the orbiter, but the demands on the crew in power-off recoveries, including an approach by instrument reference, will also be considered.

The terminal approach and landing following reentry is expected to consist of an energy dissipation phase integrated with an initial approach to a preselected runway offset point, a comparatively steep straight-in approach to the runway, an initial flare to transition into a conventional 3^{o} slope, and a final flare and landing maneuver. Landing speeds for both the booster and orbiter vehicles are expected to be somewhat greater than those of jet transport aircraft.

Figure 1 also depicts the ferry flight capability established for the SSV. There is a requirement to be able to ferry both the booster and orbiter vehicles from final assembly sites or alternate landing sites to designated launch sites. A nominal nonstop ferry range of approximately 500 nm is envisioned, with provisions for strap-on engines and/or auxiliary tankage to extend the range capability.

Constraints

The major constraints expected to affect SSV development and operations are safety, reliability, autonomy of operation, and compatibility with other systems. In qualitative terms, the inherent safety level of the SSV must approach the level exhibited by commercial jet transport operations. Arbitrary safety goals for crew survival probability on the order of .999 have been adopted, and guidelines for accomplishing these goals have been established. Mission reliability requirements have been set at .95, and comprehensive programs have been initiated to identify potential failure modes and apportion reliability requirements among major SSV subsystems.

The requirement for autonomy is most clearly evident in the concepts of launch and mission control. In general, SSV launch operations will differ from those of current spacecraft launchings through a simplification of ground handling and servicing techniques and a reduction in the dependency on ground facilities for launch-readiness checks. A similar degree of independence from ground support is required during orbiter flight in that mission planning, navigation, guidance, and control functions are to be accomplished almost exclusively by onboard systems.

Major constraints on SSV design are imposed by the extensive requirement for compatibility with other systems, especially during recovery and landing operations where factors such as landing site characteristics, ground-based guidance facilities, and air traffic control systems and procedures must be considered. For the orbiter vehicle, additional compatibility requirements derive from mission assignments which entail rendezvous, docking, and/or mating operations with space stations, satellites, and other spacecraft. For example, logistics missions involving the transfer of materials or equipment may require only simple docking techniques wherein the SSV is positioned close to the recipient vehicle but is not physically attached, and supplies are transferred across space from one vehicle to the other. However, in other instances a transfer of passengers or crewmembers may be necessary, and a complete mating of the two vehicles will be required to preclude exposure to the space environment. Compatibility requirements between the SSV and interfacing vehicles/systems must therefore be examined for a wide range of mission requirements and operational conditions.

CHAPTER III

SYSTEM FUNCTIONS AND CREW ROLE CONCEPTS

A human factors support program for the space shuttle must consider the integration of crew performance capabilities in system functions as well as the more obvious human engineering design and crew support requirements. Basic issues regarding the character and extent of crew participation in system functions must be identified and resolved early in the design process so that the specific tasks which are ultimately assigned to crewmembers are compatible with system performance requirements and design constraints and consistent with established principles of man-machine function allocation. This section is a review of current thinking regarding the role of the SSV crew in major system functions.

The principal areas of design emphasis which will influence the assignment of crew roles are the SSV development goals of reusability, autonomy and fail-operational automation of mission-critical functions. Reusability results from the capability of both the booster and orbiter vehicles to return to designated recovery sites and land with minimal requirements for refurbishment and launch readiness preparations for subsequent mission assignments. Autonomy arises from design features which enable the SSV to operate with considerably greater independence from large ground support facilities than current space vehicles. Automation concepts are reflected in the extensive onboard computer control and checkout of all vehicle subsystems and in the use of an integrated avionics system for guidance, navigation,and flight control functions.

To faciliate the discussion of crew role concepts, five classes of system function may be distinguished:

(1) Mission Management
(2) Flight Control
(3) Guidance and Navigation

(4) Environmental Control and Life Support

(5) Communications

Each of these major system functions contains a subset of crew functions and, taken as a set, they account for all of the activities in which SSV crews are expected to participate. Preliminary concepts for implementing crew participation in these functions are discussed below. Design concepts for the crew-vehicle interface, i.e., controls and displays, are also discussed.

Mission Management

Mission management functions entail ongoing assessment of vehicle operational status, evaluating the immediate and projected accomplishment of mission and/or flight plan objectives, appropriate sequencing and execution of subsystem operation, and resolution of action-decision problems arising out of these assessments. Assessment functions include simple, component-specific performance monitoring as well as more complex assessments involving the application of multiple criteria to establish the significance of operating conditions and events or to derive implications for subsequent mission control actions. Onboard checkout and troubleshooting activities are also included here, as are the central data management activities required to process and sequence command signals for vehicle subsystem control and to generate crew information displays.

Implementation Concepts

Two of the most often cited design requirements stated in the SSV literature are (1) that the SSV should be essentially autonomous, i.e., insofar as it is practicable, all mission control and support functions should be performed onboard the vehicle, and (2) that a high degree of automation and functional integration will be required in order to cope with the complexity of this task and to keep crew workload within acceptable limits. It is possible to envision a spectrum of machine integrations, ranging from a vehicle that requires continuous participation by the crew in monitoring and operating systems to one that is completely automatic and requires no crew participation.

The trend in SSV design concepts appears to be toward the latter extreme, with the usual qualifying comments regarding crew responsibilities for overall system management and provisions for backup manual control. It is safe to assume that automatic control will be available in all mission phases from liftoff to touchdown and that the principal function of the crew will be to manage and oversee the operation of onboard automatic systems. The crew will monitor performance, select modes of operation, enter data to modify subsystem operations, and assume manual control when automated control becomes suspect or goes out of tolerance.

Although the mission management function in the SSV will be accomplished by an integrated avionics and data management system, the crew may be considered to be one of the key functional components of this system. One configuration for this integrated system is shown in Figure 2. At the core of this system is a central computer complex, programmed to perform the following centralized management functions:

(1) vehicle subsystem configuration
(2) onboard checkout
(3) performance monitoring and display
(4) data management
(5) onboard mission planning
(6) guidance, navigation, and flight control
(7) data processing for crew controls and displays.

Design guidelines for the SSV call for both manual and automatic control modes, especially to perform guidance, navigation, and flight control functions. It may also be expected that the crew's ability to intervene and exercise override control in nonroutine or emergency situations will be fully exploited, but many

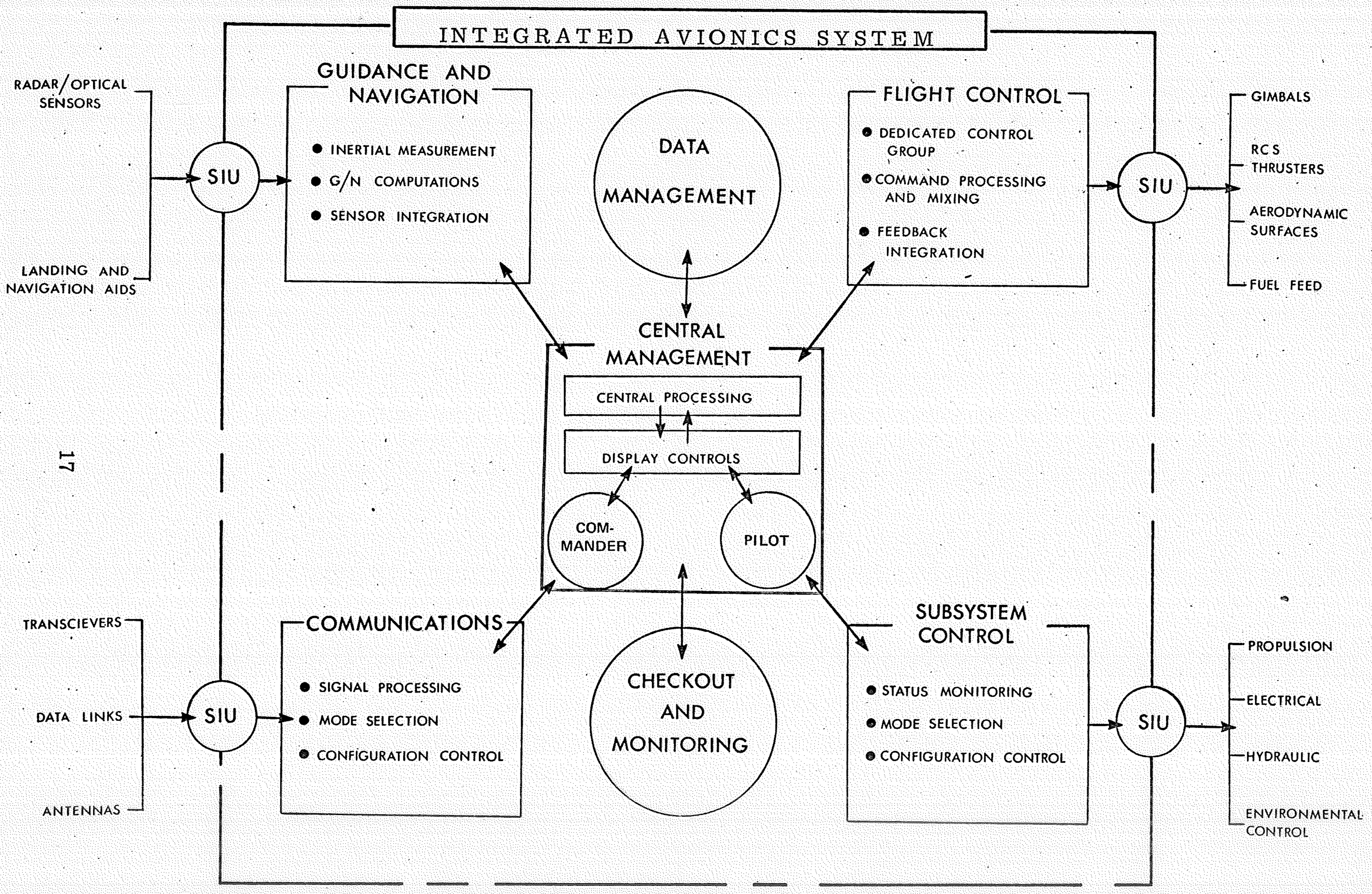


Fig. 2. Integrated avionics system.

problems with respect to control authority are expected to arise. In any event, it is clear that crew participation will be characterized more by careful monitoring of and communication with computers than by the manipulation of control devices.

Crew-Vehicle Interface

Crew participation in computer-controlled system functions will be effected primarily through a sophisticated, multimode information display system incorporating provisions for entering data, calling up desired information and/or data formats, and reprogramming established display sequences or configurations. The basic concept is to provide the crew with only the information required during a specific mission phase by means of a dynamic, preprogrammed display mode sequence. A priority interrupt feature will allow for the timely display of out-of-tolerance conditions for mission-critical and safety parameters.

Display systems comprised of multiple cathode ray tube (CRT) presentations are being proposed to support the crew in mission management activities. These displays incorporate such features as time sharing, integrated electronic and optical imaging capabilities, pictorial and graphic display formats, and the presentation of predictive information. Direct view, rear port CRTs proposed for data management and system performance monitoring are designed to present projected slide or film (microviewer) images in addition to the normal electronically generated symbology and can thus accommodate large quantities of checkout and procedural data (including complex diagrams) which would otherwise place excessive demands on digital computer memory.

The crew will have access to the central computer complex by means of an alphanumeric keyboard. This control interface will permit the crew to update mission parameters, to initiate subsystem commands for execution under computer control, to call up data and specific display configurations, and to control data recording by onboard printers for postflight maintenance purposes.

Additional control panels may also be available for more direct control of vehicle subsystems using designated control panels containing pushbuttons, thumbwheels, and twist knobs.

Flight Control

Basic vehicle control concepts for the SSV entail the use of main-engine thrust vector control (TVC) during the ascent phase of the mission, the use of a reaction control system (RCS) operating either independently or in combination with TVC for orbital maneuvers and reentry, and the use of aerodynamic control surfaces and turbojet thrust control for subsonic flight path control in the atmosphere. Flight control is the primary inflight control function in that its impact on the achievement of flight plan objectives is the most immediate and direct of all onboard operations control functions. Although, in practice, flight control is inextricably bound up with mission management, navigation, and guidance functions, it will be convenient to limit it here to just those functions required to transform guidance, navigation, and mission planning inputs into an effective pattern and time phasing of thrust vectoring, reaction jet firings, and control surface deflections.

Because of its immediate and direct effect on the vehicle's moment-to-moment state, flight control can be considered as the most critical function for satisfying crew/passenger safety requirements and for assuring mission success. Capability for both automatic and crew-controlled operation of the SSV has been cited as desirable for all essential flight control tasks. A comprehensive and definitive examination of crew performance capabilities and vehicle design features required to support manual control activities will be necessary to realize this goal without excessive penalties in terms of degraded accuracy, unacceptable crew workload, or system complexity and costs.

Implementation Concepts

In preliminary SSV design studies, flight control functions are viewed as an integral component of an interactive flight management, navigation/guidance, and propulsion/control surface control system. As such, implementation will be effected primarily through the integrated avionics system, and again the crew must be considered an element of this system. A typical system configuration is schematized in Figure 3.

A basic flight control subsystem can be defined in terms of the operations required to process data pertaining to instantaneous vehicle state and to transform commands generated by the computer or the crew into the control actuation signals needed to produce correct, stable attitude and relative movement responses. Neither the generation of vehicle state data and guidance commands nor the propulsion system and aerodynamic control system (ACS) responses, per se, are flight control functions. Rather flight control functions consist of the timely and accurate derivation of TVC, RCS, and ACS commands. (The latter system includes control of turbojet engines.) In the further discussion of SSV design concepts and crew participation for flight control, it will be convenient to cover TVC, RCS, and ACS control modes separately.

Thrust Vector Control (TVC). Boost propulsion systems, employing high pressure bell nozzle engines, will be used on the booster vehicle to provide Δv to the mated vehicles for initial ascent and to provide Δv to the orbiter for its final ascent. These engines are throttled and gimballed to limit acceleration levels and provide trajectory control. During normal ascent, control steering signals are generated by the inertial navigation and guidance computers and applied to the TVC actuators by gimbal and throttle drive electronics. One attitude control technique under consideration employs equal engine deflection for developing pitch and yaw torques and differential deflection for roll control. Differential engine throttling may also be used for attitude control.

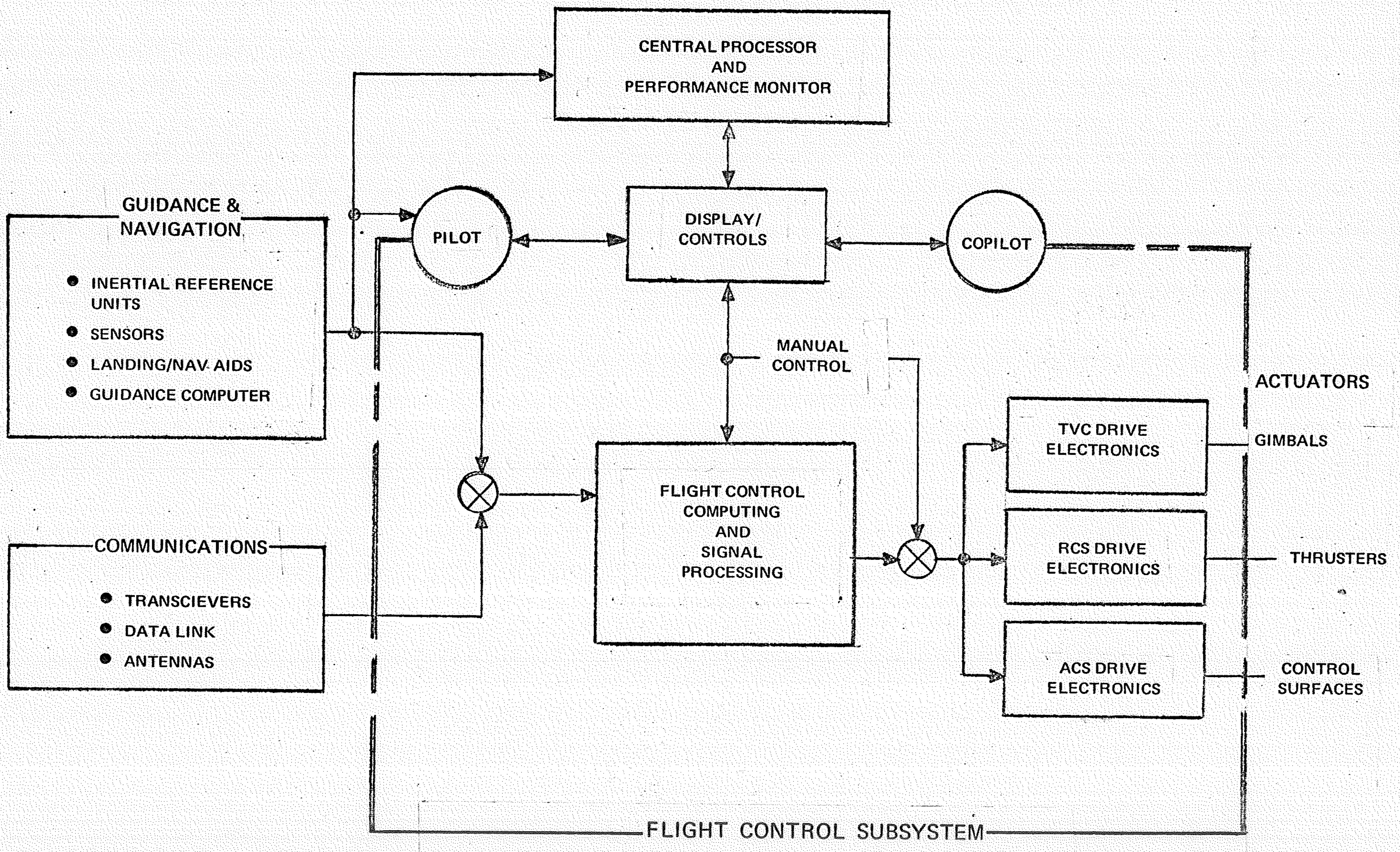


Fig. 3. Flight control subsystem.

