

Space Shuttle Integration

Lessons Learned

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OUTLINE

- **Introduction**
- **System Integration Approach**
- **Liftoff and Ascent Aerodynamics**
- **Structures**
- **Ascent Flight Control System**
- **Day-of-Launch I-Loads Evolution**
- **Avionics Architecture**
- **Main Propulsion**
- **Software**
- **Lightning**
- **Flight Instrumentation**
- **RCS Thrusters**
- **Materials and Processes**
- **Risk Management**
- **Operational Cost Drivers**
- **Margin Management**
- **Significance of Lessons Learned**
- **Other Applicable Lessons Learned**
 - Zenit Derived Launch System – Sea Launch
 - Delta IV – Separate Briefing
- **The Big Lesson**

Lessons learned from Shuttle development & operations can reduce SDLV cost and development schedule and result in a more reliable and safer vehicle.

Introduction

- **Two types of Shuttle Program Lessons Learned are addressed**
 - **Problems** – How they were resolved and their **applicability to SDLV**
 - **Success Stories** – How they were achieved and their **applicability to SDLV**
- **Lessons Learned are presented at a fairly high level**
 - Each can be expanded to any desired level of detail
- **Top-level Lessons Learned from Zenit Derived Launch Systems – Sea Launch are included**

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System Integration Approach

- **Shuttle Integration included:**
 - **Configuration tradeoffs early in the development phase**
 - **Mated system analysis and testing**
 - On the ground
 - In flight
 - Mated vehicle checkout requirements at the launch site
 - **Post flight data analysis**
- **Independent evaluation of all elements changes**
- **Definition and verification of system interfaces and interface parameters and associated documentation**
- **Integrated Hazard Analyses**
- **Integrated vehicle configuration management**

System Integration Organization

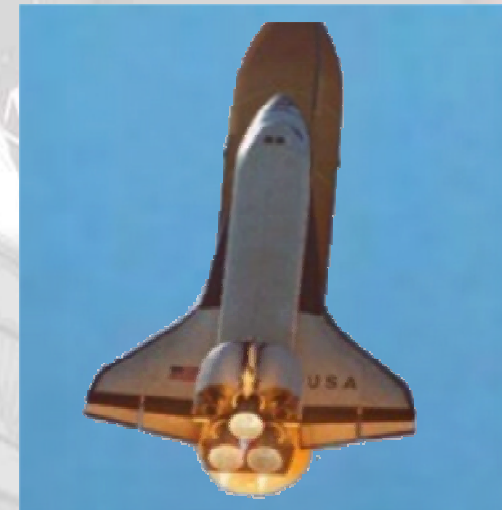
- **NASA was the Systems Integrator**
 - **Boeing, (Rockwell) was the Systems Integration contractor**
- **Owen Morris was the first NASA System Integration Manager for Shuttle**
 - **Powerful, admired and respected**
- **The importance of integration was not fully appreciated after the initial development phase**
- **NASA revitalized System Integration twice during the Shuttle Program's life**
 - **After the Challenger accident**
 - **After the Columbia accident**
 - **Each time a strong leader was put in charge of Integration and the Integration resources were revitalized**

System Integration Organization (continued)

Lesson

- It appears that the strength of Integration leadership is very important to the success of a program
- Integration should remain the “watchful” eye as the Program evolves to an “operational” status
- Continue flight data evaluation for the life of the Program

Shuttle System Definitions & Corresponding Analyses



1) Shuttle on Ground and Liftoff

- Liftoff Loads
- Ground Winds
- Liftoff Clearances
- Acoustics
- ET Pressurization
- Main Propulsion System
- Avionics Sequencing & Timing
- Electrical Power
- Integrated Hydraulics
- Software Requirements
- Integrated Checkout Requirements

2) Post Liftoff Configuration

- Winds Aloft
- High Q Loads
- Heating – Aero & Plume
- Flutter & Buffet
- Acoustics
- SRB Separation
- Control Stability & Control Authority
- ET Pressurization & MPS
- Integrated Hydraulics
- Software Requirements
- POGO

3) Boost Configuration

- High G Loads
- Heating – Aero & Plume
- ET Pressurization & MPS
- Integrated Hydraulics
- Power
- Control Stability & Control Authority
- POGO
- Software Requirements
- ET Separation

- Evaluation of flight test results and the establishment of operational boundaries for all flight phases

