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- **Assess Total System Architecture's Operational Viability**
  - Can the ground system requirements functionality be verified to mitigate the risk of catastrophic failure:
    - Active Vehicle Supports
      - Saturn I First Stage Launch Support
    - HORIZONTAL T–0 Swing Arms
      - Saturn V Required Several T-0 Swing Arms
    - Major element support systems
      - Orbiter Support Trolley
      - Vehicle T-0 Damper Arms

- **Natural and Induced Environments**
  - Program Designs for Classical Rain, Wind, Humidity, and etc.
  - Lesson learned from Apollo 12 to avoid launching with lightning potential in the local area
  - Lesson learned from Shuttle STS-1 to consider hail
  - Induced debris damage from element to element in flight
    - ET ice/frost and foam debris
    - SRB insulation debris

- Hazardous Commodities
  - Toxic fluids
    - Special personnel protection and personnel health monitoring
  - Cryogenics
    - Fire, water hammer, sensitivity to contamination, and geysering
  - Closed compartments
    - Fire and explosion potential
  - Excessive free or trapped hydrogen
    - Ignition overpressure
    - Abort shutdown risk
      - Exhaust of SSME contains nominal 26 pounds/second free hydrogen per engine
      - Exhaust of SSME during abort shutdown is up to 75 pounds per second free hydrogen per engine
    - SRB exhaust contains 51% excess fuel or 27% excess free hydrogen per motor
      - Each SRM exhausts ~5180 pounds per second unburned fuel
      - Each SRM exhausts ~2743 pounds per second unburned gaseous hydrogen

- Engineering management of Needs, Goals, and Objectives
  - Flow down of these needs, goals, and objectives into requirements to the lowest level required to achieve the objective
  - Shuttle was to replace the Saturn launch vehicle to achieve affordable and sustainable STS to allow reasonable annual budget to allow achievement of goals from operating in space.
    - 160 hour STS turnaround
    - 24 hour notice to launch from the VAB to perform rescue when needed
    - 2 hour countdown
    - 10 yr. program @ 40 launches/yr. with 4 orbiters from KSC
  - Assumption was to provide reusability and operability to achieve $100 to $300. per pound to orbit
    - Total program transportation operational cost of $2.6B to $7.8B or $260M to$780M/yr.
    - Total program delivery of 26M pounds to orbit or 2.6M pounds/yr.

The Shuttle Program: Formulation, Development, and Operations
Launch Development and Ops

- Flow down of Needs, Goals, and Objectives into requirements <u>were not accomplished adequately</u>
  - Results from focusing only on performance
    - Long ground processing time
      - 160 hour turnaround: Existing 126 day standard template (Ca. 2002) (factor **9:1**)
      - 24 hour notice to launch: Existing 26 days at the pad (Ca 2002) (factor 26:1)
    - Lack of financial commitment to provide required ground capability
      - 2 hour countdown: Existing 8-9 hours
    - Un-planned repair and parts replacement
      - ~ 40% more processing time for orbiter in OPF
      - Single orbiter productivity from 10 to 2.5 flights per year (factor 4:1)
      - To accomplish reasonable flight rate per year (less than goal) required large increase in ground infrastructure along with increased labor
      - 402 total interfaces for the orbiter to ground
      - 102 interfaces requiring fluid servicing every shuttle flight
        - 54 fluids required by the program with 27 separate fluids serviced each flight
    - Resultant flight rate capability of 7-8 flights/yr. (actual 5 flights) vs. goal of 40 flights/yr.
    - Resultant large program labor cost increase (factor ~ 20:1/flight)
    - Resultant cost per pound to orbit increase (factor ~ 30:1)
  - However: Using a reusable transportation system reduced its cost to ~ 1/3

- Flow down of Needs, Goals, and Objectives were not accomplished continued
  - Results from design trades that are driven by focusing only on performance
    - Design trades were and are determined by optimizing subsystem weight without regard to integrated impact on LCC
    - Lack of integration of vehicle discipline subsystems causes large increase in total flight and ground hardware parts count, increased dedicated ground interfaces and servicing systems, decreased reliability, and large logistics chain – results are large increase in LCC

    - Some examples with Shuttle Program:
      - Rocket engine (SSME) that requires 28 vehicle support subsystems
      - Orbiter hydraulics systems that requires its integrity to be broken every flight for ground operations
        - Distributed hydraulics vs. distributed electrical power: -- distributed hydraulics drives up hardware count, problems, labor count, and requires on-orbit heating that requires ~ 50% of all electrical power on orbit
      - SRB TVC distributed hydraulic and hydrazine powered pump: -- very complex with large hardware and labor cost

    - Orbiter FRCS (hypergolic) would be good candidate for PSRD integration for simplification
    - Lack of robustness in TPS because of weight has had large increase in LCC to program
    - Program gave up clean/smooth ET design which has increased orbiter TPS repair operation and increased LCC as well as added safety of flight risk
    - Flight attitude of shuttle (+ 4^0) sheds debris from elements on to critical orbiter TPS to maximize performance of the SSMEs – results in added safety of flight risks

- Shuttle program used safety of flight as an excuse not to perform <u>Continuous Improvements for LCC reduction</u> – Safety mitigation by flying unmanned?

CONCLUSIONS AND SUMMARY

- Lack of understanding of how to achieve the affordability and sustainability objectives of the Shuttle Program
  - The Engineering Management functions required for achievement of true LCC objectives – major systems integration and simplification with minimum ground support required
  - Understanding the influencing functions that control down time must be implemented as firm requirements to avoid growth of facility infrastructure and its additional labor and materials needed to meet launch frequency
- Affordability must be designed in from the acceptance of the architectural concept throughout the entire design/development phase – cannot add in affordability late in the design process
- The process of determining a space transportation system architecture and its development must be changed to achieve the multiple attribute objectives required to provide affordability and sustainability for space exploration