Triple redundancy in computing channels and quadruple redundancy in the critical sensor and servo actuator elements are being proposed for the SSV automatic flight control system (AFCS) to achieve specified fail-operational operating goals. Provisions for manual override control by the crew in the event of AFCS malfunction or excessive disturbance due to wind conditions or propellant sloshing are also being considered. Manual control capabilities for attitude stabilization, relief of excessive aerodynamic loads, and trajectory control are under investigation. Earlier studies have concluded that the proper choice of configuration (i.e., appropriate instrumentation for diagnosing failures and appropriate hand controller dynamics) can provide a versatile manual control system having good performance during the ascent phase in both normal and failure (AFCS backup) situations.

Reaction Control System (RCS). A reaction control system comprised of wing and fuselage mounted engines with varying thrust levels will be used to assist the separation of the booster from the orbiter and to provide for exoatmospheric control. The RCS provides three-axis translation and attitude control by means of pressure-fed oxygen/gaseous hydrogen thrusters and will be used for final rendezvous and docking, on-orbit attitude control, small maneuvers, and reentry attitude control. In the primary operating mode, the central computers will process sensor data and guidance inputs to generate RCS jet selection and firing commands for attitude control and translation thrusting.

Automatic control is specified for rendezvous, deorbit phasing and reentry, with provisions for pilot monitoring (management) and override control. Manual attitude and translation thrusting control will be available in the event of AFCS malfunction or unusual conditions, but the crew's primary role will be to monitor preprogrammed, computer control of RCS operations.

Critical maneuvers such as closure to target vehicles and docking are currently considered to be manual control functions. However, automatic methods with visual monitoring are also being studied as alternatives. If automatic control is adopted, it is likely that a crewmember will have to "approve" each RCS thrusting maneuver and that the initiation of automatically controlled final closure and mating sequences will be controlled by the crew.

Aerodynamic Control System (ACS). Following reentry, both the booster and orbiter vehicles will execute appropriate transition maneuvers and establish conditions for subsonic flight in the atmosphere. Flight control will then be accomplished through an ACS comprised of aerodynamic control surfaces, lift modification devices (e.g., flaps, speed brakes), and thrust modulation of air breathing turbojet engines. The jet engines appear to be a definite requirement for the booster vehicle to enable it to cruise back to the landing site. Engines are also being considered for the orbiter to assist in the approach and landing and to provide a one-time go-around capability. For the orbiter, however, the penalties of weight and complexity are much more critical, and the feasibility of unpowered recovery operations is being investigated. Both vehicles would require engines for cross-country ferry flights, but this capability could be provided by strap-on engines.

Flight control in the atmosphere will not differ significantly from that of advanced jet transport aircraft when turbojet engines are used. The AFCS will continue to be used extensively in the primary operating mode but considerably greater opportunities for pilot control will occur during the descent, approach, and terminal area maneuvering phases of the flight. During these mission phases, the SSV will be operating in controlled air space and must conform to established air traffic control (ATC) procedures. A fully automatic approach and landing system will be employed for low visibility operations, using some mix of onboard inertial guidance and external navigation aids.

When manual control of the ACS is assumed, conventional flight control techniques will be used, for the most part, in achieving flight path control objectives. Exceptions lie in the use of an all electronic ("fly-by-wire") control system in the SSV and in unpowered recovery operations. With the "fly-by-wire" systems, control surface actuators are manipulated through ACS drive electronics, and there will be no direct, electromechanical linkage between pilot controls and the actuators. Using this system, displacement of pilot hand controllers and rudder pedals produces corresponding angular rate and acceleration changes in vehicle motions around the pitch, roll and yaw axes. An inherent stability augmentation system is incorporated to damp the effects of vehicle disturbances.

Unpowered flight will introduce requirements for new skills in manual control of energy dissipation following reentry and in integrated energy management and flight path control down to the runway. These new flight control techniques will be especially critical in unpowered approaches under low visibility conditions when the vehicle must be maneuvered by instrument reference.

Crew-Vehicle Interface

Displays for AFCS monitoring and manual flight control will be presented on CRTs located in prime visual areas directly in front of the two crewmembers. Display formats for given mission phases (both flight and subsystems data) will be computer-generated but selected by the crew as required or desired. Provision will also be made for automatic (i.e., computer-commanded) display of caution and warning information relating to mission-critical conditions.

Electronic Attitude Director Indicators (EADIs) are expected to replace conventional electromechanical instruments for displaying vehicle attitude in all axes, velocities, guidance commands (flight director), and other vertical situation symbology. Optical and sensor-derived images may be time shared on the same CRT or located on a second CRT.

In addition, special pictorial and graphic displays can be generated for AFCS monitoring and/or control of orbital maneuvering, rendezvous, energy management during approach, and ground-referenced flight paths. Preliminary SSV design concepts also include such special devices as a head-up display for presenting computer-generated flight situation symbology on a combining glass located in the pilot's line of sight while he is controlling the vehicle by external visual reference. Such devices have been developed for low visibility approach and landing operations in military jet and civil transport aircraft. Applications of the head-up display to SSV docking maneuvers as well as landing are under consideration. The head-up display is also being examined as a backup alignment aid for navigational sightings in space.

Conventional controls consisting of control column, rudder pedals and throttles are being proposed for the ACS. Advanced panel-mounted or side-arm controllers such as those developed for the SST may be used to replace the bulky control columns for pitch and roll control. Hand controllers for attitude and translation thrusting control in the TVC and RCS control modes will also be available to the SSV crew. Studies are in progress which may lead to the elimination of the conventional control column and rudder pedals in the SSV, with full attitude control in the ACS mode also accomplished through the hand controller.

Implementation of manual control capability will be a very sensitive and challenging task in view of the complexity of the proposed multiply redundant AFCS with its interacting sensor/guidance inputs and varying control element actuation requirements. To illustrate the complexity of this crew-vehicle interface, consider the integration scheme proposed by one contractor. The principal features are illustrated in Figure 4 and provisions for pilot interventions in the vehicle control loop are described as follows:

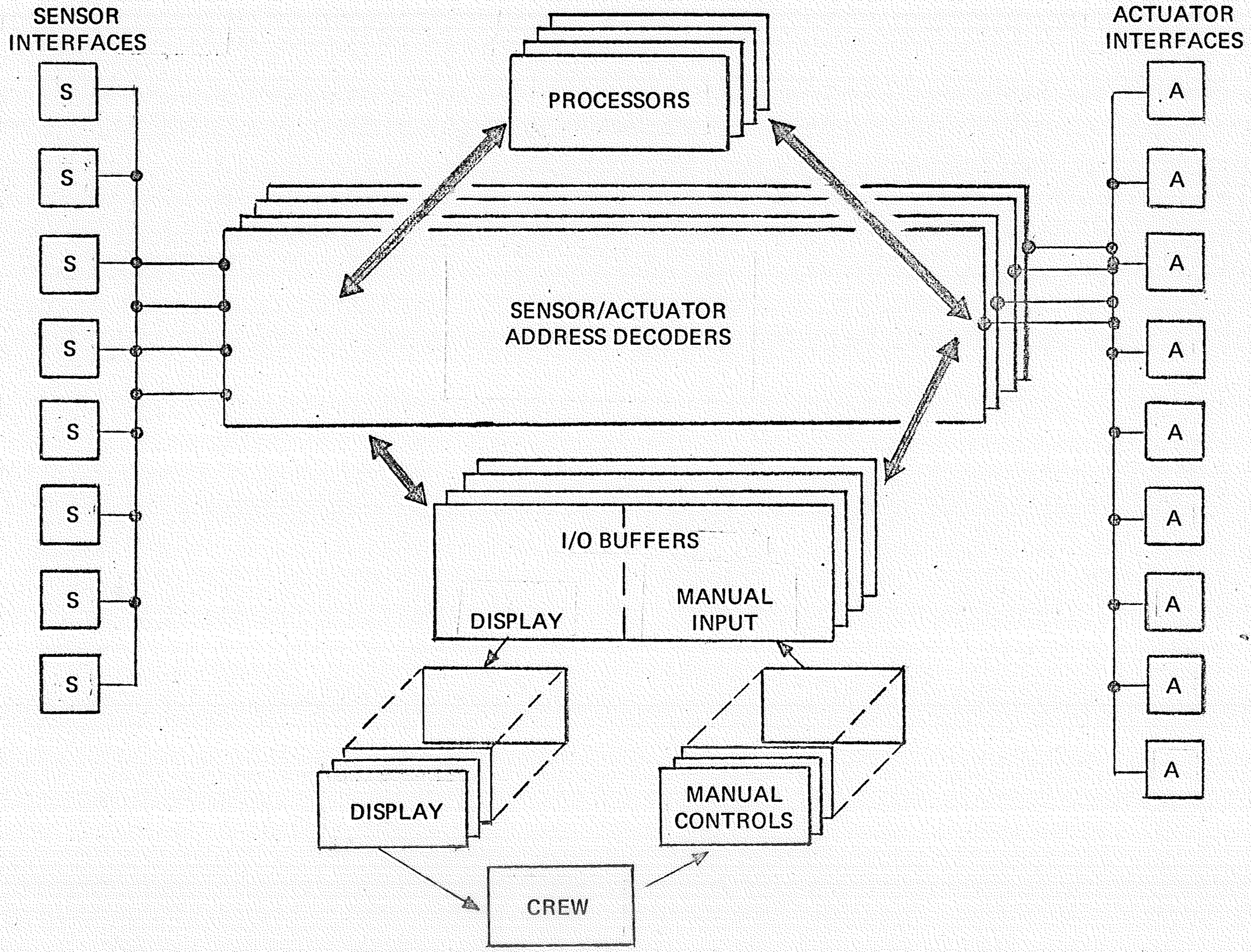


Fig. 4. I/O Buffer system and associated components.

> All data concerning the spacecraft status are obtained through a sensor. The sensor signal is converted to a digital form by an interface. Similarly, every physical action involved in the control and functioning of the spacecraft is achieved through an actuator, a device which actuates according to a digital message placed in its interface.
>
> To achieve any desired degree of automation, each of the several processors in the central computer can address the sensor and actuator interfaces and obtain full information on the vehicle's condition, and thus control its activities. The integration of the crew into the vehicle control loop is made in a fully redundant manner. Hence, anything a processor can do, the man can do and vice versa. In the automatic modes, the crew will observe the displays and confirm that the operation is as desired. In most manual modes, the processors will modify the manual control instructions (adding such things as smoothing, cross-coupling, etc.) and will embellish the displays with more thoroughly digested and filtered information. In the fully manual-backup-only mode, the processor will be completely out of the loop. Raw sensor data will appear on the displays, and direct control will be exercised over vehicle functions.
>
> ...Sensor outputs and actuator inputs are addressable by any of the processors just as if they were ordinary memory locations. Any and all processors can address them subject to restrictions included in the computer program. The I/O buffers can similarly address the sensor and actuator interfaces. The crewman thus has independent access to the sensor data and control of the actuators and can, to the extent of his physical abilities, duplicate the functions of a processor in controlling the spacecraft. (North American Rockwell, 1969).

Guidance and Navigation

SSV guidance and navigation functions encompass all requirements for prelaunch boost trajectory and mission profile computations, determination of optimum powered ascent and orbit insertion trajectories, computation of landing site reach data for aborts, orbit transfer and adjustment computations for navigation to rendezvous, precision guidance for docking maneuvers, navigation and guidance computations for deorbit and entry, return to base cruise guidance, and precision guidance for terminal area approach and landing. Guidance and navigation functions are to be performed onboard the vehicle, using ground and other navigation aids as supplements when appropriate. For this discussion, navigation will be defined as the determination of vehicle position and velocity. Guidance will refer to the computation of thrust control and attitude adjustments required to achieve the desired trajectory or ground-referenced flight path.

Implementation Concepts

Guidance and navigation functions will be implemented by the integrated avionics system discussed earlier and schematized in Figure 2. A typical equipment configuration for these functions would include:

1. triply redundant inertial measurement units
2. a dedicated navigation computer
3. integrated optical and IR sensors
4. a radar for rendezvous and station keeping
5. a multimode laser sensor/tracker for docking
6. LORAN, TACAN, radio altimeters, and air data sensors and computer for augmenting the inertial navigation capability
7. an advanced all-weather approach and landing guidance system
8. appropriate interfaces with the central computer complex and crewmembers.

During ascent, control steering signals will be generated for the ascent trajectory, staging, and booster reentry by the inertial system. Booster cruise and return to the landing site will be supported by the air data sensors and VOR/TACAN inputs from ground stations. Range and relative angular information for rendezvous and stationkeeping will be provided by the multimode radar, with an alternate capability provided by the optical tracker. Precise angular and range data for docking will be obtained from the laser system. Attitude alignment and orbit ephemeris data will be obtained from the optical and IR trackers. Accurate attitude data for inertial system alignment will be obtained by tracking stars with the optical sensor. Earth-edge tracking will be accomplished using the IR sensor. The central computers will be used for evaluation, data filtering, and the determination of best estimates of velocity and position from the various data sources. Retrograde attitude and time will be established by the central management complex, as will energy management during the reentry phase.

Terminal area guidance for approach and landing will be self-contained only under nonroutine or abort conditions. Though not yet definitely established, the SSV is expected to operate with some sort of ground-based landing guidance system. A strong candidate is the Advanced Integrated Landing System (AILS) currently undergoing development and evaluation by the FAA. AILS combines certain features of the conventional instrument landing system (ILS) and GCA and is capable of providing guidance information throughout the approach, flare, and touchdown. The AILS is expected to improve accuracies and provide precision approach radar monitoring by ground operators.

Test pilots at the NASA Flight Research Center at Edwards AFB are investigating precision instrument approach and landing techniques which can be accomplished by the orbiter vehicle without relying on turbojet power. The feasibility of various guidance schemes for unpowered terminal area maneuvering, energy management following reentry, and precision approach and landing under full IFR conditions is being examined. At the Ames Research Center, studies of integrated inertial/radio navigation techniques and of ILS-independent approach monitor displays are in progress.

Crew participation in guidance and navigation functions will vary across mission phases. Time constraints will probably limit crew involvement to monitoring position, velocity, and attitude displays during ascent and staging. Crew participation will increase during rendezvous and docking phases and could include such activities as sensor mode selection, control of optical sightings, new data insertions, and keyboard call up of specific data for display as well as manual flight control or the ongoing monitoring of computer-controlled guidance and navigation functions.

