NASA Lessons Learned on Reusable and Expendable Launch Vehicle Operations and Their Application Towards DARPA's Experimental Spaceplane (XS-1) Program

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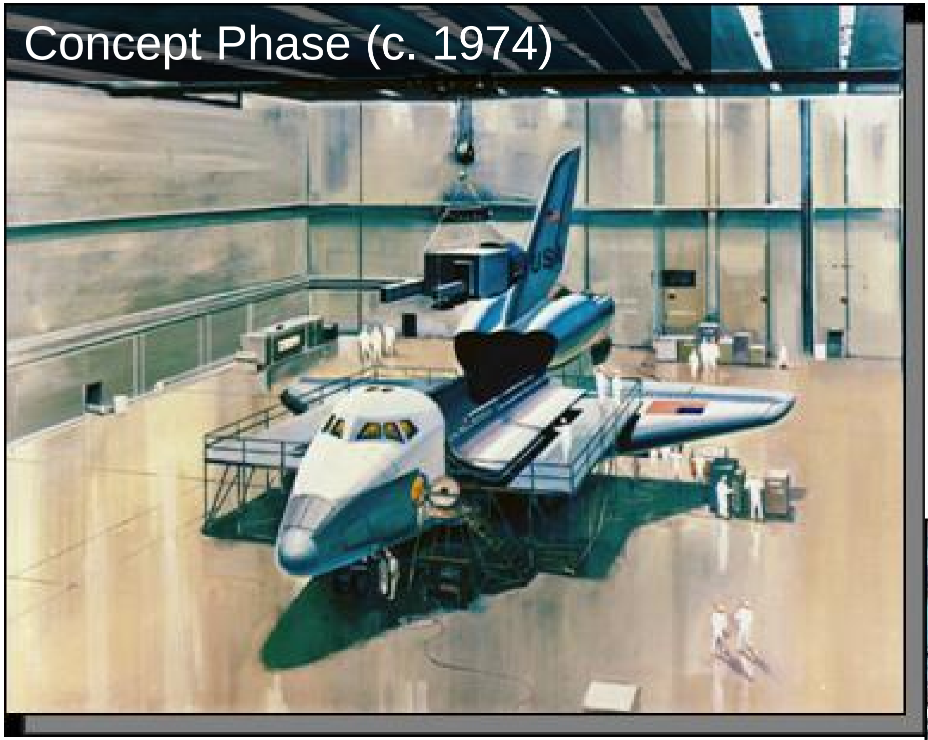
15 Jan 15

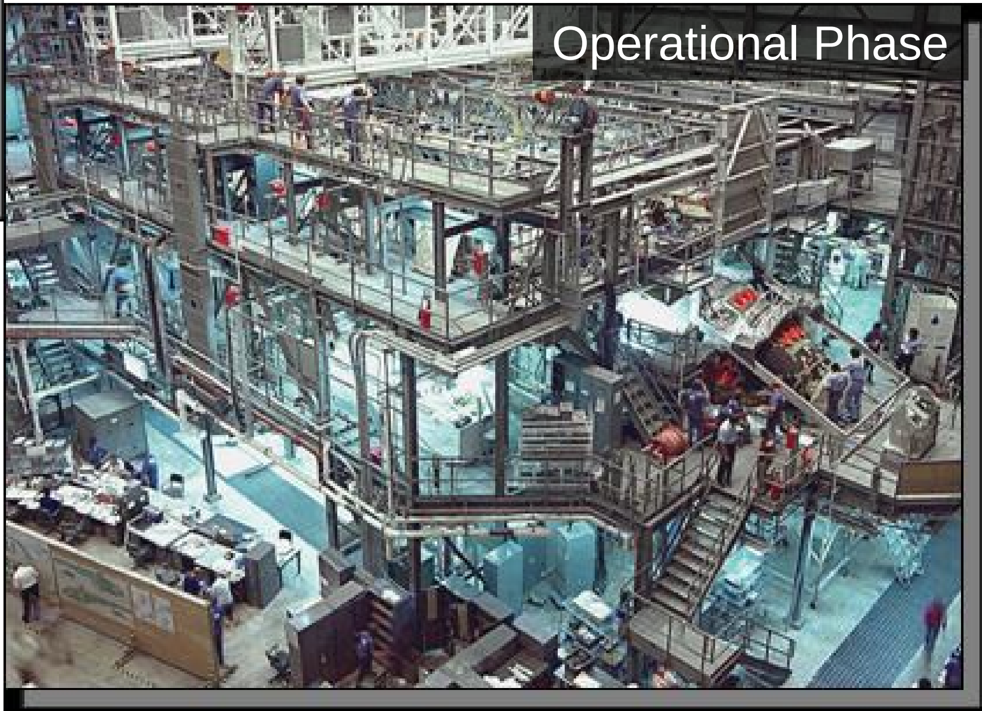
Outline

- Selected Historic Shuttle Operations Data
- Shuttle Lessons Learned Recommendations for Lower Cost, Operationally Efficient Launch Vehicle Systems
- Selected Expendable launch vehicle experiences
- Past NASA Launch Vehicle Development Programs, Studies (1985 to present)
- Discussion: Suggested applications of NASA Lessons Learned to already-baselined contractor XS-1 Phase I concepts

Selected Historic Shuttle Operations Data

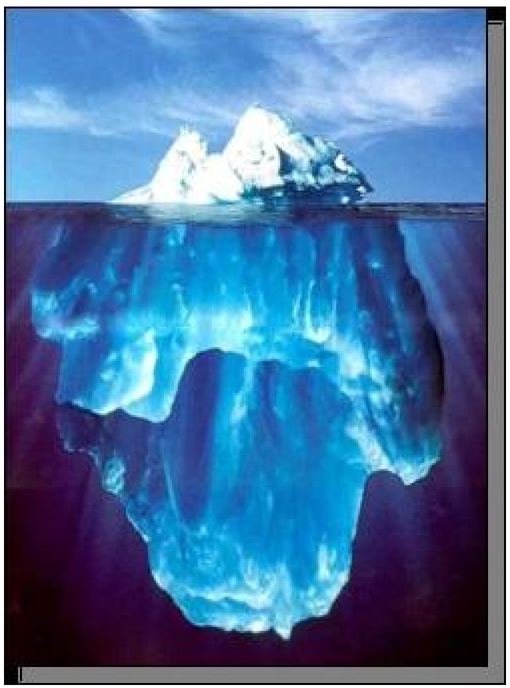
Original Shuttle Ops Concept vs. Actual





Overall Results of Cost Analysis

- “Direct” (Most Visible) Work <u>Drives</u> Massive (and Least Visible) Technical & Administrative Support Infrastructure
- <u>Example</u>: Direct Unplanned Repair Activity <u>Drives</u> Ops Support Infra, Logistics, Sustaining Engineering, SR&QA and Flight Certification



Direct (Visible) Work
“Tip of the Iceberg”

\+

Indirect (Hidden)

\+

Support (Hidden)

Recurring Ops $$s

STS Budget "Pyramid" (FY 1994 Access to Space Study)		
Generic Operations Function	***Total $M FY94***	***Total (%)***
Elem. Receipt & Accept.	1.4	***0.04%***
Landing/Recovery	19.6	***0.58%***
Veh Assy & Integ	27.1	***0.81%***
Launch	56.8	***1.69%***
Offline Payload/Crew	75.9	***2.26%***
Turnaround	107.3	***3.19%***
Vehicle Depot Maint.	139.0	***4.14%***
Traffic/Flight Control	199.4	***5.93%***
Operations Support Infra	360.5	***10.73%***
Concept-Uniq Logistics	886.4	***26.38%***
Trans Sys Ops Plan'g & Mgmnt	1487.0	***44.25%***
Total ($M FY94)	**3360.4**	***100.00%***