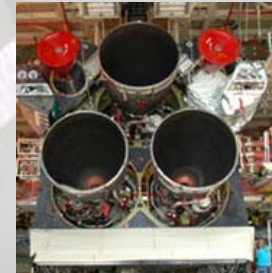
Shuttle Elements



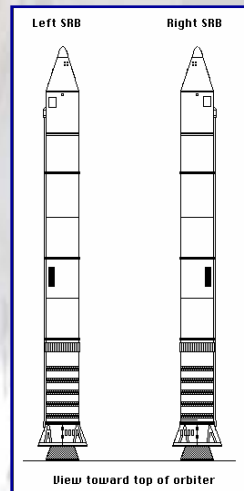
Ground Systems



External Tank



Shuttle System Main Engines

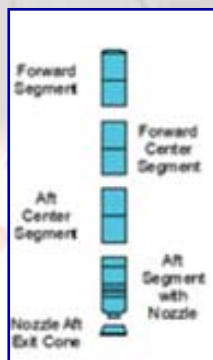


Solid Rocket Boosters (SRB)



Orbiter*

* Two cargo configurations analyzed – 65K lbs and 0 lbs payloads



Solid Rocket Motor (SRM)

System Integration Support to Element Designers

- **NSTS-07700 consisted of a series of requirements documents that were imposed on the elements**
- **System Integration analysis results were documented in Induced Environments Data Books and used by element designers**
 - **Loads**
 - **Aerodynamics**
 - **Aeroheating**
 - **Plume heating**
 - **Vibro acoustics**
 - **Separations**
 - **Main propulsion**
 - **Other**
- **Technical panels were established early in the development cycle to provide a forum for the smooth interchange of information between system integration and element experts**
- **The Systems Integration technical effort was iterative and involved several Design Cycles**

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- Lightning
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STS-1 SRB Ignition Overpressure (IOP)

Problem

- **SRB IOP measured at the vehicle exceeded the 3-sigma liftoff design environment**
 - Accelerations measured on the wing, body flap, vertical tail, and crew cabin exceeded predictions during the liftoff transient
 - Support struts for the Orbiter's RCS oxidizer tank buckled
- **Post flight analysis revealed that water spray designed to suppress SRB IOP was not directed at the source of IOP**
 - Source of IOP was believed to be at the plume deflector
 - STS-1 data analysis showed the primary source located immediately below the nozzle exit plane
- **Tomahawk ignition transient used for preflight characteristics were very different from that of the SRB**

STS-1 SRB IOP (Continued)

Corrective Actions

- Solution to the SRB IOP was treated as a constraint to STS-2
- IOP “Wave Committee” organized with participation of the NASA and the contractors
- A 6.4% model was modified to allow simulation of simultaneous ignitions of two SRBs with the firing of one motor only
 - Add a splitter plate in the flame bucket
- A new scaling relation was developed based on blast wave theory
- A series of 6.4% scale model tests were conducted to evaluate various concepts of IOP suppression schemes
- Final fixes
 - Redirected water spray for SRB IOP suppression toward the “source” of SRB IOP (Figure 1)
 - Installed water troughs in the SRB exhaust duct
 - Very significant IOP reduction was achieved (Fig. 2)