The requirement for crew involvement in guidance and navigation will also increase during reentry, return phasing, cruise back, approach, and landing phases. Flexibility in selecting landing sites, in determining flight plans for cruise and terminal area approach, and in establishing the appropriate mix of navigation and guidance data sources and computations for approach and landing will require crew assessments and decision making and entail intervention in computer control of subsystem configuration and display sequencing. In general, however, the primary operating mode for guidance and navigation will be preprogrammed, and the crew's role will be to monitor, manage, and augment system performance.

Crew-Vehicle Interface

The principal media of interface for these functions are the computer-driven, multi-function CRT displays and the alphanumeric keyboards which give the crew access to the central computer complex. Guidance and navigation data will be presented on vertical and horizontal situation displays and on associated multimode CRTs. As many as seven multimode CRTs have been proposed for installation in front of the two crewmen. Crewmembers will be able to view different data formats on their respective displays, or they can view the same data simultaneously.

Extensive use of the integrated sensor-derived imaging capability and computer-generated data in pictorial or graphic formats is envisioned for navigation functions. As an example, while the docking maneuver is being executed, a symbolic display of azimuth, elevation, range, and relative velocity may be superimposed on a TV or radar-derived image of the space station. For ground-referenced navigation tasks, pictorial situation displays would be generated to integrate all of the pertinent position and velocity data into a simple and readily interpreted format. Special purpose guidance displays, such as a head-up display for superimposing flight director symbology on out-the-window visual fields to aid in docking or landing, are also being being considered.

Environmental Control and Life Support

The system requirements in this area include a shirtsleeve environment for passengers and crew, basic provisions for life support under both routine and emergency conditions, and habitability of the crew and passenger compartments. For the orbiter vehicle, these life support and habitability requirements must be satisfied for nominal missions of up to seven days duration and for as long as a month when special provisions are made available. Specific environmental control and life support (EC/LS) functions include:

1. the supply and control of cabin atmosphere
2. control of temperature and humidity
3. carbon dioxide and trace contaminant removal
4. supply of food and water
5. waste and trash management
6. personal hygiene, microbial control, and medical support
7. illumination, noise control, and comfort features.

Implementation Concepts

Basic EC/LS functions such as gas supply and control for breathing and cabin pressurization, thermal regulation, water and waste management, and emergency life support will be largely automated. Under routine conditions, then, the crew would not be required to participate extensively in controlling EC/LS subsystem operations. Provisions will also be made for continuous self-check and performance monitoring, and the system will be armed to alert the crew when any trends toward out-of-tolerance conditions begin to develop. Crew participation in basic EC/LS functions thus will consist mainly of passive status monitoring, with occasional servicing activities such as replacing canisters or disposal of accumulated wastes. More active monitoring and/or manual override control will be necessary only when the automatic system malfunctions.

Manual control of cabin illumination and of such items as temperature and seat adjustments will be provided for to accommodate individual requirements. It is also obvious that use of food, water, personal hygiene facilities, and medical supplies will be initiated and controlled by crew and passengers and will represent important design requirements for the man-machine interface.

Crew-Vehicle Interface

EC/LS operating status and alarm readouts will be displayed, probably on a time-shared basis, on one or more computer-controlled CRT displays on the primary crew instrument panel. Additional dedicated status indicators and warning lights will also be available to augment the CRT display. It is also reasonable to assume that auditory signals may be used for more critical crew alerting functions. In view of the design goal of eliminating or minimizing the use of electromechanical controls such as toggle switches or select knobs, EC/LS functions will probably be controlled through the computer by function-select buttons on a keyboard. However, it may not be feasible or desirable to eliminate conventional controls completely, and they may be used on overhead and side-console panels for controlling cabin illumination and specific, backup environmental control functions.

Detailed designs for food and water supply, waste management, and personal hygiene have not been developed. Separate stations for food and water management and for personal hygiene, located adjacent to the crew's normal operating stations, have been proposed. Similar stations will be available for passengers. These stations will include special dispensing facilities, accommodations for storage of consumable materials, and provisions for collection, storage, or disposal of waste materials generated during the mission.

Communications

The mission activities projected for the SSV imply the requirement for a communication system that provides voice/data transmission and reception, onboard communication, and record/playback capability. Using both direct and relay-satellite techniques, the crew of the SSV will be able to communicate with ground control, space stations, landing sites, and personnel on emergency EVA. Communications functions will encompass all SSV requirements for data exchange, including voice channels for shuttle-ground links and onboard intercom, data links for status reporting and receipt of command and/or maintenance data from ground or space stations, voice channels for EVA, TV reception, and onboard data recording and playback. The principal SSV communication links are shown in Figure 5.

Implementation Concepts

Anticipated improvement in communication system techniques will make possible nearly continuous communication with the shuttle, thereby contributing

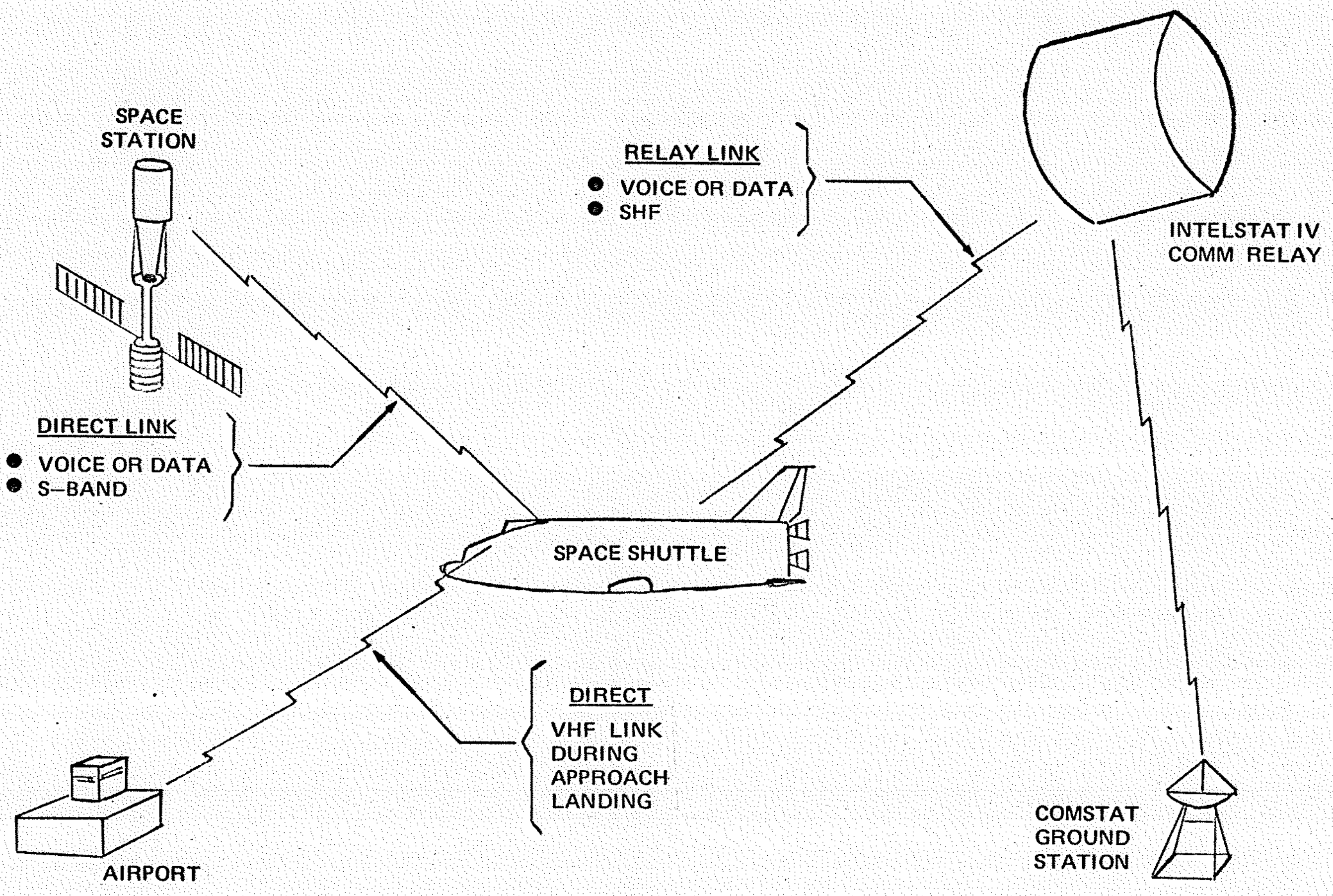


Fig. 5. SSV communication links.

to safety, crew morale, mission reliability, and the capability for real-time remote control of the vehicle via data link. In general, communications may be thought of as three subsystems: direct communications, satellite communications, and record/playback communications.

Direct communications will probably be provided by a UHF/VHF/S-band type system. This system will handle communications with ground support during launch, on-orbit vehicle-to-vehicle communications for rendezvous and docking, communications with astronauts on emergency EVA, and intravehicular communications. This system will also be compatible with the present air traffic control communication system for approach and landing and ferrying operations.

Satellites will probably be used to improve communications over that now available with the manned space flight network. The improvement is expected to be manifested in an expanded ground-to-orbit communications capability. It will be possible for ground stations to be in contact with the orbiter vehicle a much greater proportion of the time. While it is assumed that the communication relay satellite system will be one of the developmental systems expected to be operational in the early 1970s (Intelsat IV), new concepts such as dedicated UHF-SHF offer advantages still under consideration.

In addition to the direct and satellite communication systems, it is likely there will be some type of onboard recording and playback system which will store information for later analysis on the ground in much the same way an inflight recorder does in current aircraft. It would also be feasible to use this system for telemetering certain types of data, particularly if advance telemetering of information could facilitate prelanding preparation for maintenance and refurbishment thus minimizing turn-around time.

Crew-Vehicle Interface

Communications are not expected to impose unusual demands on the crew. The shirtsleeve environment suggests the use of lightweight headsets similar to those now being used in commercial aviation. Routine activities such as communications checks and status monitoring, frequency selection, and possible vernier alignment of highly-directional antennas are expected to require only infrequent attention during rendezvous and on-orbit mission phases. Following reentry, crew involvement in communication activities will increase. During orbiter recovery operations (and cruise-back and recovery of a manned booster), requirements for interacting with ground navigation and control facilities may approach the levels experienced by commercial airline operations.

Communication functions will be monitored and controlled through the Integrated Avionics System. The principal display interface for status read-outs is expected to be time-shared presentations on the CRT displays. Manual control will be exercised by means of computer-function selector switches and/or keyboard entries.

CHAPTER IV

HUMAN FACTORS TECHNOLOGY REQUIREMENTS

This chapter contains a select listing of human factors problem areas related to the operation of the space shuttle system. The problems presented are those which it is felt will require advances in human factors technology in order to solve. Problems which require application of existing human factors technology, new design approaches, or extensive engineering effort are not taken up here. While such problems represent legitimate and important human factors concerns, they do not require new technology to be solved. Thus, the scope of the discussion is restricted to those areas where additional research, often of a very basic nature, is required to develop information upon which to base solutions. The objective is to define for NASA's consideration the outline of a research program for developing the human factors technology which will be needed in later stages of SSV design to insure optimum utilization, protection, and comfort of the human crewmembers.

Three sources of information were drawn upon in preparing this chapter:

1. A detailed review of the space shuttle system and its planned mission, based for the most part from contractor Phase A reports,

2. Prior studies by BioTechnology, Inc. indicating that human factors technology is weak with respect to the topic under consideration,

3. Statements from industry and government personnel, obtained from personnel interviews and documents.

Problem Area No. 1:
Reentry Transition

Description

There are certain unique aspects of the proposed space shuttle mission profile related both to the vehicle system itself and to the human operator of the system which have important implications for the reentry transition phase of SSV operations. First, if present plans are implemented, space shuttle missions could last as long as 30 days. Exposure to the weightless environment for this long a period of time is unprecendented. Secondly, the SSV orbiter, if it is to be fully controllable in both the space and atmospheric flight regimes, will of necessity have more aspects of a piloted vehicle than any space vehicle so far. Furthermore, the control modes required for each of these flight regimes are altogether different from one another. In the space environment, reaction jets will be used for orbital maneuvering, whereas in the atmosphere ordinary aircraft control surfaces will be employed. The potential difficulties of making the transition from one regime to the other, which are in themselves formidable, may be further complicated by physiological changes in the pilot of the vehicle as a result of rather prolonged exposure to the zero gravity environment. Although previous space flight experience has indicated that spacecraft reentry accelerations posed no appreciable performance problems for astronauts, anticipated reentry accelerations of about 2 to nearly 3 G's for the space shuttle orbiter may be of concern, since in the latter case, performance requirements are inestimably more rigorous. Further, the seat orientation currently being considered would result in inertial forces in the head to foot direction rather than the chest to back forces previously experienced and known to be more easily tolerated (Sullivan & Coworkers, 1970).

Specific Human Factors Issues

The two areas that appear to pose potential problems and require further human factors technology development related to reentry transition are described in the following paragraphs. There are undoubtedly a number of other possible problem areas. For example, in addition to the cardiovascular deconditioning problem it is possible that prolonged space flight may pose some problems related to the musculoskeletal system. For about five days after the 18-day Soyuz flight, cosmonaut Nikolayev recalled that he and the copilot "had trouble when they lay down to sleep because they felt that great pressures were pushing through them to their backs (Wilford, 1970)." "We did not anticipate," he said, "that it would be so difficult in readjusting our limbs and other parts of the body." The present discussion will, however, be restricted to an elaboration of the one physiological problem area which has been consistently observed in both American and Russian space flight experience, that is, the problem of cardiovascular adaptation and its implications for reentry transition. The human factors issues and technology implications related to control dynamics will focus on the manual control modes.

Cardiovascular Adaptation. Over lengthy periods of time in the space environment (precisely what length of time remains undefined), the reduced load on the heart, lowered blood pressure, and reduced hydrostatic pressure differences might produce a system which had adapted to the weightless environment so completely that exposure to the acceleration of reentry in the shuttle orbiter might be intolerable and physiologically catastrophic. Thus far, space flight exposure has been shown to produce postflight reduction of work capacity and reduced orthostatic tolerance, in some cases to the point of syncope. There is evidence to suggest that these reactions are the result of an inflight adaptation to weightlessness involving body fluid balance shifts and fluid loss, with associated endocrine and electrolyte changes and total body potassium depletion (Berry, 1971). Crews and passengers who have adapted to the weightless environment in this way could experience syncope when exposure to the long duration 1.5 to 1.8 $+G_z$ acceleration component, with peaks of 2.2 to 2.4 $+G_z$. This G loading would be even more significant if the individuals subjected to it were in the seated mode rather than the supine mode.

One component of the cardiovascular adaptation problem, reduction of hydrostatic pressure gradients, can be illustrated by the diagram in Figure 6. If the cardiovascular system is considered as the column pictured in the figure, it becomes obvious that pressure exerted in the supine position is equivalent to the width of the column or 12 mm Hg. In the vertical position, on the other hand, pressure will be equivalent to the height of the column, or 85 mm Hg. The ability of a heart and blood vessels which may have lost a certain degree of tonus through disuse at zero G to pump a column of fluid up the long axis of the body could very conceivably become impaired. This problem could be further aggravated if the pressure regulators of the cardiovascular system fail to give appropriate cues to control the amount of fluid in the system after long periods of transmitting signals diametrically opposed to those which must be transmitted in a gravity environment. Further, there is reason to suspect that peripheral vascular resistance may also decrease and be contributing to the observed decreases in work capacity.

Manual Control Modes. Participation of the SSV pilot in reentry guidance and control functions could begin with deorbit thrusting and continue through the critical deceleration and cross-range maneuvering accomplished to bring the vehicle to a prescribed end-of-reentry footprint area near the intended landing site. The complexities of the flight control task for lifting reentry vehicles which generate moderate values of L/D at hypersonic velocities has been under investigation for many years (Miller, 1965). Attitude control is especially critical in lifting body vehicles and angle of attack must be closely controlled if the required flight path is to be followed.