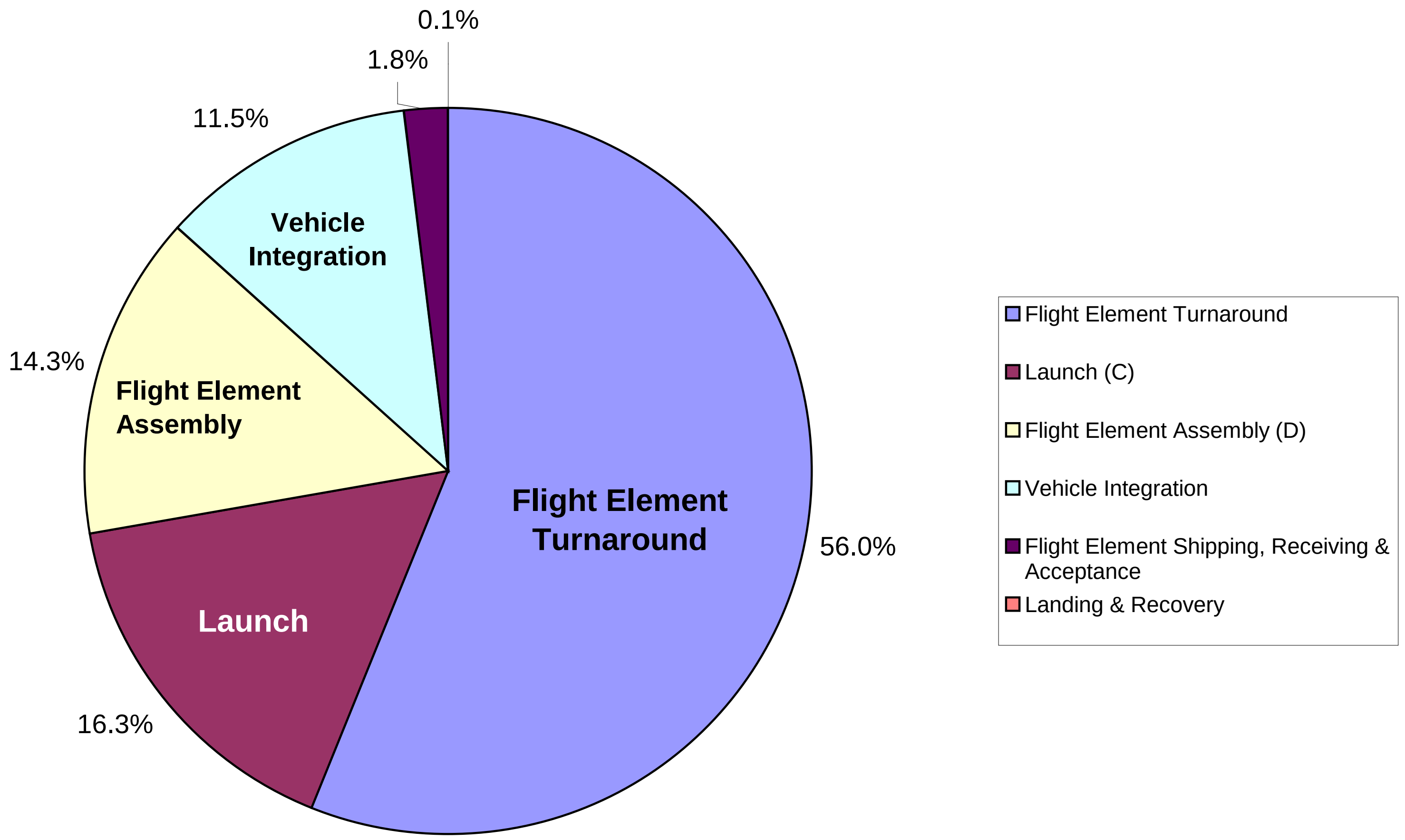
<10%

~20%

~70%

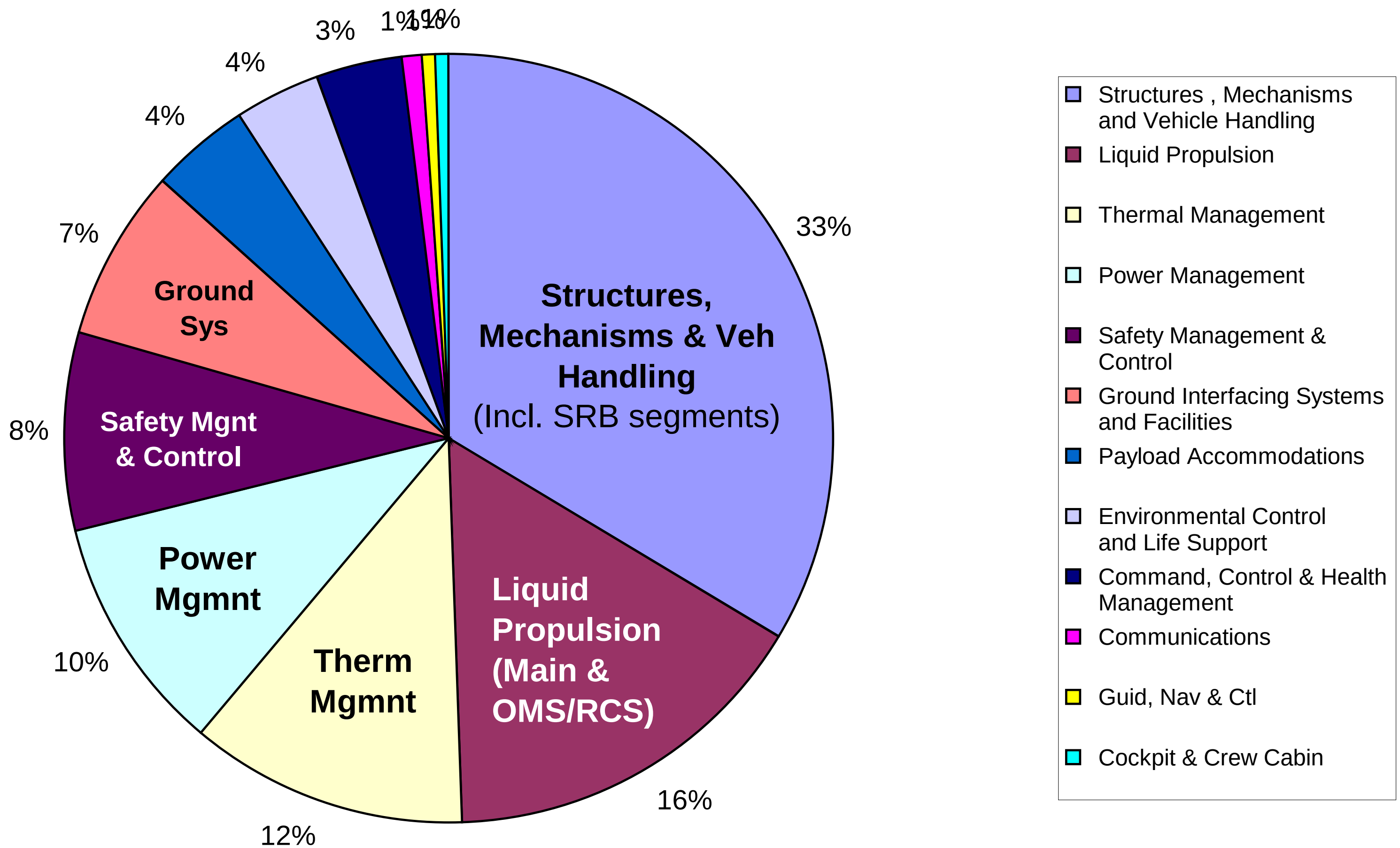
Overall Direct Work Content Concentrations