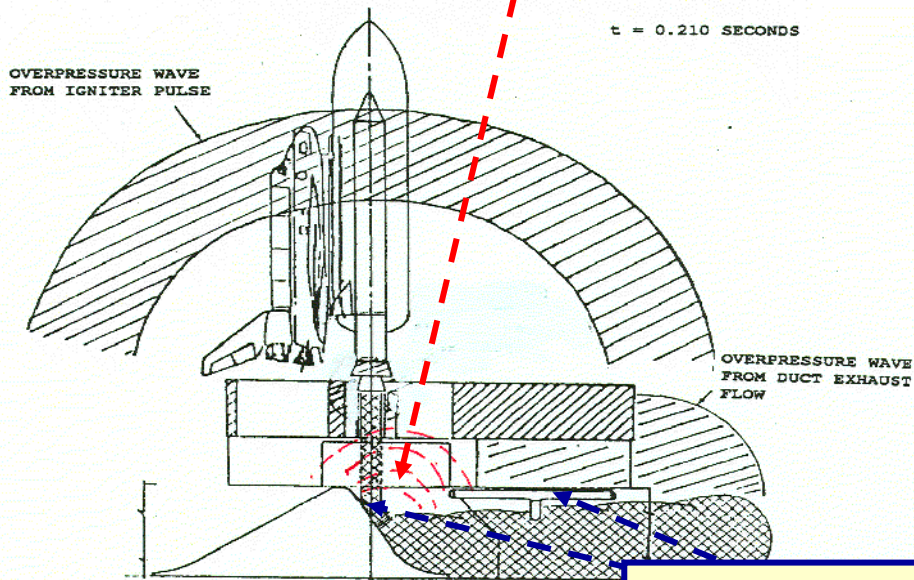


Figure 1: STS-1 and STS-2 SRB IOP Suppression Configuration

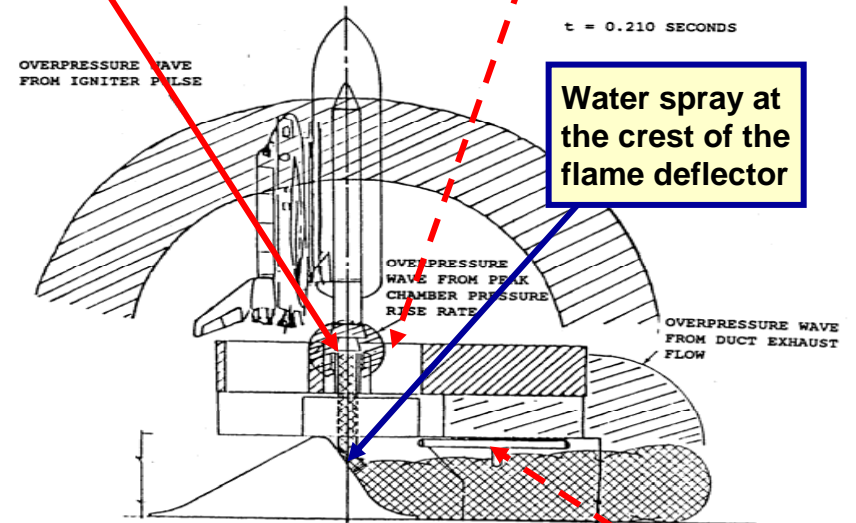
Water spray for STS-1 was designed for IOP Source at flame deflector

100,000 GPM of water injected into the SRB exhaust beneath the nozzle exit plane

Water troughs cover the SRB duct inlet



Water spray at The flame deflector and side pipes along the duct



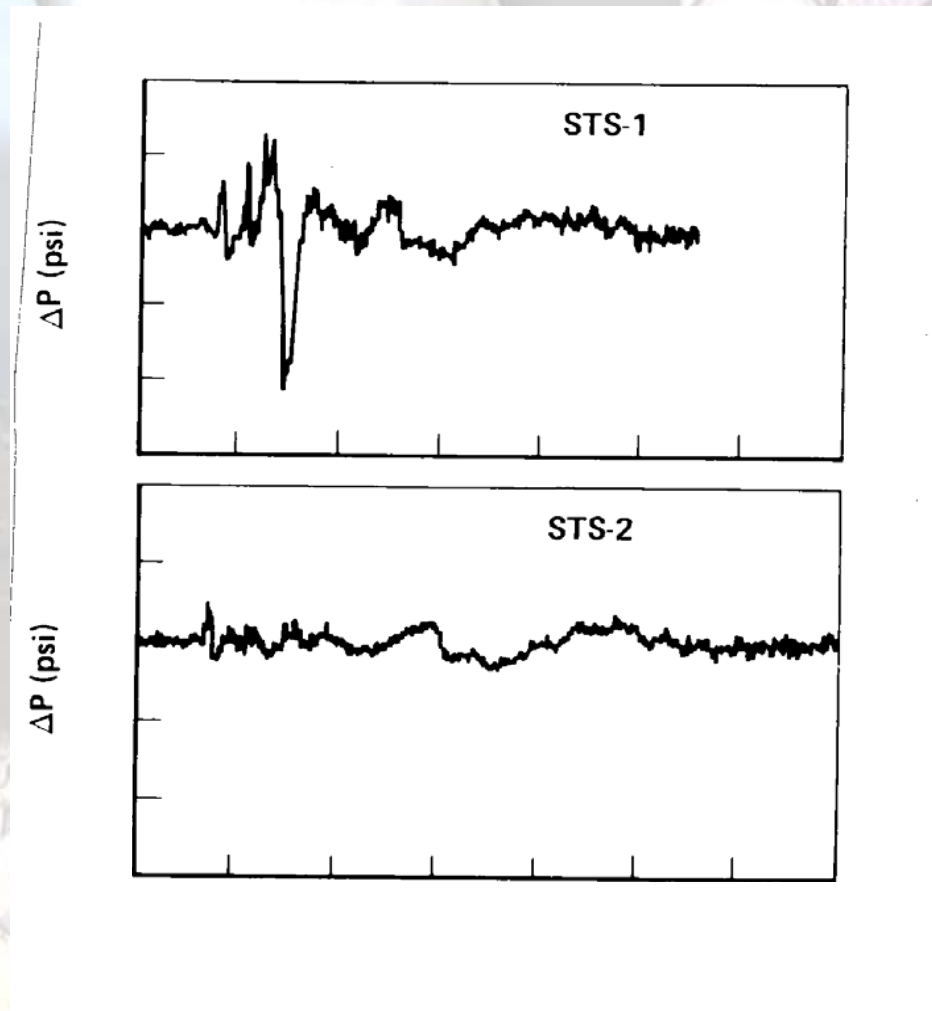
Water spray at the crest of the flame deflector

