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PROPULSION AND POWER SYSTEMS PERSPECTIVE

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The Space Shuttle has its roots in a number of studies and programs dating back to the early 1940's. The first of these was the A-10, a V-2 derivative proposed as a winged hypersonic glide bomber capable of reaching the east coast of the United States when launched from Germany. After World War II, similar studies were conducted in the United States as secret Air Force programs named ROBO and Brass Bell. These studies evolved into the Dynasoar program of the mid 1950's. Dynasoar went through various phases and missions. By 1957, Dynasoar was proposed as a manned orbiting vehicle capable of reuse after landing. A conference of National Advisory Committee for Aeronautics (NACA) experts in all of the aeronautical research disciplines was convened at the NACA Ames Research Laboratory in October 1957 to review the feasibility of such a program. This group concluded that although there were many difficult engineering research and development problems to be solved, there were no fundamental reasons why such a vehicle could not be successfully developed. Dynasoar, for various reasons, was not immediately funded. It was later revived on a smaller scale and then canceled.

The NASA manned and unmanned space program had its beginnings at that conference even though NASA was not formed until a year later. There were serious discussions between various factions at the conference on the desirability of basing a manned orbital vehicle on the supersonic and hypersonic research airplane technology being developed at Edwards Air Force Base or on ballistic missile launch vehicle and reentry technology. There were also serious discussions about starting an all-solid-propellant launch vehicle to compete with the Vanguard Program.

The ballistic missile launch vehicle and reentry technology approach was studied in detail by a small group of engineers at the Pilotless Aircraft Research Division of the NACA Langley Research Center for the year following the conference. The same group did detailed studies and planning on a four-stage solid-propellant vehicle capable of placing small satellites in orbit. These studies were thorough enough to become the basis for Project Mercury and the Scout missile with the creation of NASA in October 1958. Project Mercury was successful, cost effective, and completed on a relatively short schedule because it bypassed all of the different engineering research and development problems associated with Dynasoar and utilized existing ballistic missile launch vehicle and reentry technology. The Scout program was successful because it was based on 15 years of small solid-propellant launch vehicle technology developed at Wallops Island.

Unmanned space operations used liquid-propellant launch vehicles such as Redstone, Thor, Atlas, and Titan, and their uprated derivatives. These launch vehicles had been rendered surplus by the introduction of smaller solid-propellant systems such as Pershing, Polaris, and Minuteman. The smaller solid-propellant systems were not capable of launching large satellites or manned vehicles into orbit. The number of surplus large liquid-propellant launch vehicles was limited, and there were no active production lines or programs to replace them. The Saturn V production line was shut down before completion of the Apollo Program. In the early 1970's, the future of manned and unmanned space programs looked bleak.

While the Apollo Program was winding down, some of the same engineers who started Project Mercury along with veterans of Mercury, Gemini, and Apollo missions began an in-house study of a reusable manned operational vehicle which could handle all the foreseen manned and unmanned space launch requirements. The vehicle was, in essence, a large upgraded version of Dynasoar with a different mission. Many things had happened since the Dynasoar proposal of 1957. Mercury, Gemini, Saturn, Apollo, X-15, manned reentry body research programs, and new ballistic missile systems had spawned advances in structures, materials, fabrication, processing, propulsion, aerodynamics, avionics, communications, guidance and navigation, and other technologies not available to Dynasoar in 1957. A reusable spacecraft did not seem so difficult any more. The initial reaction was to recover everything possible and to design both the booster and the orbiter around existing Saturn-Apollo technology. The vehicle was sized to accommodate the largest existing known payloads of the time.

Evolution from the original vehicle size and configuration to the present Shuttle was not easy. The number of different concepts, configurations, designs, payload weights and volumes, and operational requirements was unlimited, and everyone in the government and industry aerospace business had a legitimate reason for wanting a specific vehicle size and configuration to be selected. There were serious differences in philosophy regarding the cost effectiveness of using existing technology as opposed to tying the success of the program to promising, new, sophisticated but unproven technology.

*Retired.

Propulsion and power subsystems usually constitute 85 to 90 percent of the weight and volume of the entire system and have a profound effect on the overall launch vehicle size and configuration. Programmatic requirements and factors also have a significant effect on the overall propulsion system design and configuration. Some of these factors and requirements are shown in figure 1. The program requirements will generally be responsible for sizing the propulsion and power systems and establishing minimum system requirements. The program factors affect the selection of the configuration and have a strong influence on component design. The interaction between these factors is so complex that it defies any logical explanation or comment, and the success of the Shuttle is the result of hundreds of wise technical and management decisions that would have challenged Solomon.