Overall Results of Shuttle Direct Work Content (By Operation)



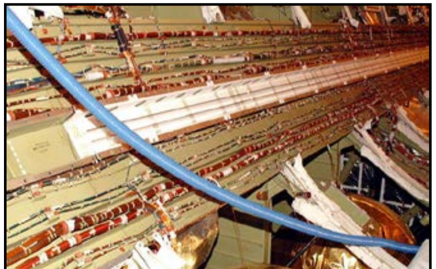
Overall Direct Work Content Concentrations

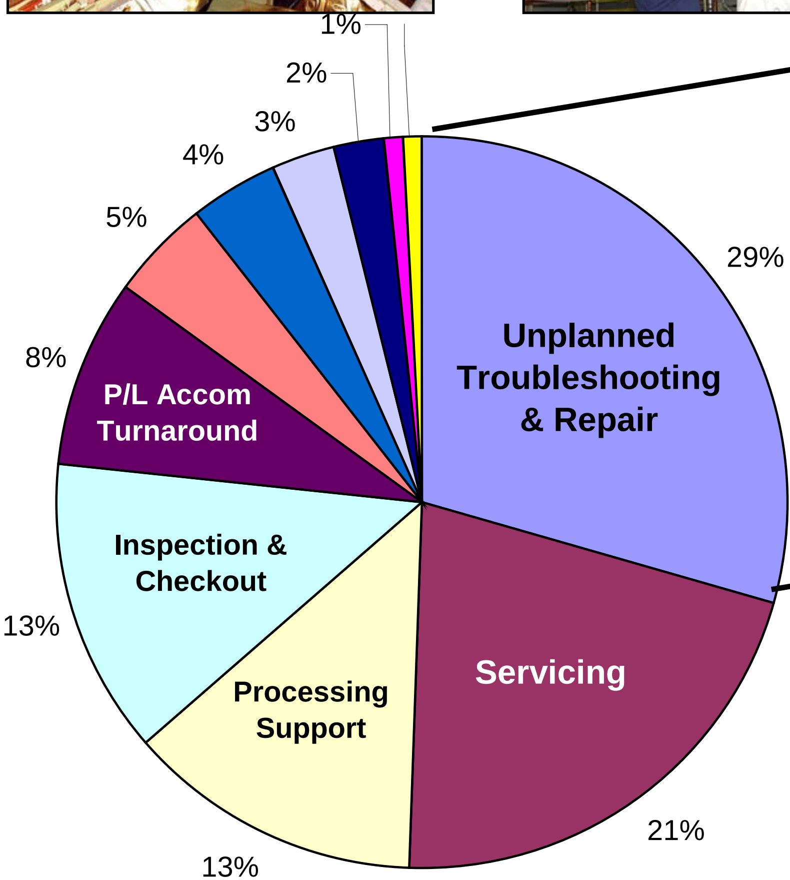
Overall Results of Shuttle Direct Work Content (By Design Discipline)

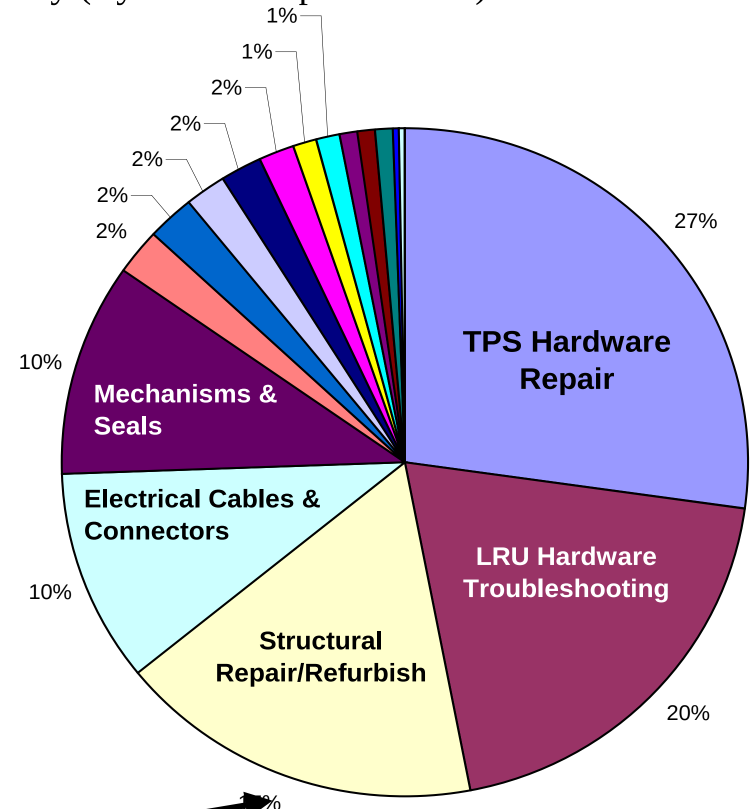


Overall Direct Work Content Concentrations

Orbiter Turnaround Work Content Summary (By Generic Ops Function)







Unplanned Troubleshooting and Repair)

Top-Level Design Root Causes

Common Themes and Recurring Causes Found and Substantiated by Work Content Analysis:

- (24%) Excessive Unplanned Troubleshooting and Repair
- (19%) Complex Element Assembly, Handling, Access and Mating
- (18%) Excessive Flight System Servicing
- (14%) Lack of Demonstrated System Dependability and Resulting Functional Verification
- Excessive Facility and Ground Equipment Preps and Refurbishment
- Complex, Customized Payload Integration with Flight Vehicle

Conclusions: Operator Needs
Operator-Driven Systems Engineering & Integration

- Traditional Transportation System Conceptual Design Process is <u>*Outside-In*</u>
  - Determine Vehicle Payload Lift Requirement
  - <u>Up-Front Cost/Initial Mass</u> (e.g., initial mass in low Earth orbit (IMLEO) for *Constellation*) Dominant Design Drivers
  - Assess, Down-Select and Commit to Configuration
  - Fill-In System/Subsystem Details

- Need Operator-Driven Design Requirements Up Front…an <u>*Inside-Out*</u> Approach
  - Need for Systems/Subsystem Design Integration for Benefit of Operator
  - Combine system disciplines and like vehicle/ground functions into common support systems & working fluids
  - Trade extra hardware and subsystems for robustness/dependability

- Recognition Up-Front of Full Functionality of Working Architecture
  - Space Propulsion Synergy Team System Breakdown Structure (SBS)
  - Six-Level Functional Definition Covering Flight/Ground for Exploration Transportation Systems

- Up-Front Operator Input Can Avoid Major System Shortfalls

Shuttle Lessons Learned Recommendations for Lower Cost, Operationally Efficient Launch Vehicle Systems

Six Critical Steps to an Affordable, Economically Sustainable System Design

- Step 1: Simplify the vehicle/ground system architecture
- Step 2: Efficiently package each vehicle element’s propulsion system (i.e., tank, engine and compartment layouts)
- Step 3: Integrate vehicle element functions into the lowest number of subsystems/components with minimum ground support requirements
- Step 4: Integrate ground element functions into the lowest number of work stations, facilities, and support equipment
- Step 5: Simplify avionics and flight control design into minimum components; then, power and automate what’s left
- Step 6: Extensively flight test to demonstrate accomplishment of all production and operations needs and objectives for full operational system capability with the affordability objective met

Step One
Simplify the Vehicle Architecture

- Keep the ground infrastructure across the enterprise to a minimum (recurring production, ground facilities and systems, logistics supply lines, etc.)