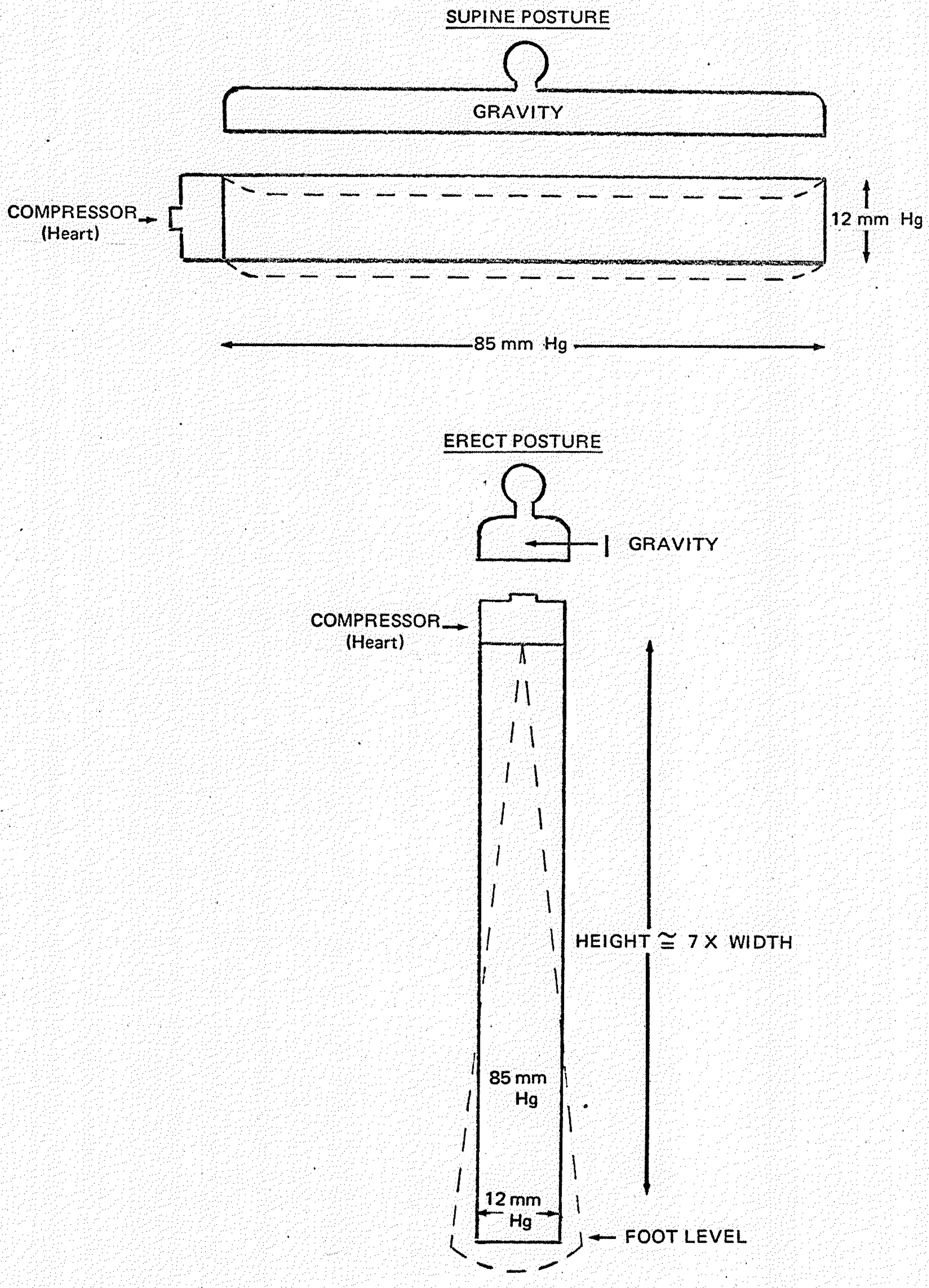


Fig. 6. The hydrostatic pressure effect of gravity (From Sullivan & coworkers).

The comparatively high L/D orbiter vehicle will require a three-axis stability augmentation system (SAS), probably with variable-gain damping. A direct manual control mode (no stability augmentation) is not likely to be a feasible option, since the vehicle may be only marginally controllable without the SAS in certain Mach number/angle of attack regimes. Various SAS-augmented manual modes, with pilot-selectable or automatically computed control loop gains can be considered and different levels of manual intervention in the flight control loop may be available (for example, reprogramming the AFCS and mixed manual and automatic commands as well as split-axis and/or full-axis manual control). In the manual control modes, the pilot would command vehicle rates around the three-body axis using a hand controller.

One potential human factors problem derives from the rapid transition, during reentry, from control system dynamics appropriate to attitude control in the space environment, with essentially zero dynamic pressures, through the changes necessary for hypersonic maneuvering as dynamic pressure builds up and the vehicle begins to develop lift and finally to control dynamics appropriate to the transition to subsonic flight. Little is known about the demands of this rapidly changing control task on the pilot's perceptual-motor abilities. The precision and speed of response requirements appropriate to the changing demands of the reentry maneuver must be determined and related to alternative mechanization concepts for the hand controller.

A related problem can be identified in the determination of display requirements for manual control during this flight segment. Special display requirements which may be expected to arise include display support for monitoring the performance of the automatic flight control system and resolving decision problems with respect to manual intervention. Conditions appropriate to the pilot's exercise of the various manual augmentation or override control options must be precisely defined in order to identify display requirements for this decision.

When continuous manual control is assumed by the pilot, requirements emerge for an integrated display of vehicle orientation in all three axes and its flight path projections relative to terminal area navigation constraints. The crew's ability to cope with the manual reentry control problem within the context of ongoing system management activities must also be assessed. The focus of attention on the control task must not degrade crew monitoring of vehicle heating and critical subsystem performance parameters during reentry.

Implications for SSV Human Factors Program

The related problems of cardiovascular deconditioning and manual vehicular control during reentry transition can be examined by various techniques, both separately and independently. Increased emphasis on ground-based simulation studies is suggested as a useful approach to both better definition of the manual control mode requirements and the cardiovascular deconditioning problem. In the latter case, bed rest studies of the type being undertaken under the direction of the NASA Ames Research Center will undoubtedly offer some clarification as to the extent of the potential deconditioning problem. Should bed rest studies indicate that "orbitally deconditioned" subjects cannot tolerate orbiter reentry accelerations and/or that simple management measures are not effective, this would provide a clear indication that, at the very least, a new approach to seat design will be required. Articulated seats have, for example, been suggested (Sullivan & coworkers, 1970) as one possible alternative solution. Any concept selected would, of course, have to be thoroughly evaluated from its anthropomorphic, anthropometric, and operational aspects.

Problem Area No. 2:
Manual Control of the Booster Vehicle During Ascent and Initial Exoatmospheric Maneuvering for Reentry

Description

A capability for backup manual flight control of the mated orbiter-booster vehicles during launch and aborted launch is implied in the delineation of desired SSV characteristics. Provisions for manual control during booster reentry, fly-back, and landing are treated somewhat more explicitly in SSV planning studies. Also, suggestions have been made for investigation of the feasibility of pilot override control during the boost phase of the ascent trajectory. Such investigations should consider the crew's ability to determine when they should intervene in the primary, automated control sequence and should establish the hand controller and display characteristics necessary to insure the crew's effectiveness in performing the vehicle control task manually.

Nominal SSV launch operations will not, of course, be under manual control, and conditions necessitating an assumption of manual control during the ascent phase are expected to be very low probability events. Routinely, guidance and commands required to achieve optimum powered ascent trajectories and the execution of corresponding thrust vectoring commands will be accomplished automatically by the integrated avionics system. Redundant computing channels and control actuator drive electronics will be employed to cope with failures. The pilot's role will be to monitor the ascent trajectory and assume manual control only when critical automatic flight control system (AFCS) malfunctions occur or when such vehicle performance limits as maximum aerodynamic loading and attitude change rates are exceeded. Manual flight control tasks could include attitude stabilization and structural load reduction as well as trajectory control. Further, manual control might be assumed by the crew to augment AFCS capabilities in achieving flight plan objectives or to deal with emergency and launch abort conditions.

Specific Human Factors Issues

Three specific human factor issues should be resolved in the development of this capability for the SSV:

1. Under what conditions, if any, is pilot intervention in the automatic control process feasible and desirable, and what are the pilot's capabilities for recognizing and/or assessing these conditions?

2. What levels of modes of pilot/AFCS control interaction are necessary and effective for flight control during ascent?

3. What combination of hand controller dynamics and vehicle state/guidance command display is best suited for these manual flight control tasks?

Potential problems associated with manual guidance and control of large launch vehicles have been under investigation by NASA for several years (Hardy, 1969), but these studies have focused on Saturn launch vehicles and mated Apollo/Saturn configurations. The general conclusions are that:

> The pilot is a good adaptive optimizing servo for systems with rapidly and widely varying controlled element dynamics such as might occur with step variations in the vehicle augmentations due to system failures or variations in the vehicle dynamics that can occur during very short time intervals... In essence, then, the pilot can be incorporated as a primary element in both guidance and control loops provided he is given appropriate displays, appropriate instrumentation for diagnosing failures, and appropriate control system characteristics.

The applicability of these findings to mated SSV booster-orbiter configurations is not known and should be reassessed as more information becomes available on such SSV characteristics as vehicle stability, structural flexibility, vibration levels, fuel sloshing dynamics, changes in vehicle configuration at staging, and the effects of adverse environmental conditions (e.g., wind shear). The earlier feasibility studies of pilot control during launch operations suggest that such control can contribute substantially to mission success probabilities.

For example, in one assessment of AFCS failure modes it was determined that the addition of a piloted "load relief" (reduction of aerodynamic loads) backup control system could reduce mission criticality to a factor of better than two (Hardy, 1969). Moreover, manual control techniques significantly reduced trajectory dispersion, particularly for those failure modes which caused large attitude errors to be developed by the automatic system.

Controllability of the SSV vehicle during launch will also be a critical factor in defining emergency abort procedures and in determining the probability of their success. Careful study should be made of the question of automatic versus manual control during abort from the pad, including a "once-around" abort maneuver. Another area requiring close attention is the issue of control authority between the mated booster and orbiter vehicles during aborted launch and in emergencies during the initial phases of ascent.

Implications for SSV Human Factors Program

The investigation of this problem area from a human factors point of view can be expected to provide guidelines for establishing hard constraints on pilot intervention in automatic control loops during launch and for insuring that he is adequately supported by cockpit displays and controls when these interventions are necessary. Manual control problems during three phases of launch operations should be explored. The first is the initial ascent phase following liftoff where the principal control tasks are to stabilize the vehicle and maintain structural loadings within acceptable limits. This task may be complicated by the mated booster-orbiter configuration, aerodynamic instabilities, wind disturbances, and propellent sloshing dynamics. On entering the second phase outside the atmosphere, significant changes in aerodynamic loading occur, and the attitude stabilization problem is less severe. Control emphasis will shift to more precise trajectory control and to efficient staging. The third phase, launch abort, is an area of extreme concern because of the jeopardy to crew and passengers and the short time available for manual intervention. The implementation of manual control during aborted launch rests ultimately on the philosophy of mated vehicle control authority and on the human capacity to take any sort of effective action during liftoff emergencies.

Human factors studies should be directed toward definition of conditions and events which would underlie the command pilot's decision to assume manual control and the detemination of crew performance capabilities using various display/control devices. The transition from the role of systems monitor to active controller under severely time-constrained and stressful conditions is expected to be the most challenging aspect of these studies. Displays optimized for quick situation assessment, decision, and action are likely to be inadequate for flight control. An unbalanced approach to this problem can be expected to compromise one capability or the other.

Problem Area No. 3:
Life Support Technology/Habitability

Description

In the development of the manned space shuttle system the foremost concern is maintaining the space traveler in an environment which falls within the very narrow tolerance limits established on earth. This function is performed by five basic systems: (1) the oxygen system, (2) the carbon dioxide and contaminant control system, (3) the thermal and humidity control system, (4) the waste management system, (5) and the food and water provision system. Much of the equipment and technology to accomplish these functions have been developed and proven in earlier space programs. However, some of the existing hardware is not completely satisfactory from the human point of view; and, in certain cases, there is doubt about the ability of present systems to meet the demands of SSV missions.

The reference mission for SSV design is space station logistics supply (North & Stoll, 1970). The basic requirements for the life support system in this mission are relatively simple. Since total SSV turn-around time will be less than two weeks, regeneration of supplies and consumables will be unnecessary. Likewise, there is no requirement for extensive inflight maintenance activity. Any problem which may arise, if it is minimal, can be handled by onboard checkout and removal and replacement of system modules. A massive malfunction of the life support system would be handled by a return to earth on emergency supplies.

Although satisfaction of basic requirements appears straightforward and within the reach of current technology, it is reasonable to expect that the design of the life support system will pose special problems because of differences in both the goals and the "tolerance limits" of persons participating in SSV flights, as compared with earlier space missions. Where earlier missions were staffed by highly motivated astronauts willing, able, and intensively prepared to tolerate extreme conditions, the role of the space shuttle voyager will take on many more of the aspects of pilots and passengers in transit. This being the case, considerably more attention must be given to the habitability and comfort of the environment since mission success may rest very heavily upon whether or not individuals participating find the environment an acceptable one. Habitability and comfort are relatively unknown quantities in future space missions. The wants and needs of personnel of widely different backgrounds and training, as well as of both sexes, on space shuttle missions can only be inferred from past simulation and isolation studies and from space flights of relatively short duration with highly selected crewmembers.

Special Human Factors Issues

The major human factors technology problems related to life support/habitability lie in the areas of waste management, personal hygiene, and food service. This opinion, voiced by a number of the individuals interviewed in the course of this study, is shared by many in the aerospace industry. Representatives of two prime contractor organizations recently stated, "Of all the orbiter environmental control and life support systems, these [waste management and food management systems] are the least developed for space flight use. Intensive development coordinated with space station hardware development should be undertaken." (North & Stoll, 1970). The next sections treat human factors problems relating to space shuttle waste management and food service. Personal hygiene, although it is essentially an intergral part of the waste management system, will be treated separately for the sake of clarity.

Waste Management.

The waste management systems currently being considered for space shuttle applications are:

1. A collection bag and storage technique similar to that used for Apollo missions,

2. A collection bag, inserted in a canister, with sufficient airflow to provide bolus detachment and entrainment. (In this case, storage will incorporate a sublimation chamber.)

3. An integrated collection storage container which may have sufficient capacity for a complete mission, or, if there is a space limitation, which can be removed when it is full and remotely stored.

The third of these systems, the integrated collection unit, could include a urine collector and could have the capacity to handle other wastes (wash water, used paper wipes, food containers, emesis, nail parings, and the like).

Whatever the system chosen, wastes must be collected and transported to storage and/or processing equipment in a manner such that they do not contaminate the crew and the internal environment of the vehicle. Waste must be treated to avoid the production of noxious gases and preclude the growth of microorganisms. Basically the problem revolves around the difficulty of collecting solid and liquid wastes in a zero gravity environment.

Up to the present, spacecrafts have employed a collection bag and storage device for fecal management. Both of these systems have met the requirements of environmental contamination control, but they have been aesthetically unacceptable and considered even by the astronauts to be marginally adequate (Berry, 1969). In addition, the capacity of the fecal control system has required that the amount of feces excreted by minimized through the use of low bulk diets and drugs. The drawbacks are obvious. Finally, the urine collection technique is appropriate only for use by males; SSV crew or passengers may include women (Pecoraro, 1971).

The second system mentioned above was developed for Apollo missions but has never been fully qualified. This technique has several advantages from the human standpoint in that airflow through the collection bag aids bolus detachment, provides for odor control, and facilitates control of bacterial growth since bagged feces are stored and vented in a compartment which sublimates the feces. Since the bag must be removed by hand, aesthetics problems still remain.

The human factors problems associated with fecal elimination and urination in space would be better dealt with by the third concept listed above, a collection and storage system more like the conventional toilet system used on earth. This system is currently under development for NASA. The collector uses an air entrainment approach for zero gravity collection of feces and vacuum dehydration of stored feces and other wastes. Airflow across the user's buttocks carries the stool into the rotating slinger of the device where it is shredded and subsequently vacuum dried. The same device could also handle urine collection, again operating on an air entrainment principle.