When the Shuttle requirements were better defined and management decisions were made concerning the relative importance of some of the factors, the process of selecting one of the various configurations, design concepts, and system components from the many available options was started. Some of the more serious configuration options are presented in figure 2. Each of these was the subject of extensive contractor and government studies. The configuration option selected is enclosed by a rectangle.

Single stage to orbit is the goal or ideal of every space vehicle designer. Unfortunately, extremely low structural and subsystem weight fractions are required to keep the vehicle size manageable, and predictable high propulsion system performance is required. Very small percentage of weight growth or reduction in propulsion system performance in the course of vehicle development could result in negative payload margins. Commitment to a single-stage-to-orbit concept did not appear worth the risk. The integral propellant tank would result in a very large orbiter, and there was no experience in recovery of eggshell tanks reentering from orbital activities over a dispersed area. A recoverable drop-tank option is a possibility for future operations.

When boosting an aerodynamic vehicle with a large lifting surface in one plane, tandem booster arrangements produce extremely high structural bending loads and high control-moment requirements. Experience in launching many airplane configurations at Wallops Island in the 1950's showed that piggyback arrangements with parallel staging could alleviate this problem. Parallel staging of small solid-propellant launch vehicles was also developed at Wallops Island in the 1950's and successfully applied to the Delta and Titan programs on a much larger scale. An asymmetric piggyback configuration with large lifting surfaces in one plane and dual propulsion systems located above and below the center of gravity having different and varying thrust levels with large shifts in the vertical center of gravity is a control system nightmare.

A serious proposal was made to locate the Space Shuttle main engines (SSME's) aft on the external tank and to transport the engines into an empty payload bay using permanently attached mechanical arms. Such an arrangement could, it was reasoned, more easily track the center of gravity shifts as propellant was expended, reduce the overall required control authority, and possibly use a fixed-nozzle solid rocket booster (SRB).

PROGRAM REQUIREMENTS

- PAYLOAD WEIGHT
- PAYLOAD VOLUME
- ORBIT ALTITUDE AND INCLINATION
- ON ORBIT OPERATIONS

PROGRAM FACTORS

- TRAFFIC MODELS
- REUSABILITY AND REFURBISHMENT
- MAINTAINABILITY
- GROUND OPERATIONS
- TURNAROUND
- PRODUCTION COSTS
- OPERATIONS COST
- MANUFACTURING, TEST AND LAUNCH SITES
- SCHEDULE

FIGURE 1.- PROGRAM REQUIREMENTS AND PROGRAM FACTORS.

- NUMBER OF STAGES
  - SINGLE STAGE TO ORBIT
  - TWO STAGES
- PROPELLANT TANK
  - INTEGRAL WITH ORBITER
  - EXTERNAL - NON-RECOVERABLE
  - EXTERNAL - RECOVERABLE
- BOOSTER ORBITER ARRANGEMENT
  - TANDEM STAGING
  - PARALLEL STAGING (PIGGYBACK)
- ORBITER MAIN ENGINE LOCATION
  - AFT ON ORBITER
  - AFT ON EXTERNAL TANK (SWING ENGINE)

FIGURE 2.- CONFIGURATION OPTIONS.

Many of the reasonable propulsion and power system options considered are presented in figures 3 to 8 without comment. The selected options generally used existing military or Saturn-Apollo technology except where these systems would not permit reuse or where the system or component performance could not be easily upgraded to Shuttle requirements. Some of the reasons which led to selection of a specific design or concept and factors which contributed to successful development and operation of the system in a cost-effective manner are discussed in other papers in this session. Each reader can determine whether he thinks the selected approaches were cost effective and were indeed the best choice. No justification for the choices is necessary as the success of the program to date provides confirmation that options selected are adequate.

Some of the work is still unfinished. The Shuttle must yet demonstrate the originally advertised payload capability and turnaround time. Costs per launch must be reduced. There is little or no growth available in the existing propulsion and power systems without major redesign. There are, however, many system design features to take care of problems with low probability of occurrence and areas of excessive redundancy and design margins which have been incorporated into the program at the expense of payloads.

For the first time, there will be a small fleet of operational vehicles which will fly many missions and provide the necessary operational experience and a data base to eliminate the difference between real and imagined performance and design requirements. The existence of this data base alone should result in substantial increases in payload capability. This data base will also provide information to eliminate unnecessary design complexity, design margins, redundancy, and excessive estimate of propellant requirements for enhanced versions of the Shuttle and future space transportation systems.

- **LIQUID PROPELLANT**
  - **LOX-H_2**
  - **LOX-HYDROCARBON**
  - **EARTH STORABLE**
  - **FLYBACK - REUSABLE**
  - **BIG DUMB BOOSTER**
- **SOLID PROPELLANT**
  - **NONRECOVERABLE**
  - **RECOVERABLE**
    - **CASE**
    - **MONOLITHIC**
    - **SEGMENTED**
    - **METAL**
    - **FILAMENT WOUND**

FIGURE 3.- BOOSTER OPTIONS.