- Reusability keeps routine purchase of elements and replacement parts by the owner-operator of the system to a minimum—maximizes equipment utilization

- Simpler vehicle architecture with fewer elements to receive, assemble, integrate, service and checkout, launch and recover results in less work, and therefore, fewer time-consuming tasks

- Savings in work and time increases the use, affordability, and sustainability of the system for the owner-operator

Step Two

Efficiently Package Each Propulsion System

- Use minimum number of main and auxiliary propellant commodities, (e.g., day-of-launch-loaded liquid oxygen (LOX) and liquid hydrogen (LH2) only)
- Keep ground interface connections close to ground level to avoid a series of elevated, articulating umbilicals—particularly, lift-off umbilicals
- Avoid complexities of common-bulkhead, tandem tank arrangements and separate auxiliary propulsion systems
- Use a minimum number of main engines with a minimum amount of turbo-machinery and interconnecting main propulsion system plumbing

Step Three

Integrate Functions into the Lowest Number of Subsystems/Components

- Create generic functional systems breakdown structure for each element
- Combine (or integrate) as many functions into singular systems
- Provide a minimum of standalone, dedicated subsystems
- Minimize accumulated subsystems, components, and interfaces
- Combine propulsion & power functions with common propellants/commodities to avoid separate fill and drain, storage and distribution subsystems, ground interfaces, and ground support equipment (GSE)
- Use technical approaches that inherently require fewer separate support subsystems to perform the function (e.g., electro-mechanical actuators (EMA), electro-hydraulic actuators (EHA))
- Big Benefits: Cumulative design, develop, test, and evaluation (DDT&E) effort is greatly reduced (flight & ground systems)
  - Recurring production effort
  - Number of separate suppliers required to sustain the system
  - Recurring ground operations work:
    - Processing times are reduced
    - Recurring labor, materials, and other direct costs

Step Four
Integrate Ground Functions into the Lowest Number of Facilities and Equipment

Ten (10) items specified in paper. Examples include:

- Objective is to first minimize requirements for ground interfaces
- Then, eliminate requirements for elevated umbilicals…locate near ground level
- Avoid toxics, ordnance, etc. that drive dedicated facilities
- Avoid explosive devices (separation, pyro-valves, gear deployment) when other means available
- Avoid interstitial spaces to avoid active purges. Integrate the purges that are left into smallest number of storage tanks and plumbing
- For reusable systems, design vehicle for phased maintenance (several specifics identified)
- Degree of reusability (functional retention upon recovery) greatly influences facility & equipment infrastructure across the enterprise:
  - Highly Reusable (complete retention of function upon recovery)
  - Reusable (most functions retained upon recovery)
  - Moderately Reusable (many functions retained upon recovery)
  - Expendable (High fixed cost burden and steep variable cost-per-flight)
  - Salvage and Reuse (High production/assembly and recovery/retrieval costs)

Step Five
Simplify Avionics and Flight Control Design Using Minimum Components…Power & Automate What's Left

- Use simple, dependable flight control mechanisms that do not require routine fluid and/or gas servicing (and support systems and infrastructure) during ground operations

- Keep number of dedicated avionics boxes to an absolute minimum to the point where no dedicated active avionics cooling subsystems are required—know this limit and manage like weight budgets

- Build-in enough mass margins to account for avionics cable lengths and interconnectivity hardware

- Avoid specialized ground power

- Build in remote autonomous avionics functional verification every time systems are powered-up

Step Six

Extensively Test/Adjust the Design to Qualify the System and Achieve the Objectives

- Prove-out design assumptions of simplicity
- Build technical and managerial confidence in a simple, robust system prior to committing to production
- Allow flight test program that schedules improvements in system design that reduces turnaround work content prior to production
- Maintain a separate, developmental component, subsystem, system, and flight test infrastructure and capability
  - Offline from operational transportation service to continually work in improvements
  - Take flight risk of new improvements off-line from operational systems
  - Progress in affordability should allow less expensive flight testing
  - Creates technology maturation capability (beyond technology rediness level (TRL) 6) needed by our space transportation industry

Selected Expendable Launch Vehicle Experiences

Expendable Launch Vehicle (ELV) Planned and Unplanned Ground Operations Bear Some Similarities to Manned Launch Systems

- Following data is historic (1963-1997)
  - More than one contractor and stage
  - Specifics not provided if felt would be classified sensitive but unrestricted (SBU) today
  - Specific numeric values are likely obsolete, but general trends & lessons learned still applicable

Launch Pad Procedures with Greatest Schedule, Staff Impact

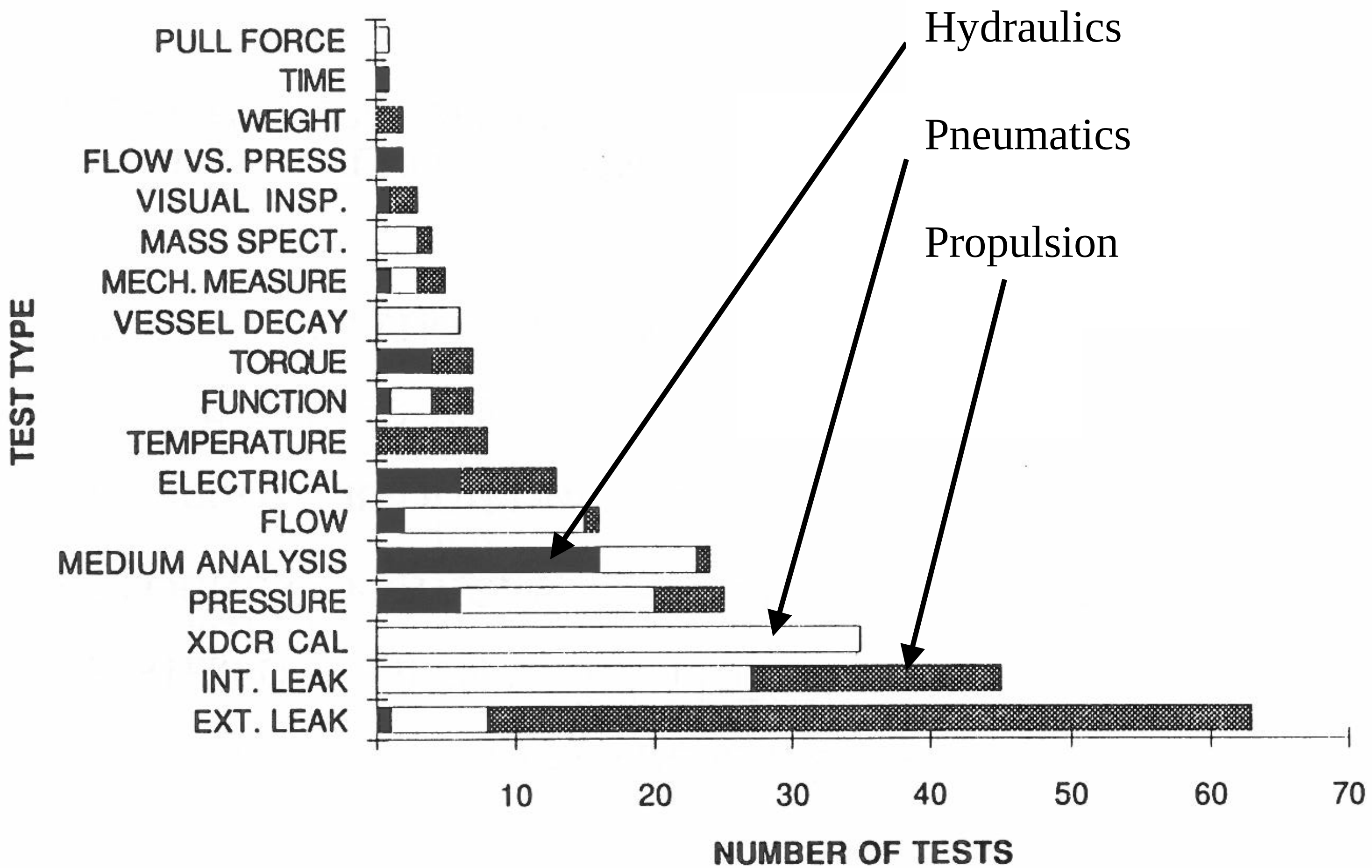
("typical historic ELV")