This integrated waste management system solves some of the problems inherent in presently used devices; it is applicable for use by both men and women and does eliminate manual treatment of waste. A prototype unit developed by General Electric has been tested in the NASA sponsored 60- and 90-day manned tests of an integrated life support system. Although it has proved satisfactory from an engineering standpoint, it has still not met all human factors requirements. During the 60-day test, crewmembers found the toilet system satisfactory only after the unit had been adapted by the addition of a standard hinged toilet seat. This modification is acceptable in a 1 G environment but unacceptable in zero gravity where the orifice of the commode must be kept as small as possible. Further, when crewmembers were asked at four separate times during the test to rank factors potentially contributing to annoyance, toilet facilities were rated seventh highest on a list of nineteen items (McDonnell Douglas, 1968). The use of the commode device in a zero gravity environment additionally requires application of some sort of sealant material between the buttocks and the orifice of the device to control odor. Here again, the influence on acceptability is obvious. Finally, the use of a sit-down type device for fecal and urine elimination in zero gravity would probably require some sort of restraint system which, like all other aspects of the total waste management system, must be acceptable from the user's point of view.

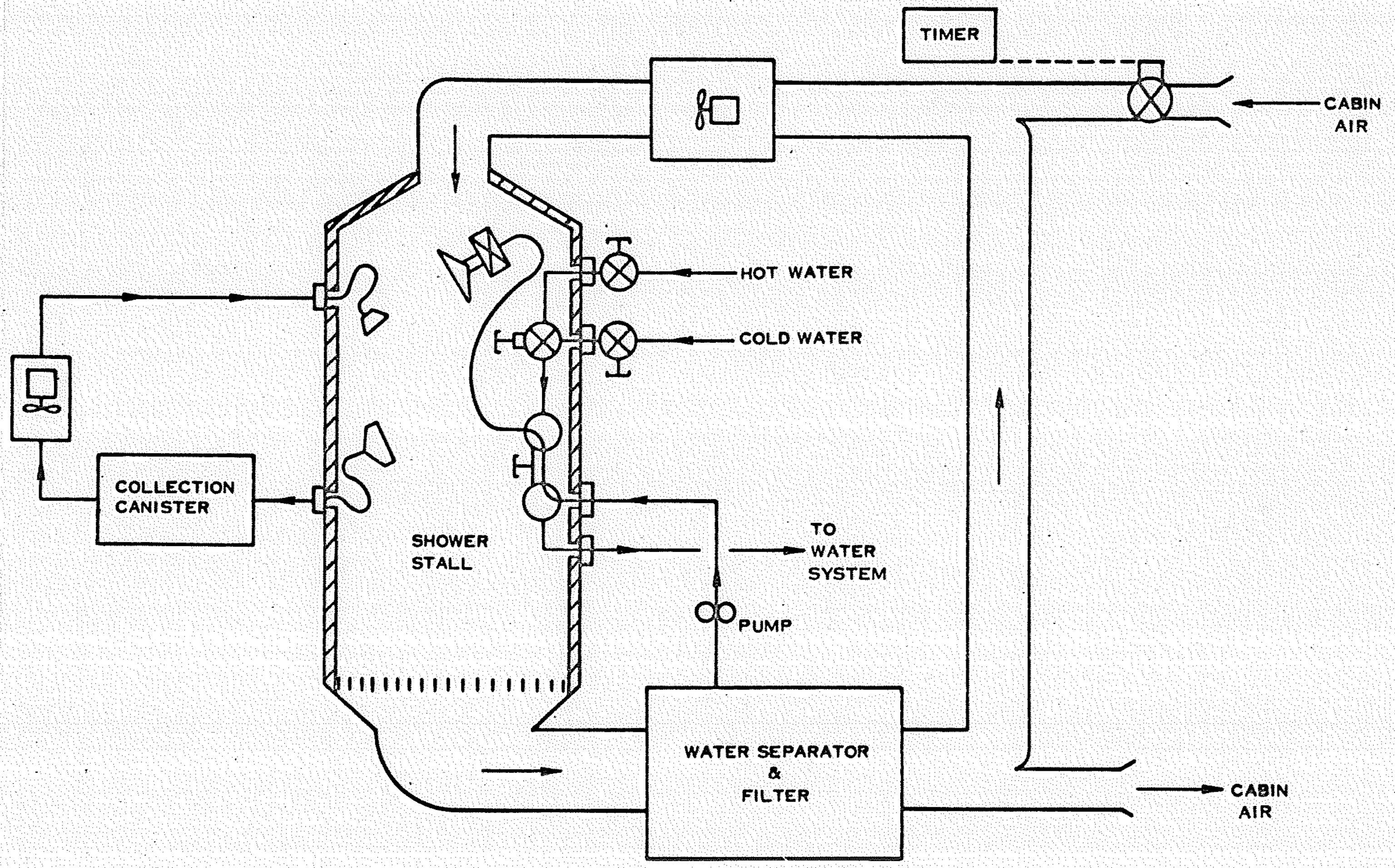
Personal Hygiene. The personal hygiene aspect of waste management in closed environments has psychological overtones which are significant above and beyond the medical implications of cleanliness. Although there is very little question of diseases of the skin or body orifices from lack of cleansing in the time periods being considered for space shuttle missions, emphasis on this area of human factors is nevertheless very important from a morale standpoint. Gemini VII astronauts, for example, looked forward with a good deal of relish to the opportunity to have a "hot shower" on their return. In our cleanliness oriented culture, attention to hygiene in space shuttle missions would, additionally, provide a very much needed link with earth-bound patterns and attitudes during stays in space. Careful attention to the hygiene provisions would contribute not only to the degree to which members would find space shuttle missions acceptable but might also provide some alleviation of the sense of isolation from the familiar world.

Fraser (1968) suggests that the prime requirements for maintenance of personal hygiene are : (1) adequate supply of water, (2) adequate supply of cleansing agents, and (3) changes of clothing. Providing these items is basically a matter of logistics and engineering, which falls outside the realm of discussion. However, the manner in which cleansing facilities are provided does have relevance for the human factors aspect of life in space. The value of personal hygiene and basic grooming, apart from a health standpoint, should not be overlooked for the psychological bonuses of comfort and a sense of well-being.

The principal technological problem related to personal hygiene is the selection of the optimum system for "bathing." Several approaches are available. First, and this is the minimal alternative, bathing could be restricted to selected body areas. Second, and ideally, the whole body could be cleaned. A third approach would be periodic whole body cleaning supplemented by selective cleaning.

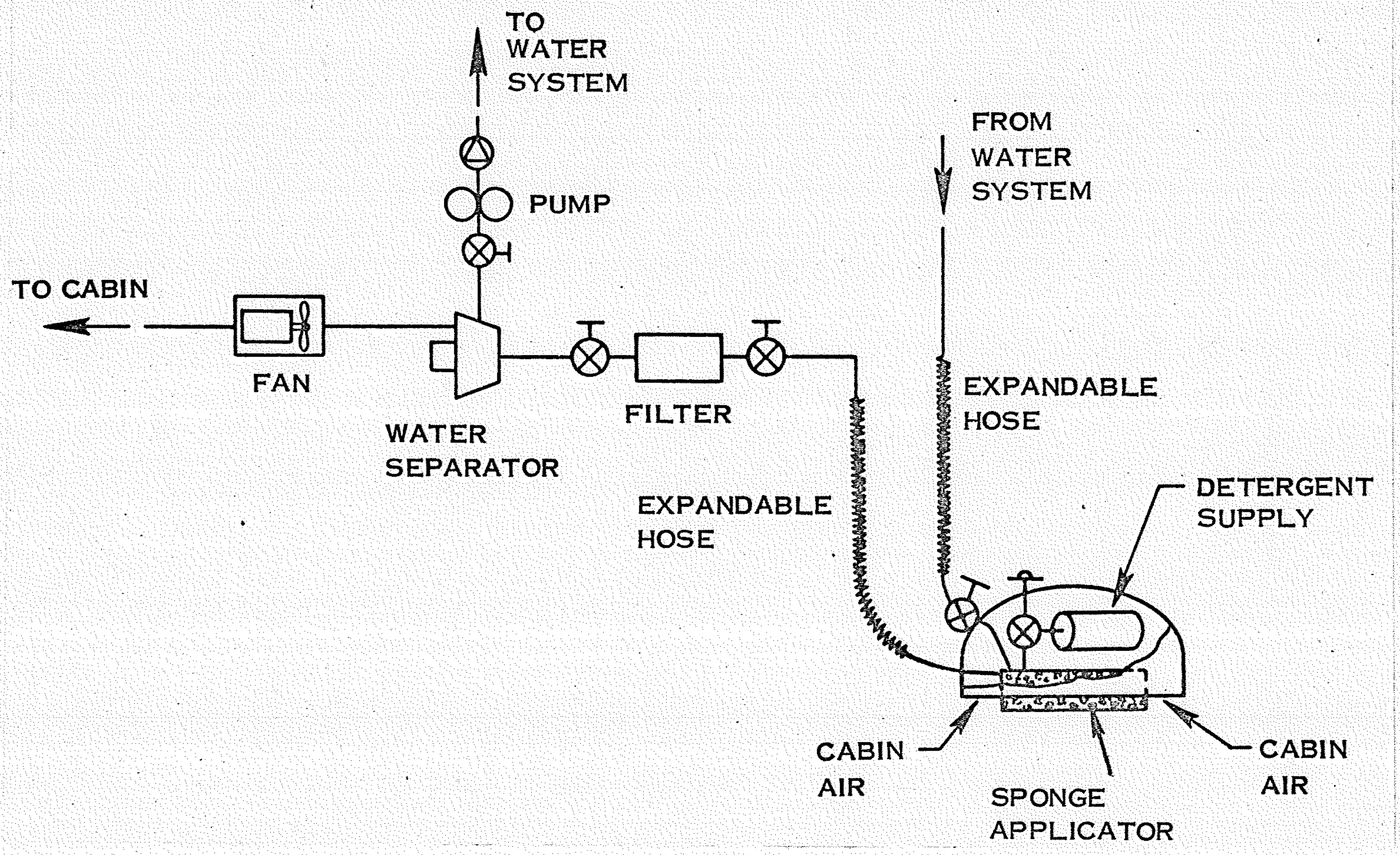
At present, the only practical way to clean small body areas in space flight is thought to be with reusable wet wipes, although alternatives such as bacteriastatic liquids and creams or ultraviolet sterilization do exist (United Aircraft, 1970). Wet wipes are a perfectly acceptable method and can be made more attractive by the use of fabric towels for drying (as was the case in both Gemini and Apollo missions). Earlier studies (Coburn, 1967) indicated that wash cloths were more acceptable to the user than chemically treated wipes. This approach would, however, not be feasible unless laundry facilities were available since these cloths become malodorous and dirty within a few days.

In view of the anticipated crew complement, undoubtedly the most suitable approach would be a whole body cleansing technique, ideally a shower. Figure 7 illustrates a representative shower concept for zero gravity application. There are other alternatives available, for example, an automatic sponge system (Figure 8). A shower system is, however, superior both from the point of view of effectiveness of cleaning and from the psychological standpoint. Showering provides simultaneous cleaning of the body and scalp and is so effective that it may need to be used only at three-day intervals (United Aircraft, 1970). From the psychological standpoint, showering provides a feeling of well-being and relaxation and represents for many an important link with the conventional earth-bound daily routine. The use of wipes treated with a pleasant smelling bacteriacidal solution could be used between the intervals of whole body cleaning. However, there may be toxicological effects from the use of bacteriacides in a closed environment.



(United Aircraft, 1970)

Fig. 7. Shower for space vehicle.



(United Aircraft, 1970)

Fig. 8. Automatic sponge for space vehicle.

There is every reason to believe that the use of wipes alone would be unsatsifactory from a psychological standpoint for missions in excess of a few days. For one thing, they do not permit washing of the hair or scalp. Further, this technique not only fails to provide a psychological boon, but may also become a chore since the effectiveness of cleansing depends upon the thoroughness with which the crewman uses the wipes.

Food Service. The preparation and serving of food during space shuttle missions is an area in need of significant attention. Food has long been known to serve as a positive motivating factor and must be viewed in that light, particularly for long term missions. During the Project Tektite studies, an ever increasing importance came to be attached to meal time activities. Dining became a major social event and was a time during which experiences of the day were shared and problems discussed. The act of food preparation itself became a major source of recreation for at least two of the four scientists-aquanauts involved in the first Tektite mission. The freeze-dried reconstituted foods used for previous space flight applications simply will not provide the positive reinforcement required for the individuals likely to be included in space shuttle missions. New approaches to the food service problem are needed. More variety is needed both in terms of specific items of food and forms in which these items are supplied (frozen, canned, freeze-dried, and fresh). In addition, varying preparation techniques (boiling, broiling, frying, etc.) and careful attention to an attractive serving system would add to overall enjoyment of the dining experience and contribute significantly to perceived habitability of the shuttle craft.

Implications for SSV Human Factors Program

The consensus among planners of the space shuttle program and industry personnel is that waste management, food service, and personal hygiene are the three life support areas most in need of attention and development of new technology in the immediate future. In other areas, according to the best information available at the NASA Langley Research Center (Osborne & Clark, 1970), "Technology exists for the design of components to accomplish life support functions for the shuttle orbiter..." The only remaining problem in this regard is "how to assemble components into an integrated system."

In the waste management and food service areas the level of requisite funding, the necessary facilities, and the required personnel still need to be defined. Strides are being made in this direction but much remains to be done. With the recent establishment of the environmental research facility at the NASA Langley Research Center, centralization of some of these efforts can be achieved. Further progress along the lines already identified (for example, the integrated waste management system) will undoubtedly result.

Clearer definition of the food technology issue is required in the light of the need for increased attention to sociopsychological variables. Cooperative efforts with industry, particularly in the food technology area, should receive greater emphasis. The Aerospace Food Technology Congerence held at the University of South Florida in April 1969 is an example of the sort of effort that will lead to progress. This conference was sponsored with the Apollo Applications Program in mind. A similar meeting in the near future, aimed at resolving the problems of food service in the space shuttle craft, might be extremely valuable. Meanwhile, new concepts in food preparation and service could be more extensively studied in conjunction with planned integrated system tests and in any number of simpler ground-based tests. Novel items of food or foods prepared by new methods could be evaluated relatively inexpensively in consumer preference studies.

Resolution of the problems in the area of personal hygiene will require a good deal of innovation. Thinking should not be restricted to conventional notions alone. Varied approaches, including new cleansing agents and new application techniques, should be pursued. If, after extensive study, only familiar approaches are viewed as acceptable by representative potential users, it may even prove desirable to consider come redesign of the vehicle or modification of the mission to accommodate the requisite system.

Although many adjustments can be made by the human operator to make a chosen system work more effectively, this is an undesirable choice. It is far better to design the system to suit the user than to restructure the user's habits and preferences to suit the system. This latter approach, simpler and expedient in the short run, has the built-in potential for sacrifice of human performance capability and compromise of the mission in the long run.

Problem Area No. 4:
Crew and Passenger Safety

Description

The safety of space shuttle crewmembers, passengers, and the vehicle itself will be attained through design features which make the catastrophic happening an extremely low probability event. Major functional elements will be designed for the most part to fail operational, fail operational, fail safe before total failure of the element occurs. Since mission abort procedures can be started with the failure of the first component, and a landing achieved in no more than a matter of hours, it is unlikely that the second or third component failure will occur in this short period of time. For example, loss of an engine during the boost phase will not prevent continued flight. Remaining engines will still have an adequate thrust-to-weight ratio ($T/W>1$) to achieve staging and orbital flight. In all, the design of the vehicle and the planning of appropriate abort modes should make SSV missions as safe as engineering can make them.