- **TVC**
  - **NONE**
  - **LIQUID INJECTION**
  - **GIMBALLED NOZZLE**
- **THRUST TERMINATION**
  - **NO**
  - **YES**
- **PROPELLANT**
  - **PBAA**
  - **HTPB**
  - **OTHER**

FIGURE 3.- CONCLUDED.

- **ORBITER MAIN ENGINE (SSME)**
  - **J-2, J2-S**
  - **NEW HIGH PRESSURE GAS GENERATOR**
  - **HIGH PRESSURE STAGED COMBUSTION**
  - **AEROSPIKE**
- **ORBITAL MANEUVERING ENGINE**
  - **RL-10**
  - **LOX-HYDROCARBON**
  - **EARTH STORABLE**
    - **COOLING**
      - **ABLATION**
      - **REGENERATIVE**
    - **FEED SYSTEM**
      - **PRESSURE FED**
      - **PUMP FED**

FIGURE 4.- ORBITER PROPULSION OPTIONS.

- **MOUNTING**
  - **INTEGRAL WITH VEHICLE**
  - **EXTERNAL POD MOUNT**
- **PROPELLANT ACQUISITION**
  - **GRAVITY-THRUST SETTLING**
  - **CAPILLARY SCREENS**

FIGURE 5.- ORBITER MANEUVERING SYSTEM OPTIONS.

- **PROPELLANT**
  - GASEOUS O_2-H_2
  - LOX-LH_2
  - LOX-HYDROCARBON
  - $\boxed{\text{EARTH STORABLE}}$
  - MONOPROPELLANT
- **INSTALLATION**
  - FIXED
  - $\boxed{\text{REMOVABLE POD OR MODULE}}$
- **TANKS**
  - BLADDERS
  - OTHER POSITIVE DISPLACEMENT
  - $\boxed{\text{CAPILLARY SCREENS}}$
- **VALVES**
  - SOLENOID
  - $\boxed{\text{LINE PRESSURE ACTUATED}}$

FIGURE 6.- REACTION CONTROL SYSTEM OPTIONS.

(1) HYDROGEN-OXYGEN
(2) EARTH STORABLE BIPROPELLANT
(3) LOX-HYDROCARBON
(4) $\boxed{\text{MONOPROPELLANT}}$

- POWER (SPEED) CONTROL
  (1) PRESSURE MODULATION
  (2) $\boxed{\text{PULSE MODULATION}}$
- **PYROTECHNIC SYSTEMS**
  - NO
  - $\boxed{\text{YES}}$

FIGURE 7.- AUXILIARY POWER UNIT OPTIONS.

(1) TURBINE - ALTERNATOR
(2) BATTERIES
(3) $\boxed{\text{FUEL CELLS}}$
 - $\boxed{\text{BASIC}}$
 - ACIDIC
(4) SOLAR CELLS

- **REACTANT STORAGE SYSTEM**
  - $\boxed{\text{SUPERCRITICAL STORAGE}}$
  - SUBCRITICAL STORAGE

FIGURE 8.- ELECTRICAL POWER OPTIONS.

Another reason for presenting the various propulsion and power system options without comment is that the issues are not yet settled. In the past years, numerous studies of enhanced or next generation space transportation systems were based on many of the options originally rejected, as well as on such new propulsion concepts as the dual fueled engine. Remembering that it was 15 years between the Dynasoar of 1957 and the Shuttle, and that 10 years have already elapsed since the Shuttle design concepts converged, it is not unreasonable to assume that new information or technology is or will be available which would result in selection of an entirely new concept or design, or one originally rejected, when future Space Transportation System (STS) programs are undertaken. The propulsion and power systems used technology from Department of Defense (DOD) programs, Saturn, Apollo, and some developed concurrently with the Shuttle. The success of the Shuttle program to date speaks for itself. Unfortunately, with the introduction of solid-propellant rockets into the ballistic missile program, recent emphasis on cruise missiles, and assignment of responsibility for all space transportation to NASA, DOD is no longer funding the large liquid-propellant technology programs which have benefited NASA in the past.

Lack of funding of new technology, cancellation of old launch vehicle programs, and no new production in sight threatens the existence of old line companies capable of developing and manufacturing the propulsion systems required for future space transportation systems. If new technology programs with substantial funding are not forthcoming soon, there may not be a single surviving company capable of conducting new technology and development and production programs required to support the Space Transportation System. The responsibility is now NASA's and the future of propulsion and power technology rests solely in the hands of NASA management.