Large schedule/staffing impact operations could be mitigated by <u>avoiding</u> certain concepts, technologies

Pad procedures	System	Days	Person	Man-hr
• By serial days				
– Propellant vent system check	pneumatics	17	3	408
– Thermal radiation shields installation	structures	14	3	336
– Propulsion and hydraulics readiness	propulsion	8	3	192
– Flight and ground pneumatics check out	pneumatics	7	8	448
– Install & close out fill & drain valves	propellant load	7	8	448
– Propulsion flight readiness ops	propulsion	7	3	168
• By person count				
– Hydrazine (N2H4) loading preparation	propellant load	5	35	1392
– N2H4 flight loading	propellant load	2	35	557
– Propellant system cold flow	propellant load	1	24	192
– Hydraulic & autopilot end-to-end	hydraulics	2	18	280
– Insulation panel installation and removal	structures	2	14	224
• By man-hours				
– N2H4 loading preparation	propellant load	5	35	1392
– N2H4 flight loading	propellant load	2	35	557
– Flight and ground pneumatics check out	pneumatics	7	8	448
– Install & check out fill & drain valves	propellant load	7	8	448
– Propellant vent system check	pneumatics	17	3	408

Nature of Pad Tests by Quantity

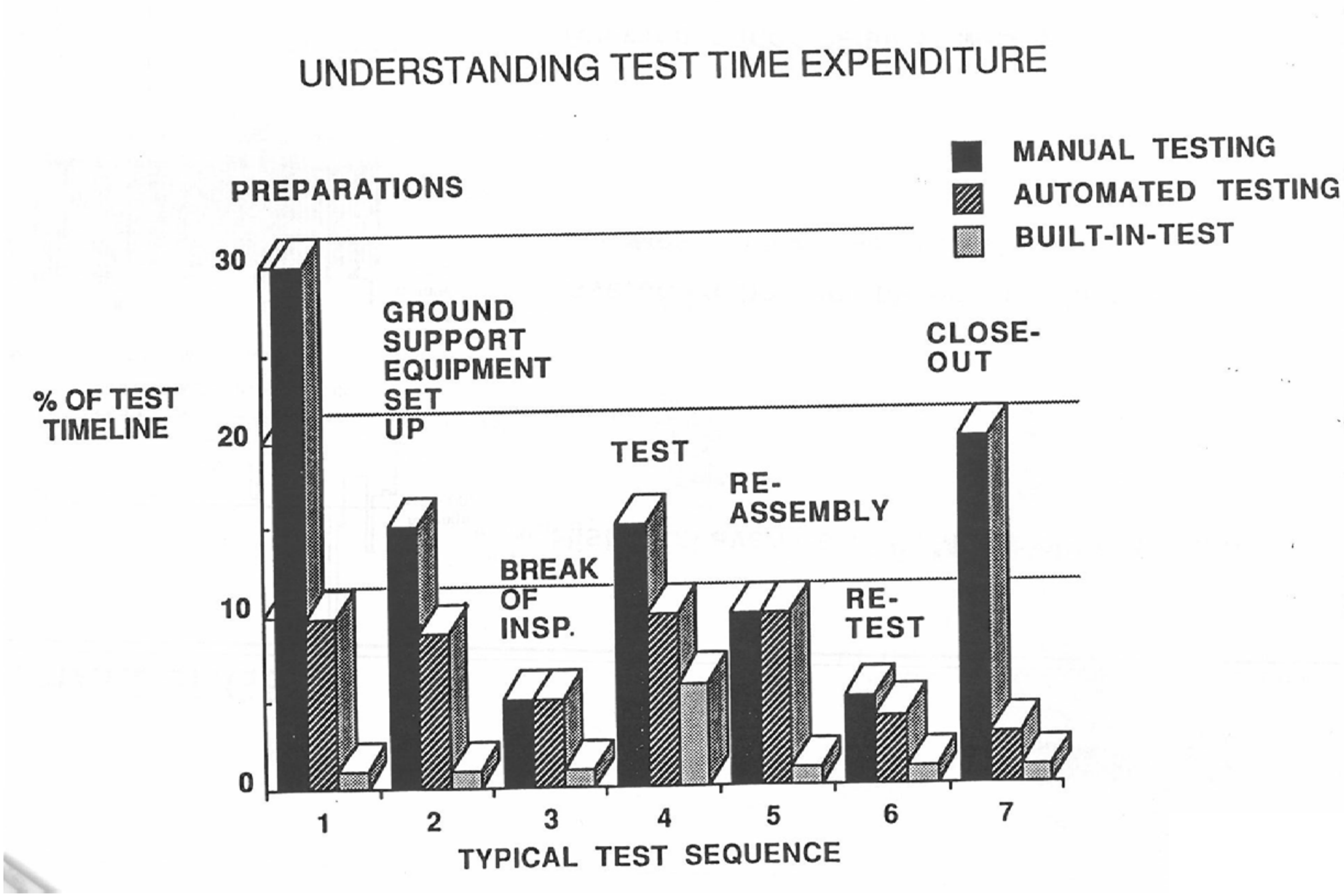
(Representative of Historic ELV Only)



Preponderance of pad tests have been propulsion, pneumatic leak-related; followed by calibration