Water spray at the side of duct deleted

STS-1 Configuration

STS-2 Configuration

Figure 2: An overall factor of 5 reduction for the primary IOP waves was achieved with the redesigned system prior to STS-2



STS-1 SRB IOP (Continued)

Lessons

1. SRB Ignition is a powerful driver in liftoff environments
2. System Integration, responsible for liftoff environment definition, accepted the Tomahawk ignition test as a sufficient simulation of SRB ignition IOP – Did not fully appreciate the effect of the differences between the SRB and the Tomahawk ignition characteristics
3. SRB ignition transient for SDLV should benefit from post STS-1 efforts on the Space Shuttle
 - MLP configuration should be evaluated to account for a single SRB
 - If the SRB propellant shape or type is changed, the effect on IOP should be re-evaluated

Ascent Aerodynamics

Problem

- **Plume simulation used during the preflight wind tunnel test program was not adequately implemented**
 - **Observed significant wing lift and vehicle lofting in STS-1**
 - **Measured strains showed negative structural margins**
- **Under-predicted ascent base pressures (base drag over-predicted)**
 - **Temperature effects were not modeled in cold jet plume simulation parameters used during testing**

Corrective Actions

- **The Post-flight tests using hot plume simulations improved base and forebody pressure predictions**
- **The ascent trajectory was changed to a flight with a greater negative angle of attack through High Q**
 - **The negative angle reduced wing lift**
 - **The negative angle had to be evaluated for Orbiter windows and the ET side wall pressures**

Ascent Aerodynamics (continued)

Lesson

- Although the hot plume re-circulation effect is less significant on an axis-symmetric vehicle, it should be accounted for when defining pressure on the base and aft portion of the vehicle

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- Lightning
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Structures

Problem

- Throughout Shuttle development and the initial years of operations many costly structural modifications had to be made to maintain the required 1.4 structural safety factor
 - The Shuttle structure was designed for a 1.4 safety factor with no additional margin to accommodate changes occurring during the development phase

Corrective Actions

- As mathematical models and definitions of the environments matured, resulting changes required many hardware changes to eliminate areas of negative margin (below a 1.4 safety factor)
 - These hardware modifications were expensive and time consuming. Additionally, they increased workload at the launch site
 - This tedious activity ensured safe flights and compliance with the safety factor requirement, however it created a significant impact on Shuttle operations

Structures (continued)

Lessons

- **If development time is short, structural margin management could be pursued to avoid costly hardware changes as loads analyses mature**
 - **A suggested approach could be as follows:**
 - **Assign additional factor to be applied to the design loads for environments with the greatest uncertainties**
 - **For example, gravity and pressure loads could have a factor of 1.0 but dynamic and aero loads could have a factor of 1.2**
 - **All factors would converge to 1.0 as a function of program maturity**
 - **A method of structural margin management could minimize costly hardware redesign, and program stand downs, but it may result in a somewhat heavier vehicle**

Structures - Aero Elasticity

Problem

- Flight data indicated a significantly higher buffet response of the vertical tail and body flap during ascent (at transonic speeds)
 - The importance of buffet loads was not fully appreciated in the early Shuttle design (flutter was properly analyzed, safe boundaries were established and stability was verified during flight)