In view of the expected level of safety, an airline philosophy has been adopted with respect to SSV crewmembers and passengers. In the airline industry, operational and emergency procedures are predicated on the assumption that the crew and passengers are committed to the safety and integrity of the airframe (McDonnell Douglas, 1969). Whatever happens to the airframe also happens to them. Obviously, this philosophy rests on the belief, well substantiated by operational experience, that a high level of airframe safety can be achieved through rigorous design and inspection procedures for flight vehicles and through extensive training of crewmen. Under this philosophy, inflight failures of system components are presumed to be either noncatastrophic or controllable by appropriate alteration of inflight procedures. This being the case, special safety training and equipment for airline passengers has not been deemed necessary. The same general philosophy is guiding the design of the operational space shuttle. For early R&D flights, of course, intensive safety training will be given, and all reasonable safety equipment, such as ejection seats, will be provided.

The airline philosophy of safety has proven satisfactory and has resulted in many millions of hours of safe and comfortable flight for air travelers. On occasion, however, it has been necessary to adjust the philosophy to account for specific contingencies. For instance, in a landing accident at Denver some years ago a number of passengers died from smoke inhalation because of their inability to locate exits and get out of the aircraft promptly. As a consequence, the location of emergency exits is now pointed out to passengers before each flight, and passenger seats must remain upright during takeoff and landing in order not to impede passenger movement in an emergency. This is an example of the manner in which training and adjustments in procedures, however minimal, are effected to achieve greater safety. In this case, a number of avoidable deaths in an aircraft accident triggered the changes. In the SSV, it is reasonable to suppose that, through extensive study and simulation of scheduled missions, the appropriate safety training and procedures can be developed before the fact.

During the SSV development program, test crews will be provided with escape systems. In all likelihood, these will take the form of ejection seats for the two crewmembers. The escape rockets used in Mercury and Apollo will not be appropriate since there is no SSV crew module which can be separated, as was the case with the earlier vehicles. With the operational SSV it appears that only minimal escape capability will be provided.

Specific Human Factors Issues

In normal operation of the SSV, particularly during reentry and landing modes, the vehicle will be in a horizontal position. During launch preparations, however, the vehicle will be vertical. If the passenger-carrying capability is being utilized fully, occupants will be seated on a number of levels, one above the other. Should there be an indication of serious difficulty during launch preparations, rapid emergency egress from the SSV would be required and passengers should know exactly what to do and have every possible aid to egress provided for them. Airline experience indicates that the stress of the moment may degrade performance such that effective egress is impossible. Unless extensive training can be provided to passengers, it may be necessary to develop effective performance aids so that egress performance can be guided quite firmly through each step of the operation. Research is required to define the exact nature of these performance aids, or of any other techniques which might be used to insure that evacuation of the vehicle can be accomplished in an orderly manner and within a specified period of time.

Implications for SSV Human Factors Program

Planning related to the safety of SSV crewmembers and passengers should proceed in two steps. First, there must be a decision as to the exact philosophy which will be followed with respect to occupant safety. If automatic escape systems are to be used, passenger training and indoctrination will be straightforward and will deal only with the proper utilization of the system. If an airline philosophy is to be followed,however, it may be necessary to conduct fairly extensive simulation studies, using a full-scale mockup of the SSV in launch position, to determine the optimum combination of procedures, training, and performance aids to insure that rapid and effective egress can be accomplished when circumstances warrant.

Problem Area No. 5:
Role of the Crew in Mission Management and Subsystem Control

Description

Two key SSV development goals underlie the human factors problems discussed in this section. The first goal is to achieve maximum autonomy in SSV operations. Insofar as practicable, all mission control and vehicle control functions will be accomplished onboard the spacecraft, with minimum support from ground facilities. The second goal is to achieve a high degree of automation by means of onboard computers and prelaunch programming of mission and flight control functions.

The aim for autonomy will place extensive demands on the SSV crew and central computer complex for mission management and for ongoing monitoring and control of vehicle subsystem performance. The range of decisions to be made onboard the vehicle is expected to be considerably greater than in previous space flight operations, and the volume of data processed onboard will increase significantly. Unfortunately, with the focus of attention on automation of mission management functions and increased functional capacity of onboard computers there is a tendency to overlook the question of crew participation in these critical functions.

The general problem is illustrated by the frequent reference in SSV planning and preliminary design documents to the allocation of all essential control functions to a flexible and sophisticated automatic system, principally the Integrated Avionics System. When it is mentioned at all, the role of the crew is most often characterized by the term "monitor" and the more passive connotation of "watch-keeping" is usually implied. The crew is expected to oversee and manage the automatic systems which carry out control functions and regulate system operation. However, little consideration is given to the complex issue of control authority and to definition of the nature and degree of crew-computer interactions which will have to take place.

A related concern is the extent of SSV autonomy which is feasible and desirable, i.e., the extent to which mission control and flight management should be retained by ground facilities and personnel. As SSV mission assignments extend beyond that of a transport vehicle to include independent orbital observations and scientific experiments, additional consideration must be given to ground-based mission management in direct support of scientists/observers conducting onboard experiments.

Specific Human Factors Issues

There appear to be four critical human factors issues in this area. They are closely interrelated, and to avoid redundancy no attempt will be made to treat each separately. The issues are these:

1. To what extent is it realistic and practicable to assign mission management responsibilities to SSV commanders and control authority to the central computers without compromising the commanders' ability to carry out command functions and without limiting system performance?

2. Given a realistic assignment of mission management responsibilities to the crew, what specific data processing and display/control features are required of the system to support the crew in diagnosing mission-critical conditions and events and in making timely decisions or taking prompt action?

3. What levels and modes of override control should be available to the crew for effecting changes in ongoing, computer-controlled system functions? Selection of operating mode only? Manual augmentation of computer-controlled processes? Full manual control?

4. How will limitations and/or constraints on command pilot control authority (especially in mission-critical and life support/habitability functions) influence crew and passenger performance and acceptance of routine SSV operations?

Consideration of the first issue listed above is basic to any meaningful assessment of designs for the SSV crew station and subsystem interfaces, especially those now being evolved for the Integrated Avionics System. It is also basic to the resolution of the other three issues. Traditional approaches to system design and the allocation of man-machine functions are not adequate to deal with the issue of command responsibility and control authority in the SSV. For instance, it is realistic and practical to assign command and management responsibility to the SSV crew without giving them the means to exercise their authority except through partially autonomous data processors and automatic control devices? Command may reside in the crew, but who or what is really in control? This is probably an overstatement of the problem since, in even the most fully automated system, it is unlikely that designers will find it practical and crews will find it acceptable to delegate to machines the final authority for operations critical to mission success and occupant safety. However, stating the issue in extreme form emphasizes the basic point. The projected SSV designs call for a fundamental rethinking of the issue of automatic versus manual control. And as a corollary, careful attention must be given to the means for supporting the commander in his role of mission manager, including a clear delineation of the limits which the equipment design will place on his ability to perform.

Crew performance capability will be defined by the way in which issues two and three are resolved. The trends outlined in Chapter III of this report are toward the use of multifunction CRT displays, with provisions for flexibility in the selection of display formats and data content and with crew control of subsystem functions by means of general purpose keyboards and reprogrammable control buttons. This approach offers considerable latitude to the crew for system management. However, special attention must be given to the definition of specific crew tasks and information needs in system management if this potential is to be realized.

The degree of crew participation in system operation may range from active to passive. A more active role for the crew would entail such activities as assessing the ongoing flight situation with reference to mission and safety objectives, judging the character and significance of vehicle operating status, and exercising final authority with respect to subsystem configuration and operating modes. In a more passive role, the crew would simply monitor advisories or survey the consequences of actions commanded by the computers, and, on occasion, carry out prescribed and tightly constrained manual control actions. An appropriate level of crew involvement, with corresponding display and control support, should be established for each phase of the SSV booster and orbiter flight profiles.

Implications for SSV Human Factors Program

Definition of the role of the SSV crew in mission management and subsystem control will entail a careful analysis of how information is used by the crew in monitoring mission progress, in assessing the effectiveness of computer-controlled system functions, and in making decisions and taking action when out-of-tolerance conditions develop. This analysis should help to identify limitations of the crew's ability to process system data, thereby leading to more precise definitions of crew task assignments and to formulation of specific requirements for display support.

The aim of this analysis would be to develop an information processing model of the SSV mission management function. By means of this model it will be possible to distinguish crew task requirements which impose unrealistic performance demands and to identify crew activities which are especially vulnerable to degradation as a result of time stress or limitations in data available through the system. Analyses based on the descriptive model of crew information processing will disclose specific requirements for improved display support and/or crew control of the display function. Analysis will also identify elements of the mission management function which clearly exceed the crew's perceptual-cognitive abilities and must be assigned to the computers.

Examining these issues with an initial bias toward assigning system management responsibilities to the SSV command pilot is all the more important in view of the apparent readiness of system designers to assign all such functions to the central computers. This tendency has been noted in the development of centralized electronic management systems for the advanced jet transport aircraft (SST) and was summarized by one writer (Richardson, 1963) as follows:

> To anyone familiar with the extreme versatility of a digital computer, it becomes almost a case of self-hypnosis to allow it to absorb more and more functions until, without one realizing it, the supersonic transport will seemingly become a pilotless drone--almost a guided missile with human passengers. It therefore becomes necessary to apply judicious restraint to such enthusiasm, realizing that there must be a reasonable trade-off between the exact capabilities of a computer and interpretative ability of the human.

In the SSV, the versatility and data processing capacities of the central computer complex should be fully exploited. However, if this is done in a way that unnecessarily limits the crew's capacity to exercise their judgment and control options, the desired flexibility and safety of SSV operations may be compromised. An unbalanced assignment of management functions to computers may also lead to crew acceptance problems, particularly when the SSV emerges from the developmental and experimental phases and enters routine operational use. Lack of crew acceptance can lead to underuse and misuse of onboard systems and become and additional source of stress for the crew.

An optimum allocation of man-machine authority in system control and management can be envisioned as one that would allow crewmen to recognize and resolve decision problems as they arise during the SSV mission. The multimode CRT displays and flexible manual control provisions which are under consideration for the SSV could allow the commander to deal with emerging problems and to act in accordance with both the demands of the situation and his own problem solving strategies. Human factors analysis and empirical studies will be needed to determine the extent to which this concept of a more active crew role can be adopted for the SSV and to define the hardware and software required for its implementation.

Problem Area No. 6:
Pilot Monitoring and Vehicle Control During Recovery Operations

Description

The flight segment of interest here is the post-reentry descent from an altitude of approximately 100,000 ft and the subsequent terminal area maneuvering, approach, and landing. Potential human factors problems addressed in this section include determining the primary flight control modes for this flight segment, the impact of powered versus unpowered flight on crew task requirements and acceptance attitudes, and display requirements for low visibility (IFR) operations. With certain exceptions which will be noted, the discussion is applicable to both the booster and orbiter vehicles.

To facilitate the discussion, a brief overview of the recovery flight sequence is given below. For each phase of this flight sequence, the general flight conditions are indicated, alternative vehicle control techniques are described and the principal uncertainties in operational procedure (e.g., the terminal area guidance scheme to be adopted) are identified.

A generalized recovery flight sequence is shown in Figure 9. For convenience, the recovery sequence is partitioned into four overlapping phases:

Maneuvering Descent - deceleration and energy dissipation maneuvering down to a preselected "high key" point for initiating an approach to the runway.

Initial Approach - continued descent and energy management maneuvering to position the vehicle on the desired glide path and align its direction of flight with the runway centerline.

Final Approach - maintaining runway alignment and descent on the glide slope toward a preselected aim point for initiating the landing maneuver.

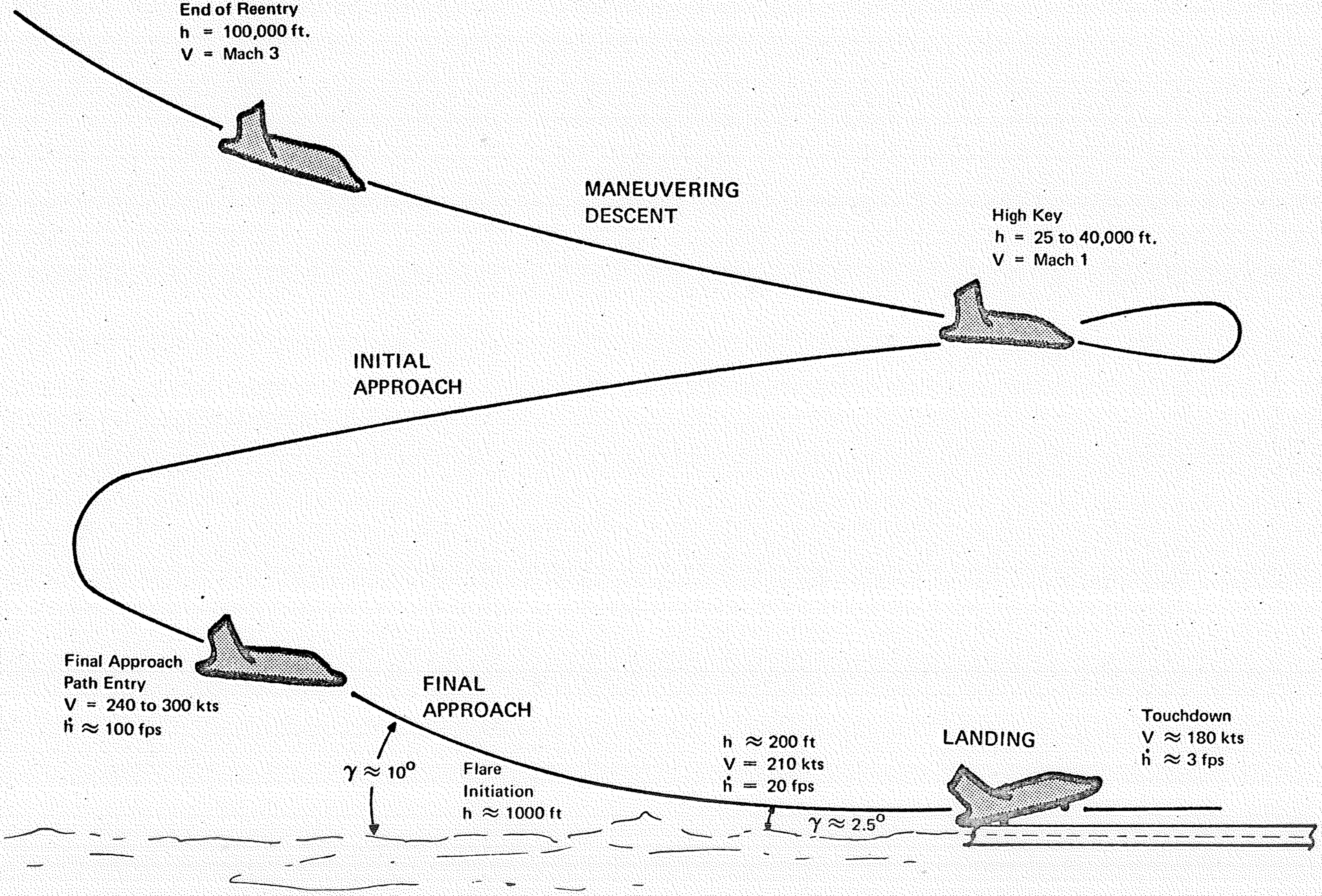


Fig. 9. Generalized recovery flight profile.

Deceleration and Touchdown - initial flare to a shallow glide path and subsequent deceleration and execution of the landing maneuver to touchdown at a desired point on the runway.

The initial conditions for the Maneuvering Descent phase have been established as a height of 100,000 ft and a velocity of about Mach 3. These conditions represent a somewhat arbitrary point defining the completion of the reentry maneuver and an initiation point for the recovery operation. At the outset the vehicle will maintain the very high angle of attack established for reentry. The maneuvering required for attaining the desired heading toward the landing site will be accomplished by bank angle modulation at a constant angle of attack. The vehicle will descent at maximum L/D, continue to decelerate and execute a transition maneuver to establish an optimum angle of attack (stable trim attitude) for subsonic flight.

During the descent, guidance and navigation functions must be integrated with energy management to bring the vehicle to a selected offset point for initiating the approach to the runway. This point will be referred to as the "high key," and its height and position relative to the intended touchdown point can be expected to vary as a function of prevailing visibility and wind conditions, the ground guidance system being used, and the energy management techniques adopted for the approach. Baseline conditions assumed for this discussion include power-off flight throughout the recovery profile and unrestricted visibility conditions. The special requirements of power-assisted operations and IFR flight will be examined as extensions to this baseline situation.