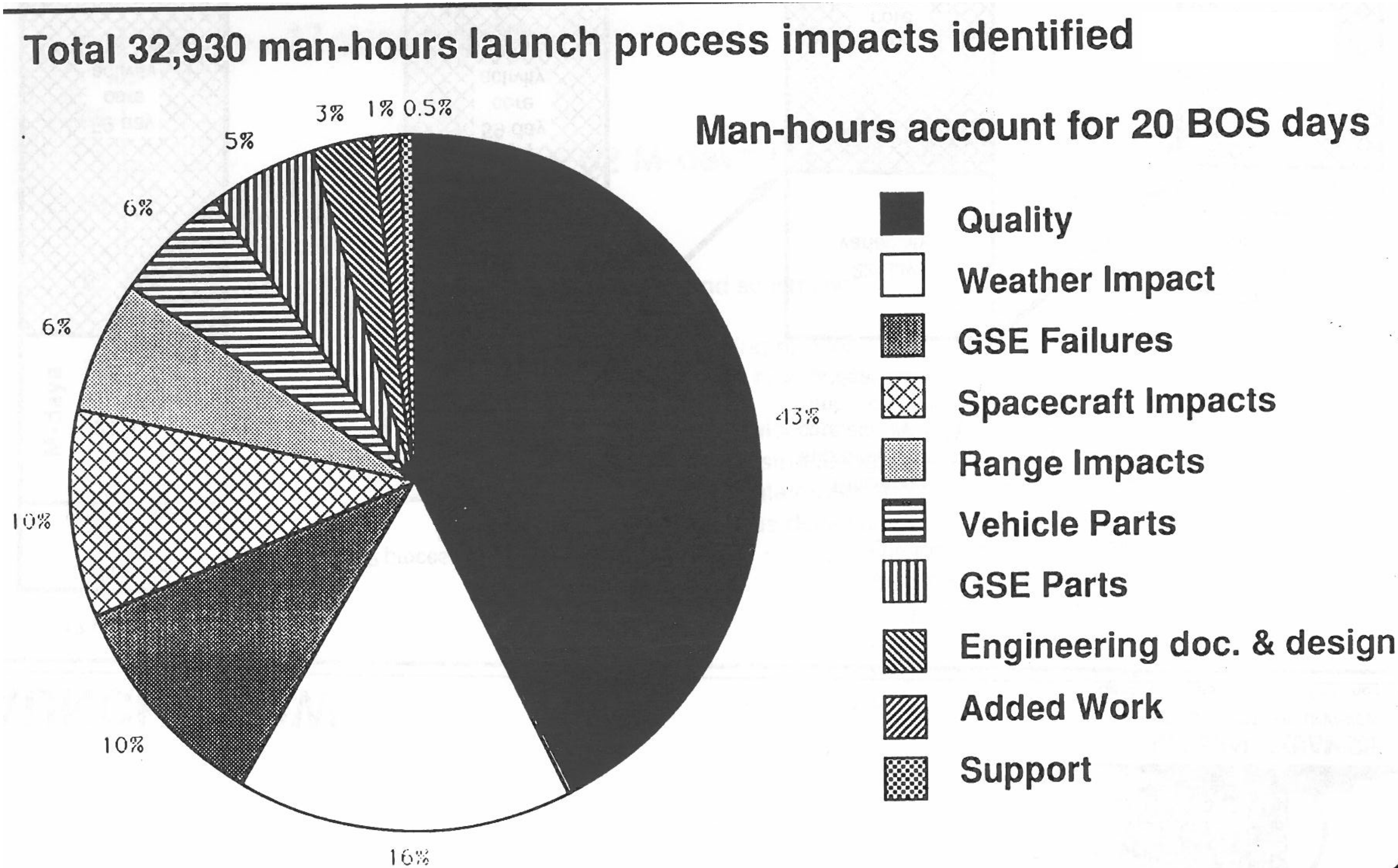
Built-in Testing Can Greatly Improve System Schedule

(Representative of Historic ELV Only)



Unplanned Schedule and Cost Impact Sources

(Quality shortfalls account for ~43%)

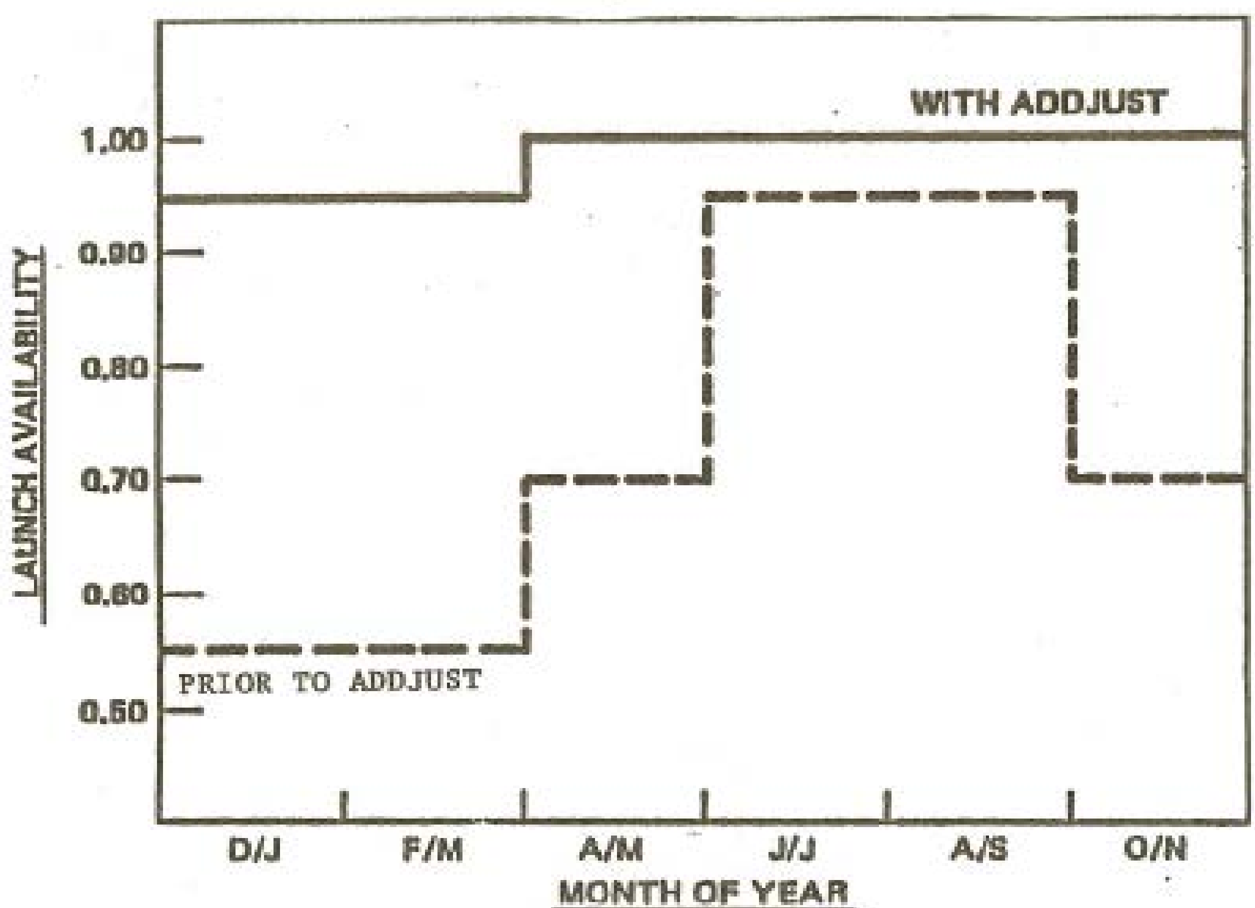


Booster Steering Program Evolution

Genesis of need for improved launch availability and the creation of:
Automatic **D**etermination and **D**issemination of **J**ust **U**pdated **S**teering **T**erms (ADDJUST)

Dates	# Vehicles	Centaur Booster	Booster Steering	Residual Angle of Attack (degrees)
1962-66	9	Atlas	Seasonal pitch programs (4)	2.0
1967-72	18	Atlas	Pre-designed launch day-selectable pitch & yaw programs (10 pitch (P) & 10 yaw (Y))	2.0
1972	1	Atlas	Pre-designed launch day-selectable pitch & yaw programs (10,000 P & Y combinations) **(scrubbed three days for winds)**	1.5 to 2.0
1973 - present	>100 8	Atlas Titan	Launch-day-designed pitch & yaw programs **(ADDJUST)**	~ 0.5

