I. Session 1: Designing the Space Shuttle Propulsion System

A. Introduction – Shuttle Propulsion Overview – J. Owen

The major elements of the Space Shuttle Main Propulsion System include two reusable solid rocket motors integrated into recoverable solid rocket boosters, an expendable external fuel and oxidizer tank, and three reusable Space Shuttle Main Engines. Both the solid rocket motors and space shuttle main engines ignite prior to liftoff, with the solid rocket boosters separating about two minutes into flight. The external tank separates after main engine shutdown and is safely expended in the ocean. The SSME's, integrated into the Space Shuttle Orbiter aft structure, are reused after post landing inspections. Both the solid rocket motors and the space shuttle main engine throttle during early ascent flight to limit aerodynamic loads on the structure. The configuration is called a "stage and a half" as all the propulsion elements are active during the boost phase, and the SSME's continue operation to achieve orbital velocity approximately eight and a half minutes after liftoff. Design and performance challenges were numerous, beginning with development work in the 1970's. The solid rocket motors were large, and this technology had never been used for human space flight. The SSME's were both reusable and very high performance staged combustion cycle engines, also unique to the Space Shuttle. The multi body "side mount" configuration was unique and posed numerous integration and interface challenges across the elements. Operation of the system was complex and time consuming. This paper discusses a number of the system level technical challenges including development and operations.

B. External Tank (ET) – Structural Efficiency – K. Welzyn

The largest single element of Space Shuttle is the External Tank (ET), which serves as the structural backbone of the vehicle during ascent and provides liquid propellants to the Orbiter's three Main Engines. The ET absorbs most of the seven million pounds of thrust exerted by the Solid Rocket Boosters and Main Engines. Structural efficiency and light weight were essential to increase payload mass to orbit. The design evolved through several block changes, reducing weight each time. The initial configuration, the standard weight tank, weighed 76,000 pounds and was an aluminum 2219 structure. The light weight tank weighed 66,000 pounds and flew 86 missions. The super light weight tank weighed 58,500 pounds and was primarily an aluminum-lithium structure. Toward the end of the program a series of weight neutral structural modifications were incorporated to alleviate welding issues observed in the aluminum-lithium welds on complex curvature domes. The final configuration and low weight enabled system level performance sufficient for assembly of the International Space Station in a high inclination orbit, vital for international cooperation. Another significant challenge was the minimization of ice formation on the cryogenic tanks. This was essential due to the system configuration and the choice of ceramic thermal protection system materials on the Orbiter. Ice would have been a major debris hazard. Spray on foam insulation materials served multiple functions including conditioning of cryogenic propellants and thermal protection for the tank structure during ascent and entry. The key design features and the evolution of the design will be discussed in detail.

C. Space Shuttle Main Engine (SSME) – Reusability and High Performance – K. Van Hooser

The Space Shuttle Main Engine is the only reusable rocket engine ever developed and is the highest performance earth to orbit system. A significant design challenge for the SSME was development of a dual pre-burner staged combustion engine, which represented an advance in technology. The efficiency (specific impulse) delivered by the staged combustion cycle, substantially higher than previous rocket engines, minimized volume and weight for the integrated vehicle. The dual pre-burner configuration permits precise mixture ratio and thrust control while the fully redundant controller and avionics provide a very high degree of system reliability and health diagnosis. The main engine controller design was the first rocket engine application to incorporate digital processing. The engine was required to operate at a high chamber pressure to minimize engine volume and weight. This allowed the base region of the Orbiter to be small, enabling flight like a glider during landing. The engine was reusable, another first, and power level throttling was required to minimize structural loads on the vehicle early in flight, and acceleration levels on the crew late in ascent flight. Emphasis on fatigue capability, strength, ease of assembly and disassembly, inspectability, and materials compatibility were all major considerations in achieving a fully reusable design. During development, a major challenge was development of the engine start sequence (valve timing). During the 30 year Program the design evolved substantially. The initial, first manned orbital flight configuration was upgraded to a phase II configuration during the 1980's. The block I, Block IA, and Block II upgrades evolved the design by adding two duct power head, redesigned high pressure pumps, a large throat main combustion chamber, and other component upgrades. The improvement of the SSME has been a continuous undertaking, with the objective being to increase safety, reliability and operational margins, reduce maintenance and improve component life. Among the improvements a major innovation included an intelligent health management system. The SSME's thrust-to-weight ratio, specific impulse, full throttling, gimballing and reusability requirements drove the development of an engine whose performance is still unmatched. These challenges and evolution of the design will be discussed in depth.

D. Reusable Solid Rocket Motor (RSRM) – Human Rated – D. Moore

Each Reusable Solid Rocket Motor (RSRM) provides nearly 3 million pounds of thrust to lift the integrated Space Shuttle vehicle from the launch pad. The motors burn out approximately 2 minutes later, separate from the vehicle and are recovered and refurbished. The size of the motor and the need for high reliability were challenges. Development of a solid rocket motor of this size required scaling from smaller scale systems, and addition of design margins to account for human rating. Thrust shaping, via shaping of the propellant grain, was needed to limit structural loads during ascent. The motor design evolved through several block upgrades to increase performance and to increase safety and reliability. The initial Solid Rocket Motor configuration evolved the High Performance Motor during the early 1980's. A major redesign occurred after STS-51L with the Redesigned Solid Rocket Motor. Significant improvements in the joint sealing systems were added. Design improvements continued throughout the Program via block changes with a number of innovations including development of low temperature o-ring materials and incorporation of a unique carbon fiber rope thermal barrier material. Recovery of the motors and post flight inspection improved understanding of hardware performance, and led to key design improvements. Process control was a key to assuring system flight readiness. The paper discusses the performance, design challenges, and design improvements during the Program, including the redesigns following STS-51L.

E. Solid Rocket Booster (SRB) – Recovery and Reusability – D. Wood

The Solid Rocket Booster element integrates all the subsystems needed for ascent flight, entry, and recovery of the combined Booster and Motor system. These include the thrust vector control, auxiliary power unit, avionics, pyrotechnic, range safety system, parachutes, thermal protection, forward and aft structures, and water recovery systems. This represents the only recoverable and refurbishable solid rocket ever developed and flown. Challenges included subsystem integration and severe loads including water impact sometimes resulting in hardware attrition. Extensive acceptance testing was done to assure hardware functionality at each level of stage integration. Several of the subsystems evolved during the program through design changes. These included the parachute system, the thermal protection system, the range safety system and others. Obsolescence issues occasionally required component recertification. Because the system was recovered, the solid rocket booster element was ideal for data and imagery acquisition, essential to development of system response to loads, and for situational awareness for mission operations. The paper describes the design challenges, how the design evolved with time, and key areas where hardware reusability contributed to improved system level understanding.