The initial approach will be planned with the primary objective of dissipating excess energy in the form of either altitude or airspeed and arriving at a stable "low key" position from which a smooth and consistent approach pattern can be flown to position the aircraft for the final straight-in approach. Operation of the vehicle on the front side of the L/D curve to provide sufficient excess energy for good controllability margins is preferable throughout the approach, as indicated by the following comments from a pilot in the lifting body flight test program (Dana, 1970):

> We want to position the vehicle on a flight path or dive angle to intercept a preflare aim point on the ground. This task is minimized by using a relatively steep approach (10° to 25°)... Our whole pattern, then, is just a means of establishing ourselves on this flight path. Because we generally fly well on the front side of the L/D curve, we never plan to be, and seldom are, short of energy. We modulate this energy by slowing or accelerating, or we can remain at approximately the same speed and use speed brakes to alter our flight path as required.

The latter portion of this statement describes the energy management techniques employed during unpowered flight. These include flight path maneuvering, adjustment of airspeed and/or angle of attack, and the judicious timing of speed brake deflections. Once the vehicle has stabilized on the final approach, only minor adjustments should be required to maintain the desired flight path toward the aim point and to compensate for wind effects.

The steep initial glide path angle shown in Figure 9 and the high airspeeds anticipated for approach (250 to 300 K) will necessitate that the initial aim point to be set some distance back from the intended touchdown point on the runway. In lifting body operations, using indicated airspeeds of 270 to 300 K on final, this point is approximately 1.5 miles short of the runway. At an altitude of 700 to 1000 ft above the runway, a flare will be initiated to begin decelerating to landing speeds and to establish a more conventional glide path of about 3°. The subsequent landing maneuver will be executed by establishing an appropriate landing attitude, decreasing rate of descent, and "flying" the vehicle onto the runway.

The use of airbreathing turbojet engines which could be ignited during this recovery sequence to provide a limited-duration power assist or for a fully powered approach and go-around capability is a significant unresolved issue.

As indicated in Chapter II, this capability has been specified for the SSV and is included in preliminary vehicle design concepts. It has been suggested that this requirement be set aside because of the weight and complexity penalties associated with incorporation of multiple jet engines and fuel reserves and because of recent demonstrations of the operational advantages of unpowered flight operations.

The argument for unpowered recovery operations has been concisely stated in a recent symposium at the NASA Flight Research Center (Thompson, 1970):

> We are not proposing that you eliminate landing engines or a go-around capability. If you, as designers, program managers and users, decide that you can afford landing engines or need them for any other purpose, you should certainly include them. Even our experienced pilots would not reject the engines if they were flying the shuttle; however, they would refuse to rely upon them to make a successful approach and landing. The shuttle, whether it has landing engines or not, must be maneuvered, unpowered, to a point near the destination because the engines cannot be started until the vehicle is subsonic and only limited fuel will be available. To us it seems ridiculous to maneuver to a position where power must be relied upon to reach the runway. Instead, we would maneuver to a high key position to begin an unpowered approach. Then, regardless of whether the engines could be deployed, started, and kept operating, a successful approach and landing could be made.

Another significant uncertainty in SSV recovery operations is the type of terminal area guidance system and landing aids which will be available, particularly the ground-based guidance system for low visibility approach and landing. Current specifications call for an automatic landing system which will satisfy FAA Category II (1200 ft runway visual range) requirements. Among the systems under consideration are the conventional Instrument Landing System (ILS), Advanced Integrated Landing System (AILS), the carrier-based SPN-42, and the Remote Control Recovery System (RCRS) which was developed to guide an unmanned X-20 to an automatic landing. System concepts which are less dependent on ground facilities, such as a blended radio/inertial navigation system to synthesize reference flight paths on board the vehicle, also are being investigated.

The terminal area guidance system adopted for SSV recoveries will be an inportant factor in determining the pilot's role during this flight segment. At FRC, integrated energy management and approach patterns have been flown manually by instrument reference. These guidance schemes have proven feasible with minimum inputs from ground facilities, e.g., onboard processing of relative position data (VOR, DME), azimuth and elevation angles from ground radar, and flight path advisories from precision approach radar monitors on the ground (GCA technique) (Schofield, 1970). These techniques entail more extensive participation of the pilot in vehicle guidance and control tasks. On the other end of the continuum, Sperry is investigating an automatic flight control system (AFCS) that provides full automatic control of energy management at high altitude and an optimized final approach, flareout and touchdown trajectory (Osder, 1970). In this system, manual control modes would be of questionable value except in extreme situations (e.g., multiple AFCS failures or mission aborts).

Specific Human Factors Issues

The requirements for SSV recovery operations bring into focus a number of potential human factor problems. Unfortunately, the human factor issues are currently embedded in a shifting context of uncertainties concerning AFCS mechanization concepts, the character and availability of ground guidance, and the extent to which low visibility operations are necessary and practicable. As a result it should be understood that the issues discussed here, are, in some instances, based upon preliminary system requirements and design concepts which may be revised in the near future.

1. Definition of manual control modes. Fully automatic guidance and control capabilities have been specified for the SSV throughout the recovery profile, with the implication that this will be the primary operating mode. Without minimizing the advantages of providing this capability, there is reason to believe that manual control may offer greater flexibility in the application of high altitude energy management techniques and in the judicious execution of initial and final flareout trajectories. In addition to reducing the severe demands placed on the airborne system for guidance computations, the adoption of manual control techniques for routine SSV operations may produce more positive pilot acceptance and insure that critical manual flight control skills are not lost or degraded through infrequent exercise.

The suggestion that manual flight control techniques be investigated for routine recovery operation is based in part on the assumption that, for most approach and landing sequences, external visibility will be essentially unrestricted. However, the feasibility of manual control by instrument reference has also been demonstrated for Category I IFR conditions. Recovery operations under Category II visibility conditions are clearly not considered to be routine, and perhaps this capability can be provided by augmenting onboard SSV systems with appropriate ground-based guidance.

Whether or not manual control is adopted as a primary or routine operating mode, more explicit definitions of manual "backup" or "override" control modes are needed. Are mixed automatic-manual control modes (e.g., force wheel steering) or split-axis control techniques necessary or desirable? Should pilot intervention in the flight control loop be precluded except in case of multiple AFCS failure? What are the minimum guidance computations required for manual execution of such critical maneuvers as the transition from hypersonic to subsonic flight or from the steep, high energy approach to a conventional glide path and landing attitude?

2. Manual flight control techniques. In support of the manual flight control capability during the Maneuvering Descent phase, the issue of optimum control techniques for integrating energy management with terminal area navigation must be addressed. As vehicle configuration specifications become more firmly established, such issues as hypersonic maneuvering techniques for the high cross-range delta configuration and the definition of approach patterns best suited to the contingencies of energy management can be resolved. It is important that the requirement for navigation from the "end-of-reentry footprint" area to the high key position be considered at the same time.

The onboard inertial navigation system, operating with radio navigation aids in the terminal area, can generate glide path commands to any designated point and provide displays of distance (range), bearing, glide path, and course deviation relative to a set of ground-reference positions. Flight simulations of SSV approach patterns have demonstrated the feasibility of a variety of circular and spiralling descent patterns for executing unpowered approaches without placing excessive demands on the pilot (Schofield, 1970). The implications, in terms of pilot workload and display requirements, arising from this kind of flexibility in approach technique for the SSV should be further examined.

3. Display requirements for low visibility operations. The proposed set of SSV crew displays, using multiple CRT units and a possible head-up display, appear to provide the basic devices needed for all phases of the approach and landing sequence. However, careful attention to pilot information requirements for both situation assessment and flight control tasks will be necessary to assure that this basic display capability is properly exploited. For example, studies of flight management performance during low visibility operations in jet transport aircraft (Gartner, 1970) have shown that conventional display content (including display elements which might be reformatted and presented on electronic attitude director indicators) is not adequate for

accurate monitoring and assessment of an automatically controlled approach under Category II visibility conditions. Additional display support problems are envisioned when the requirements of transitioning from monitoring to active, manual flight control are considered.

During low visibility operations under automatic control, the SSV pilot must be able to assess continuously the ongoing flight situation in such a way that he is ahead of the vehicle and can anticipate critical events. Moreover, he must be equipped to exercise control authority over the AFCS on the basis of his assessment and to take corrective action at any point in the approach. The critical resource underlying these performance capabilities is the information the pilot is able to extract from his flight instruments. Current studies of this problem indicate that special purpose display elements, such as pictorial runway perspectives, flight path angle and potential flight path angle, aiming points, and reference flight path alignment cues, may be needed.

With respect to the head-up display (HUD), additional study is required to determine its potential utility and application to the SSV recovery operation. It is being proposed as an aid for monitoring the low visibility approach, but problems with field of view limitations, scale factors,and registration of HUD symbology with elements of the external visual field may argue against this application, especially for the delta wing vehicle. An important HUD application which should not be overlooked, however, is its potential utility as an aid to more precise monitoring and control during VFR operations. The HUD concept was initially developed to aid flight control by visual reference. It may also prove to be an excellent aid for assessing the effectiveness of energy management throughout the SSV recovery profile and for more flexible control of the steep approach and flare maneuver.

Implications for the SSV Human Factors Program

The foregoing delineation of human factor issues establishes a requirement for an integrated analysis of crew factors in SSV recovery operations -- an analysis designed to influence the final SSV configuration and design of the Integrated Avionics System. Separate studies are in progress or being planned at major NASA research centers to examine flight control and guidance system design requirements. All of these efforts would be directly supported by, and contribute to, a widely coordinated and integrated effort to resolve the issues raised here. To guide the individual efforts of the NASA centers and to provide a frame of reference for evaluating the SSV design there is a need for a common understanding of the pilot's role, the implications of powered and unpowered flight profiles, the guidance schemes for energy management and flight path control, and the impact of low visibility operations.

The more ambitious aim of this analysis would be to establish a generally accepted position regarding crew participation in the flight control function. Designers concerned with the crew-vehicle interface should not treat this consideration as a "philosophical issue" or as an after-the-fact rationale for vehicle and/or subsystem design features adopted on other grounds. It is anticipated that agreement can be reached on the most effective utilization of the crew in achieving recovery operations objectives and that the following goals can be realized:

1. Operational effectiveness in both manual and automatic modes, accepting some increase in crew workload and degradation of accuracy in manual modes.

2. Smooth transitions from fully automatic to semi-automatic and augmented manual control modes, with minimum disruption to ongoing crew information processing.

3. Maximum use by the crew of onboard digital computer flexibility and display generation capabilities.

4. Crew and passenger acceptance of routine operating modes and environmental conditions.

Problem Area No. 7:
Man-Computer Interface

Description

The SSV will be a highly computerized system. The system is so complex that preprogrammed control of a wide range of operational processes is the only reasonable approach. This will be accomplished by what is generally referred to as a "data management system." The basic system processes of flight control, guidance and navigation, propulsion, communications, life support, onboard equipment maintenance, etc. are each carried out by an array of semi-independent computers and data processors which themselves must be controlled by a central management computer.

In contrast to some types of man-machine systems, space vehicles in general and the SSV in particular can be characterized as requiring intermittent rather than continuous control over all subsystems. This means that at different stages of a mission, different functions and, consequently, different subsystems, are the main focus of attention. This characteristic permits some latitude in the allocation of control responsibility between man and machine. Specifically, the responsibilities of the human operator can be concentrated in the domain of subsystem management rather than direct process control. The concept of subsystem management then becomes a basic determinant of the design of the man-computer interface.

Specific Human Factors Issues

The key problem from a functional standpoint is data management in an autonomous, or near-autonomous, mode of operation. The purpose of data management is, of course, system control. Thus, from a human factors standpoint, the issue is: who shall control what and how? To the engineering criteria of weight, space, reliability, and cost must be added the human factors criteria of performance effectiveness and user acceptance.

It is recognized, of course, that performance is a total engineering concern. At the same time, it is well known that a component that may perform superbly at the component level can still be a source of degradation to overall system performance. This proposition is certainly true of man as a functional component; even highly competent operators can err. The proposition is also true when a man-equipment combination is regarded as an assembly since there are always possible mismatches between the two constituents. Mismatches can result, for example, when use of the equipment requires responses which exceed the capabilities of the operator.

How well an equipment item performs quite naturally influences its acceptability. However, good performance is in itself no guarantee of acceptance. Consequently, design for user acceptance must also be stressed. Although the user may be persuaded to revise his view, it is surely preferable for original design to preclude this need. Specifically, the data management system for the SSV should be designed, if possible, so that operators will not only accept it but approve it enthusiastically. The computerization of control functions in conplex systems is a general trend, and the SSV design effort reflects this trend. However, not everyone is convinced that the trend is universally beneficial, and experience in fields such as air traffic control illustrate the prevalence of this skepticism.

Implications for SSV Human Factors Program

Design of Controls and Displays. Displays and controls are the critical man-machine interface point. Engineering and logistics criteria seem to demand multipurpose items at this point. That is, a single display device such as CRT can, and probably should, be used to convey a wide variety of information in as many formats as possible. Similarly, to economize space a keyboard type control device should be employed such that subsets of keys have different meanings at different times.

However, operator response to such mulitpurpose assemblies is always problematic for several reasons. First, it is easier and quicker to scan an array of dedicated displays selectively than it is to call up several wanted items of information in sequence on a single display. Second, there may be instances when the operator wants to make a simultaneous, direct comparison between two sets of data that can only be obtained sequentially on a multipurpose display. Third, operators believe that there is a greater probability of error with a multipurpose display than with a dedicated display. Similar opinions are often expressed regarding multipurpose control. Jacowitz and Poupard (1970) stated that multiplexing of flight control commands presently exists in at least one system, the Saturn system. However, they point out, "there appears to be reluctance to accept multiplexing of critical commands even though there is no technical justification for this reluctance."

Research of the following types seems to be needed:

1. <u>Task demands and information requirements in all mission phases.</u> Some compromises might be possible in the configuration of displays, e.g., dual multipurpose displays for side-by-side comparisons. Similarly, keyboards could be designed so that different modes of operation were strongly differentiated. A master keyboard might be permanent but each major subsystem could have a different keyboard.

2. <u>Operational effectiveness and user acceptance of displays.</u> Traditional human engineering, usually performed after the system has been designed and the breadboard equipment developed, has been applied as if man were rational and it were necessary to consider only such aspects of man as his perceptual and motor capabilities. It is, however, equally important to consider man's fears, anxieties, preferences, and aspirations, as part of the design effort. What is necessary is the utilization of data on human attitudes toward the automation of specific systems and the development of additional such data where needed.

This will permit operator acceptance factors to be incorporated as criteria in trade-off analyses, which customarily include only a consideration of performance capabilities, cost, and reliability of man and machine components. It may be found, for example, that automation of particular system fuction, justifiable for engineering reasons, would not meet with user acceptance, which would probably negate the anticipated advantages.

Software Design. New concepts and applications are on the horizon. The guiding principle is "query controlled programming" which means that the program specifications are derived from the content of operator queries rather than from the characteristics of the hardware. In concert with the study of task demands and information requirements suggested above, another study task should be to consider the context and syntax of the operator's information requests in the mission setting. Some variations of conventional mission simulation method might be an appropriate technique. For example, suppose the operator were requested to state each item of information he needs or to indicate each display he consults while he is actually carrying out a task. Experimentation of this kind would be admittedly artificial, but it might bring some otherwise overlooked factors to light.

Remote or Onboard Data Management. A review should be made of effectiveness and user acceptance of analogous systems employing remote and local data management. In particular, the use of so-called data-link in air-ground-air communications should be examined. Anecdotal evidence suggests that the substantial advantages in economy and reliability attainable through data-link equipment in aircraft were discounted by users. On the other hand, the ground data management in space flights has proved to be of substantial value in lightening workload and in solving unanticipated problems. Recent aerospace experience should be collected and brought to bear in the SSV development program.

Problem Area No. 8:
Flight Deck External Vision

Description

More than any other space vehicle to date, with the possible exception of the Lunar Module, the space shuttle will require extensive external vision for crewmembers. Morris (1970) stated that the basic mission phases requiring external vision are launch abort (backup), docking, orbital inspection, atmospheric cruise, and landing. The latter two, according to Morris, will require the largest visual envelope.