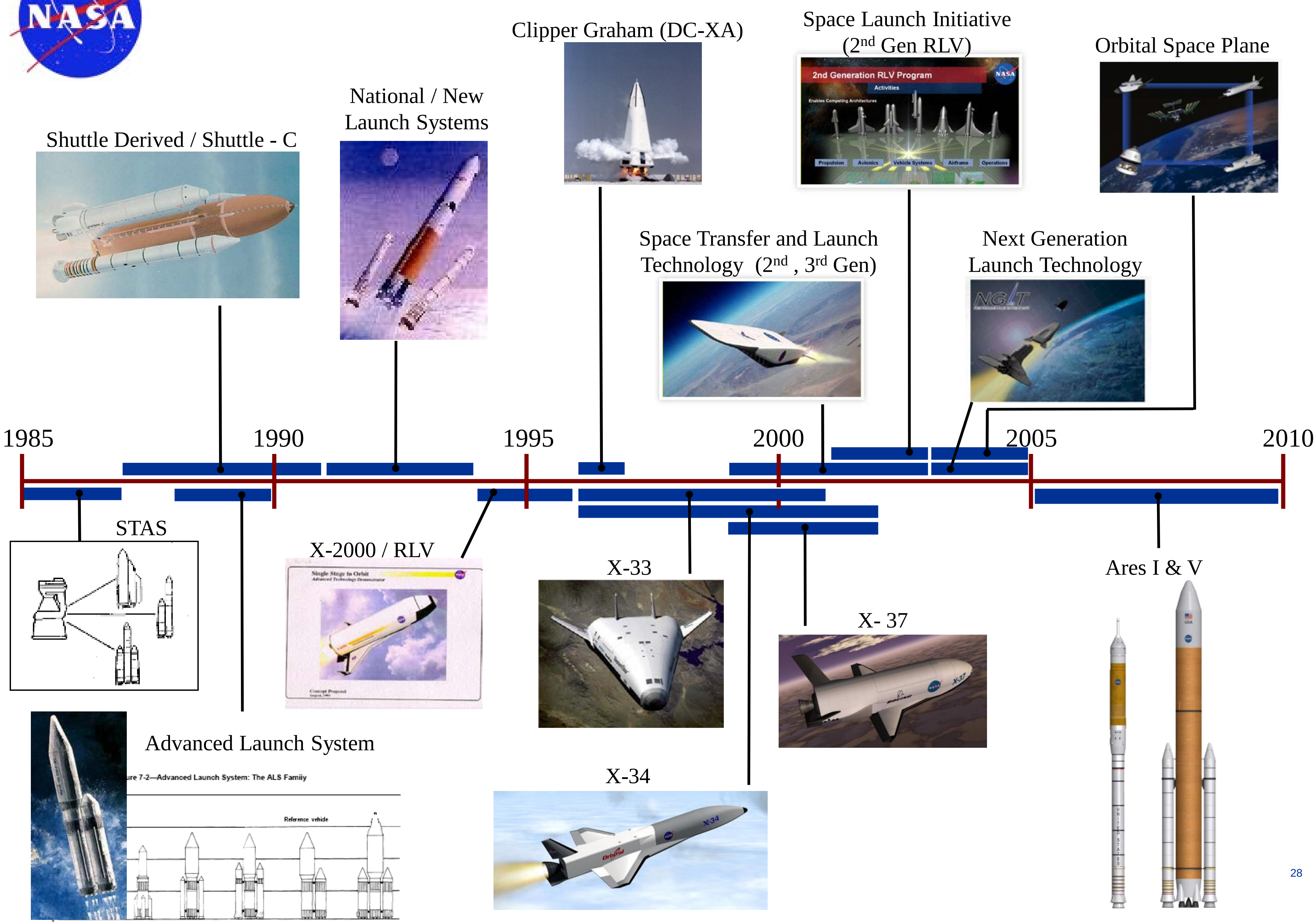
Launch Availability Improvement With ADDJUST



Flew on 51 Centaur flights (1973 – 1998) and always got a "GO" on first attempt
Prevented **countless** scrubs due to flight winds and avoided associated risks

Past NASA Launch Vehicle Development Programs, Studies (1985 to present)

Selected NASA Launch Vehicle Development Programs, Studies



NASA Launch Vehicle Development Programs and Major Studies

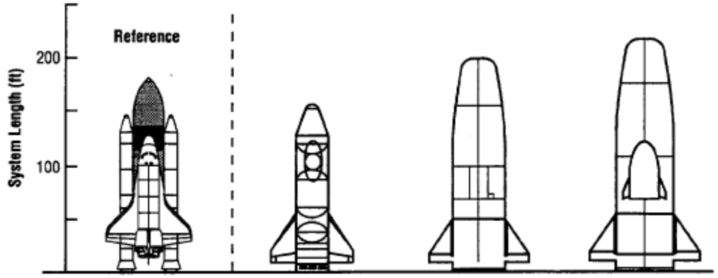
Data from "NASA Fiscal Year Budget Estimates" (1985 – 2014)
(NASA funds only)

Most Programs/Studies Stated Motivations were Cost & Operationally Driven

Years	Program / Study	Then year $M Totals	Constant FY14$M Totals
1985 - 1986	Space Transportation Architecture Studies (STAS)	24.0	58.6
1987 - 1990	Shuttle Derived / Shuttle-C	35.5	77.4
1988 - 1989	Advanced Launch System (ALS)	146.6	313.5
1989 - 1993	Advanced transportation studies (Access to Space, etc.)	96.2	182.3
1991	National Launch System (NLS)	23.9	46.2
1992 - 1993	New Launch System (NLS)	38.0	69.1
1994 - 1995	Reusable Launch Vehicle (RLV)	182.7	307.1
1996 - 1998	Advanced Space Transportation Program (ASTP)	126.0	200.5
1996	Clipper Graham (DC-XA)	17.0	27.7
1996 - 2000	X-33 (Large Scale Advanced Technology Demonstrator)	1,116.2	1,749.9
1996 - 2001	X-34 (Small Booster / Reusable Demonstrator)	194.9	297.6
1997 - 1999	Bantam	36.3	57.0
1999 - 2001	Future X / X-37 (ALTV & orbital vehicle) / X-40A Demonstrators	104.1	152.0
1999	Pathfinder	11.6	17.7
1998 - 1999	Future Space Launch Studies (STAS, etc.)	40.0	61.5
1999 - 2002	STLT (2nd, 3rd Gen) (Spaceliner 100, RBCC, TBCC, X-43C, etc.)	263.7	383.2
2001 - 2002	Space Launch Initiative (2nd Gen RLV)	691.7	962.6
2003 - 2004	Orbital Space Plane (OSP)	575.6	752.4
2003 - 2004	Next Generation Launch Technology (NGLT)	1,151.1	1,504.7
2005 - 2011	Ares I, Crew Launch Vehicle (CLV)	4,790.9	5,313.9
2008 - 2011	Ares V, Cargo Launch Vehicle (CaLV)	70.0	76.4
2011 -	Space Launch System (SLS) (2011: "Heavy Lift Launch Vehicle & Pro	6,048.5	6,218.9
	Total (then-year) $M	15,784.5	
	Inflation factors (convert to FY 2014 constant dollars)		
	Total (constant FY14) $M		18,830.2

Example: "Advanced Space Transportation Studies: Access to Space" (1993)

- Major NASA HQ chartered internal study (1993)
  - Three months intensive travel & meetings
  - Three months of final report preparation, reviews
- Three teams
  - Shuttle-based (HQ & JSC centric team)
  - Conventional technology (MSFC team)
  - New technology (broad NASA-wide team, some USAF)
- Observations from New Technology Team point of view:
  - Operations was strictly a dependent variable
    - Almost no impact on conceptual designs
    - Minimal consideration of operation maladies
    - Notable exception: no hypergolics --- attributed to constant pounding by KSC-rep that was held in high regard by leadership) Performance and technical considerations drove system design
  - Weight-based cost estimation relations (CERs) for costing --- drove performance, drove design
  - No participation by potential Users
  - "Staging is bad" was a religion
- Erroneously credited as the genesis of X-33 Program



Vehicle	Shuttle	Single-Stage Vehicle	Single-Stage Vehicle	Two-Stage Vehicle
Reusability	Partial	Full	Full	Full
Propulsion	Rocket	Rocket	Air-breather/Rocket	Air-breather/Rocket
GLOW	4.5M lb	1.96M lb	917k lb	802k lb
Dry Weight	508k lb	159k lb	239k lb	304k lb
Payload to 100 nmi circ at 28.5°	53.8k lb	41k lb	52k lb	32k lb
Payload to 220 nmi circ at 51.6°	25k lb	25k lb	25k lb	25k lb
Weight Growth Margin	—	15%	15%	15%

Efficient Operations and Lower Life Cycle Costs: Impacts on Conceptual Design and Research & Technology

- Past NASA RLV programs/studies stated goals have been lower cost and operationally efficiency, approaches still tended to be (traditional) performance and technical feasibility-driven
  - Operations (cost, sched, staffing, activities) largely dependent variables
  - Tended to minimize DDT&E costs --- risking higher cost, longer operation time lines for system life cycle

- Operability and (lower cost) reusability must be design-in at start (cannot be readily retrofitted)
  - Operations are **<u>in</u>**dependent variables
  - Focuses on minimizing life cycle costs
  - Designed for operations (ease of access, avoidance of labor/time/cost, etc.)
  - At a minimum: a co-equal design requirement with other performance metrics
  - Active participation of experienced system operators is fundamental to success of new development
  - Design approach may be open loop or iterated
    - Open loop: concept minimizes ops; performance deterministic
    - Iterated: concept minimizes ops; performance may/may not achieve goal
  - For reusability, concept must return to launch site (RTLS): big performance hit which must be designed in

- Focusing design on operability and (lower cost) reusability can lead to new drivers for research and technology
  - Robust margins (mass, dynamic loads, thrust, bandwidth, power, repeated loading, performance, etc.)
  - High quality, reliability components (to minimize inspections, repairs, replacements, and failures)
  - Minimal degradation (to maximize mean time between failures (MTBF))

Suggested Applications of NASA Lessons Learned to Already-Baselined Contractor XS-1 Phase I Concepts

How Can These NASA Lessons Learned on Reusable and Expendable Launch Vehicle Operations be Applied To DARPA's XS-1 Program ?

- Some Lessons Learned are being applied by XS-1 contractors --- but could/should be strengthened (though it is late)

- Proposal: ***perform modest, ground demonstrations of critical operations*** improvements of key sub-systems (or sub-scale) <u>in relevant environments</u> in an Iron Bird-type approach
  - Forward momentum could be maintained in an extended Phase I, while still making visible advancement in risk reduction and demonstrations of operability
  - Focus on areas which have been major drivers of past costs and schedules (KSC's Six Critical Steps to an Affordable, Economically Sustainable System Design)
  - Could be performed at a fraction of anticipated Phase II expenditures
  - Could link software and hardware together with ground crew in the loop

- Approach:
  - Intersect KSC's Six Critical Steps to an Affordable, Economically Sustainable System Design with each contractor's concept
  - Select 2 or 3 key sub-systems/technical areas (some might be common to all contractor concepts)
  - Ground test sub-systems to primary duty cycles
  - ***Measure operations*** and technical performance throughout testing (individual task schedule and staffing (including for planned inspections and unplanned remove/replace actions))
  - Tear-down & analysis post-test to ***measure component degradation*** (i.e. impact on reusability)
  - ***Apply results to modify concept***

- Additional support to DARPA
  - AFRL and NASA laboratories have shown willingness to contribute computer and test support
  - Extended Phase I testing expected to be within wind tunnel & vacuum chamber capabilities
  - In-kind facility/testing/technical support to DARPA from NASA & USAF could defray some costs for Phase I extension

> If "a picture is worth 1,000 words," then "a touch is worth 1,000 peeks."
>
> A real time demonstration, even in a ground facility, lends tremendous credibility to a system concept

Examples of Potential Iron Bird-type Ground Tests to Demonstrate Critical Improvements in Operations

- **Propulsion:** single engine with propellant feed sub-system test. Hot-fired in vacuum chamber with relevant thermal environment could demonstrate ability to perform ten duty cycles with acceptable recycle time and staffing, while demonstrating acceptable performance degradation for re-use.

- **Avionics:** a flight control system (including computer hardware & software, selected actuators, pumps, etc.) initially represented by simulation, later by proto-flight hardware in an system integration lab. Mass equivalent control effectors could be powered to produce hinge moments at critical point to verify flight control system adequacy. Demonstration would fly distinct missions, where ascent profiles would be changed to demonstrate acceptable software turnaround times.

- **Thermal Protection System**: material test of an appropriately-sized panel at a critical heating location. A wind-tunnel series of tests subjected to appropriate atmospheric conditions could demonstrate ability to perform most demanding ascent & descent profiles with acceptable recycle time (including inspection, repair, and replacement).

- **Upper Stage Integration:** ground mating test of mass simulators of both XS-1 and upper stage. Demonstrate streamlined staff trajectory optimization and performance analysis of integrated ascent profile within pre-defined/pre-certified mission box analysis.

- **Propellant Loading:** wet dress rehearsal of propellant loading (primary and reaction control system (RCS)) into sub-scale tankage. Demonstration using launch site utilities, ground crews (including Safety), interrupted by re-cycled countdown, then terminal count up to ignition. Plus-count operations could also be perform. Staffing, schedule, and assessment of tank degradation would be primary interests.

- **Aerodynamics:** subscale model flight test (tunnel or flight test). Demonstrate capability to perform critical flight maneuvers that enable XS-1 return to launch site or another predetermined location. Computational fluid dynamics (CFD) analysis over a mission box of trajectory & ambient conditions could be included in a 6 degree of freedom (DOF) model of the system, which would precede flight test.

- **Range Telemetric Support:** simulated minus and plus count support by ground or space-based telemetric assets. Weather tolerance, call-up notice, and resiliency would be primary measurements in a simulated ten launches in ten days test.

- **Payload Integration:** given an abbreviated payload requirement set, create an interface requirement document which satisfied primary XS-1standardized interfaces. This demonstration would be purely analytic, where number of staff and schedule would be measured. At a minimum: performance, trajectory, coupled loads, power, and data requirements would be the focus.

Conclusions & Recommendation

- Operability and (low cost) reusability must be designed-in at conceptual phase
  - Cannot be readily retrofitted
  - At a minimum: co-equal design requirement with other performance metrics
  - Active participation of experienced system operators is fundamental to success of new development
  - Minimizing up-front DDT&E costs risks higher cost, longer operation time lines for system life cycle

- Historic Shuttle operations data illustrates how not to design a operationally efficient, lower cost, reusable launch system

- Six Critical Steps to an Affordable, Economically Sustainable System Design --- based on Shuttle lessons learned --- provide an excellent starting point for operationally efficient, lower life cycle cost reusable launch vehicle

- Expendable launch vehicle experiences mirror many Shuttle lessons learned

- All past NASA launch vehicle development programs/studies (21 programs over 26 years) have failed to produce even a single prototype

- Efficient operations and lower life cycle costs could/should be new drivers for Research & Technology

<u>Recommendation to DARPA XS-1 Program Manager:</u>

Expedite operation demonstrations of selected, critical sub-scale/subsystems in relevant environments by each contractor to validate approach to achieving primary XS-1 goals