Proposed configurations for the SSV will provide window areas more like those of airliners that of other space vehicles. For an aircraft such as the 747 transport, the window surface area is 29.5 square feet. This contrasts with the 3.2 square feet of window surface area found in the X-15 aircraft and the 2.4 square feet of surface for the two forward windows of the Apollo Command Module (Carpenter, 1970).

If the window surface area for the orbiter SSV approaches that of the 747, and initial industry designs indicate that it might, certain problems must be faced. Paramount among these is the possibility of window failure as a result of thermal and structural stress encountered during reentry. Failures of this type were found in flight of the X-15 aircraft, a vehicle which served as a prototype for the development of a reusable space shuttle system. In a total of 199 flights conducted during the X-15 program, window failures occurred in five (Carpenter, 1970). In discussing these failures, Carpenter noted that for larger window areas, such as contemplated for the SSV, greater thermal expansion and distortion of the retaining structure can be expected, and the potential for glass failure is increased. Therefore, to minimize complexity and weight, he recommended that a small viewing surface be used in the shuttle vehicle. This, of course, will restrict the external visual field. Carpenter also noted that the potential for window failure requires a backup method for outside viewing in case visibility through the windshield is lost or partially obscured.

Specific Human Factors Issues

For vitually all mission phases of SSV operations, both the pilot and co-pilot should have out-the-window viewing comparable to that from high performance aircraft. However, structural factors may preclude the use of windows large enough to provide the desired external vision. This being the case, there are two problems which require considerable study to support design decisions:

Visibility Envelopes. It is generally acepted that the need for external vision will be greatest during flight through the atmosphere (low altitude cross-ranging) and during landing operations. Any reduction in what is considered normal or necessary visibility during these stages may result in flight control problems and most assuredly will meet with objections from flight crews. Therefore, if window area is to be reduced, it must be done so that the critical visibility envelope remains intact. However, this envelope has not as yet been defined, although it is known that during the landing phase it must include the horizon, runway aim point, runway edge surfaces, and threshold lights and markings. Sufficient visibility must be retained so that these elements, at a minimum, can be observed during the entire landing approach. It is not known to what extent motion parallax cues (provided by the apparent movement of the surface and objects on either side of the runway) will be required. The critical character of the SSV landing operation requires that the necessary visibility envelope be defined with reasonable precision.

Visibility Backup System. In the event of failure of an SSV window surface, there may be the option of relying on an automatic mode for many activites. For instance, rendezvous and docking might be accomplished by an automatic system. However, it is doubtful whether pilots would be willing to rely on a fully automatic landing system. At least, they would desire some means for visually monitoring the landing dequence, combined with a manual override capability in the event the landing did not appear to be satisfactory. Suggested methods (Lockheed MSC, 1969) for providing backup visibility systems include:

Porthole
Periscope and Mirror
Cathode Ray Tube Presentations
Projection Display Presentations
Fiber Optics Presentations

At present, all of these methods must be regarded as candidates. Much work remains to be done, however, prior to selection of a specific system or technique. First, the system must be evaluated for its basic effectiveness as a backup device and problems involved in its use. This evaluation should include variables such as three dimensional presentation quality, image clarity, distortion, light loss (optical systems only), brightness contrast, glare effects, locations in the pilot's work space, field of view, crew acceptance, and general reliability. Next, the system must be examined in terms of specific problems which might arise in adapting it to the SSV configuration.

Implications for SSV Human Factors Program

The problem of defining external visibility requirement for the space shuttle vehicle is being studied intensively at this time at the NASA Flight Research Center, Edwards, California. Since this work is proceeding concurrently with the development of final shuttle designs, it would seem the most important issue is one of maintaining continuous communication channels between the FRC program and industry design efforts. The FRC work, using test pilots who are candidate SSV crewmembers, will be of great importance both in developing a quantitative index of the required visibility envelope and in determining pilot acceptance for reduced visibility or alternative visibility devices.

Plans at the Flight Research Center call for the development of a scaled version of the orbiter vehicle (mini-shuttle). It is believed that flight testing of the subscale space shuttle would aid in the early detection of problems in aerodynamic control system design, material selection, subsystem integration, and vehicle performance. The flight test program of the mini-shuttle affords an excellent opportunity to test backup modes for providing external vision for crewmembers in the event of window failure. A test program of this type should be pursued vigorously.

Problem Area No. 9:
Personnel/Cargo Transfer

Description

Two of the important features of the space shuttle are utility and economy. These will be achieved through the reusability of the vehicle and its load-carrying capability. In all proposed shuttle missions, personnel/cargo transfer is involved to some degree. Figure 10 shows proposed SSV missions and the type of cargo which will be carried in each. It can be seen that missions range from the delivery of cargo and personnel to a Space Station/Space Base to the placement, retrieval, and maintenance of satellites (Beasley & Lewis, 1970). The cargo will vary from small packages transferred through hatches and tunnels to bulk liquid transfer to a fuel storage area using techniques similar to aerial refueling. The two most frequent missions are delivery of propellant and logistics support for the space station, which involves the transfer of

Mission Cargo	Space Station logistics support	Delivery of propulsive stages and payloads	Delivery of propellant	Short duration orbital missions	Rescue	Satellite placement and retrieval	Satellite service and maint.
• Personnel							
Crew	x	x	x	x	x	x	x
Passengers	x	x			x		
• Large equipment	x	x		x		x	
• Specialized use kits	x	x	x		x	x	x
• Dry container cargo	x	x			x		
• Liquid and gaseous cargo (small tanks)	x	x			x		x
• Bulk liquids			x				
Mission Frequency %	39	9	44	4	-	2	2

Fig. 10. Shuttle personnel and cargo transfer mission and cargo types.

several types of cargo. Other missions, while significantly less frequent, are of importance to the overall shuttle usefulness.

An examination of SSV missions shows that the transfer of personnel and/or materials is an integral and probably the most important feature of the shuttle program. In order for the transfer function to be accomplished effectively and expeditiously, techniques must be developed and perfected before the operational program begins. Beasley and Lewis (1970) stated that the required investigations should consider potential cargo sizes and volume, shuttle and space station configurations, cargo handling techniques and aids, cargo module docking and transfer techniques, operational constraints and -- by no means of least importance -- man's capabilities.

Specific Human Factors Issues

Manual Cargo Transfer Potential. Plans call for shuttle personnel to be directly involved in the trasnfer of cargo. Loats and Mattingly (1971) stated that evidence from human factors experiments and studies indicates that in weightlessness man's capability for manual cargo transfer is severely limited. Although information from previous space missions verifies the capability of man to move around inside a space vehicle and to transfer small packages, it is obvious that his ability to move cargo will be degraded as packages become larger. The major questions to be answered in support of the cargo transfer portion of the shuttle program are:

1. What are the limits of manual cargo transfer?
2. By what method is this determination to be made?

Cargo Transfer Aids and Equipment. Since shuttle crewmen transferring cargo will be operating in a weightless environment, aids to mobility will be required. Cargo can only be moved if some means is provided for the crewmen to exert the required force. Mobility aids will include hand rails, traction grips, fasteners, and any other technique by which force may be applied. However, these techniques must be developed and evaluated in terms of the specific size and shape characteristics of shuttle cargo as well as the configuration of transfer tunnels.

As cargo packages grow in mass or volume, manual handling may no appropriate. Cargo transfer would then have to be effected by powered transfer devices such as teleoperator systems. Here the need is for work to determine the optimum type of power equipment and the most effective man-machine interface to allow for control of the system by a crewmen.

Implications for SSV Human Factors Program

The issue of crew activites in SSV cargo transfer operations is quite important. Movement of cargo and personnel must be accomplished expeditiously if the shuttle program is to be considered successful. NASA management personnel are well aware of the importance of this topic and have begun an intensive program of analysis and experimentation in order to develop optimized procedures and techniques. The Langley Research Center is developing full scale mockups for use in the LRC water immersion facility and the Rendezvous Docking Simulator (Beasley & Lewis, 1970). The initial water immersion mockups will include a 15 by 30 ft segment of the cargo module with all of the various airlocks, hatches, and tunnels proposed by Phase B contractors. Studies in these facilities will evaluate the adequacy of the proposed sizes and configurations and will help develop operator techniques and job aids. Subsequent parametric evaluations will examine the effects of volume, mass, and moments of inertia on cargo transfer and help establish cargo configuration and sizing criteria.

The Marshall Space Flight Center is constructing a representative cargo transfer tunnel mockup for use in a simulator with air bearings. Cargo packages attached to any of several proposed transfer devices (such as monorails and trollies) can be supported on air bearings and transferred through the tunnel with minimum friction. Included in the Marshall studies will be analyses of man's capability to maneuver large packages in zero gravity (both unaided and with mechanical assists), crew stability/mobility requirements, interface requirements for transfer mechanisms, and similar man-system criteria (Beasley & Lewis, 1970).

The Langley and Marshall centers have excellent simulation facilities for comprehensive programs to investigate cargo transfer. No additional efforts of this type appear warranted. The only reasonable extention of these programs would be in the form of tests which might be conducted in the Skylab program which would validate the simulation data under conditions of actual weightlessness.

CHAPTER V

SUMMARY AND CONCLUSIONS

The space shuttle vehicle is a new type of spacecraft, one which puts man in a new operating environment and places new demands on his capabilities. To insure that man will operate successfully as an element of the shuttle system, one must understand the man-machine interfaces and the human factors issues posed by each. The objectives of this project were to study the man-machine interfaces in the space shuttle system, to describe potential human factors problems, and to identify advances deemed necessary in human factors technology in order to resolve these problems.

Based on a detailed examination of the space shuttle program, combined with interviews with government and industry personnel, nine major problem areas were identified. These are listed in brief form below, along with a statement of the implications for the SSV human factors programs. In many instances, these implications take the form of recommendations. However, the term "recommendation" is not used since for some problems intensive NASA research efforts are known to be underway and to recommend activities already in progress would be misleading.

Problem Area No. 1: Reentry Transition

Space shuttle missions could last for as long as 30 days, followed by a reentry during which crewmembers would be exposed to acceleration forces of 2 to 3 G's. The reentry transition may present two problems. First, there is possible cardiovascular deconditioning following exposure to extended weightlessness. Second, there is the transition from a space control system to an aerodynamic control system as the vehicle is brought to the landing site.

Implications. Should deconditioning prove to be a serious problem, a therapeutic regimen will have to be developed for use during the space shuttle mission. The transition from a space to an aerodynamic control system warrants an examination of the skills involved, the retention of these skills during stay in orbit, and the adequacy of onboard display systems to support the control transition period.

Problem Area No. 2: Manual Control of Booster Vehicle During Ascent and Reentry

Suggestions have been made for an investigation of the feasibility of providing a pilot override control capability during the ascent and reentry phases Nominally, the vehicle will be controlled by automatic systems during these phases, but there may be instances when it would be necessary for the pilot to intervene in the automated control sequence.

Implications. Research is required to establish guidelines for pilot intervention in automatic control loops and for insuring that the crew is adequately supported by cockpit displays and controls should such intervention become necessary. Control dynamics and resulting display requirements would be complicated by several factors: the mated booster-orbiter configuration, aerodynamic instabilities, wind distrubances, and propellant sloshing.

Problem Area No. 3: Life Support/Habitability

One of the first and most important problems to be faced in the space shuttle vehicle development program is that of maintaining the space traveler in an environment which falls within very narrow tolerances. Significant design problems are involved in developing an effective life support system and in providing for its mating with a space station.

Implications. In general, the basic technology to support human life in space has already been developed and tested in earlier space programs. However, new problems arise, particularly in the area of habitability and comfort, since a number of the space shuttle passengers will be scientists rather than trained astronauts. The issues of waste management, personal hygiene, and food service will require considerable development in technology prior to being acceptable for long term SSV use.

Problem Area No. 4: Crew and Passenger Safety

The safety of space shuttle crewmembers and passengers will be achieved through careful design, involving multiple redundancies and drawing on experience with earlier space vehicles. Failure of system elements may result in mission abort, but should not result in loss of life. An airline philosophy is being followed in which the safety of the crew and passengers is tied directly to the safety of the basic vehicle.

Implications. Although normal operation of the SSV should have a high level of safety, it is conceivable that some emergency during launch preparations might make it desirable to evacuate the vehicle as rapidly as possible. Since the vehicle is vertical at this time, rapid egress by passengers and crew could be difficult. It may be necessary to conduct extensive simulation studies using a full scale mockup of the SSV in the launch position to determine the optimum combination of procedures, training, and performance aids to insure that rapid and effective egress can be accomplished when circumstances warrant.

Problem Area No. 5: Role of Crew in Mission Management and Subsystem Control

The SSV will be highly "computerized." Mission control will be accomplished largely by crewmembers and onboard computers. However, the aim for autonomy which will place extensive demands on the SSV crew and central computer for mission management and control of vehicle subsystems. The range and number of decisions to be made by the crew is expected to be greater than in previous space flight operations, and the volume of data processed on board is likely to increase significantly.

Implications. There is a need for a clear delineation of the crew's role in mission management and subsystem control, i.e., what is the proper role of man in SSV operations? The answer will entail a careful analysis of information used by the crew in monitoring mission progress, in assessing the state of computer-controlled system functions,and in making decisions and taking action when out-of-tolerance conditions develop. This analysis should identify potential limitations of the crew's ability to process data available within the system and thereby help to isolate requirements for a more precise definition of crew task assignments or for specific elements of display support.

Problem Area No. 6: Pilot Monitoring and Vehicle Control During Recovery Operations

The problems in this area are to determine the primary flight control modes during recovery operations,to assess the impact of powered versus unpowered flight on crew task requirements and acceptance attitudes, and to identify display requirements for low visibility operations.

Implications. Crew task requirements in SSV recovery operations will influence the final SSV configuration and the design of an integrated avionics system. Studies are in progress or are being planned at several NASA centers to examine flight control and guidance system design requirements. These studies should contribute to a common understanding of the pilot's role. They will also help to assess the impact of powered versus unpowered recovery flight profiles and to develop a realistic concept of pilot participation in low visibility operations. The ultimate requirement is for the establishment of a generally accepted position regarding crew participation in the flight control function.

Problem Area No. 7: Man-Computer Interface

The SSV will contain a highly sophisticated computer federation. Total control of this system is so complex that preprogramming of a wide range of operational processes, using both ground-based and onboard computers, will be necessary. Much of the activities of the SSV crew will revolve around interaction with computers and data processors.

Implications. It is imperative that the man and the computer deal with each other effectively, taking into account the capabilities and special needs of each. If not, full computerization can result in a loss rather than a gain of system operating capacity and effectiveness. Extensive examinations of the construction of computer systems and formatting of data, drawing on experience from comparable systems, must be undertaken to insure that information flow is not impeded or distorted at this interface point.

Problem Area No. 8: Flight Deck External Vision

More than any previous space vehicle, the SSV will require external vision for crewmembers. External vision is important in the launch abort, docking, orbital inspection, atmospheric cruise, approach,and landing phases. Proposed configurations of the SSV provide window areas for crewmembers more like those of airplanes than other space vehicles.

Implications. Considerable research is underway at the NASA Flight Research Center to establish visibility envelopes for crewmembers during landing operations. This information is critical for SSV design and should be transmitted to industry on an ongoing basis. In an extension of this work, presumably utilizing the scaled down shuttle (mini-shuttle) comtemplated for FRC, backup methods for providing external vision (possibly involving periscopes, portholes, CRT displays, or projected displays) will be evaluated in a flight test program.

Problem Area No. 9: Personnel/Cargo Transfer

The load carrying capability of the space shuttle vehicle is one of its principal attributes. In all proposed missions, transfer of cargo or personnel will be involved to some degree. It is important that transfer operations be conducted efficiently and safely.

Implications. NASA management personnel are well aware of the importance of the personnel/cargo transfer function and have begun an intensive program of analysis and experimentation at both the Langely Research Center and the Marshall Space Flight Center. A clearer appreciation of personnel capabilities and the need for power transfer equipment should be obtained through these two efforts. A reasonable extension of these programs would be tests conducted in the Skylab Program to validate the simulation data under actual conditions of weightlessness.

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