Corrective Actions

- Flight instrumentation and ascent photography were used to measure response in flight
 - Ascent environments were updated to correspond to measured response
 - The body flap critical design case was entry (thank goodness), no action was required since including buffet loads on ascent was still enveloped by entry
 - The vertical tail had sufficient margin to accommodate increased buffet loads

Structures - Aero Elasticity (continued)

Lesson

- Even though the CLV has a significantly simpler configuration, transonic buffet, particularly for the bulbous shape, should be addressed in the early loads analyses and test programs

Liftoff Loads Analyses

Shuttle

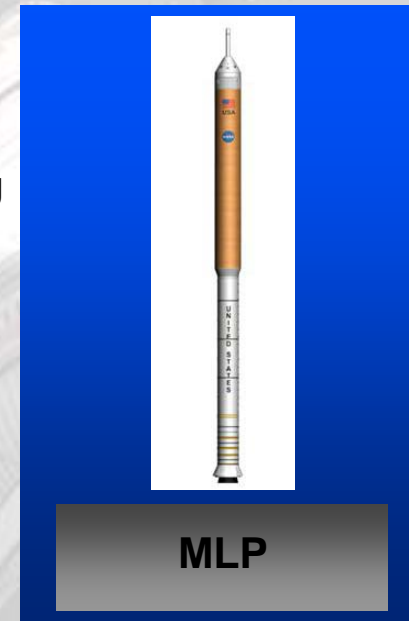
SRB growth loads are transmitted directly to Orbiter thru H2 Tank. H2 Tank provides softening compliance



H2 Tank Compliance

Common Shuttle/CLV

- SRB grows 0.9” during ignition
- MLP deflects downward
- Forward interface translates upward



SRB growth loads are transmitted directly to 2nd stage potentially creating more sever L/O loads

MLP

CLV

Problem

- Shuttle liftoff (L/O) loads were very difficult to analyze
 - Configuration complexity
 - SRB Ignition Overpressure
 - “Twang” during the SSME thrust buildup
- Vandenberg experience showed that loss of the MLP compliance significantly increased L/O loads
- Flexible washers were planned to restore compliance and avoid vehicle redesign

Liftoff Loads Analyses (continued)

Corrective Actions

- SRB ignition delayed until the SRB bending moment (due to SSME thrust buildup) was at zero
- Four independent support posts modeled in L/O simulations
- Monte Carlo method was incorporated
- Ground wind restrictions were implemented

Lesson

- In spite of the relative configuration simplicity of the CLV, L/O loads may be a significant design issue due to direct load path between the SRB and the upper stage

Conversion of Static Test Article (STA) to the Flight Orbiter

Success Story

- The Orbiter STA was originally intended for Orbiter structure strength demonstrations
 - Planned to be subjected to ultimate loads
 - Demonstration of 1.4 times limit load
 - Very difficult to simulate combined thermal and mechanical loads
- Prior to test start, the decision was made to limit loading to “limit plus” load level
 - Test article was not stressed beyond yield
 - This test was supplemented by component testing to 1.4 times limit loads in areas of low margin and sensitive joints
 - The Orbiter test article was treated as flight hardware (configuration management, problem dispositions)
- Post test, the STA was converted to flight hardware and used as the Challenger’s airframe

Lesson

- Thoughtful planning of the test hardware and transitioning it to “flight status” could result in significant cost savings

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- Main Propulsion
- Software
- Lightning
- Flight Instrumentation
- RCS Thrusters
- Materials and Processes
- Risk Management
- Operational Cost Drivers
- Margin Management
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Day-of-Launch I-Loads Update (DOLILU) Evolution

Problem

- The launch probability predictions for early Shuttle flights was less than 50%
 - More than half of the measured winds aloft violated the vehicle's certified boundaries

Corrective Actions

- System Integration led the evolution from a single ascent I-load, through seasonal I-loads, alternate I-loads, and finally arriving at DOLILU
- This process extended over a 10+ year period (Figure 3)
- Concurrently the Program executed 3 load cycles (Integrated Vehicle Baseline Characterization - IVBC) combined with hardware modifications to expand vehicle certified envelopes (Figure 4)
- Current launch probability is well in excess of 95%

Lesson

- Commit to a DOLILU approach during early development
 - Significantly improves margins

Figure 3: Ascent Design Operations Evolution

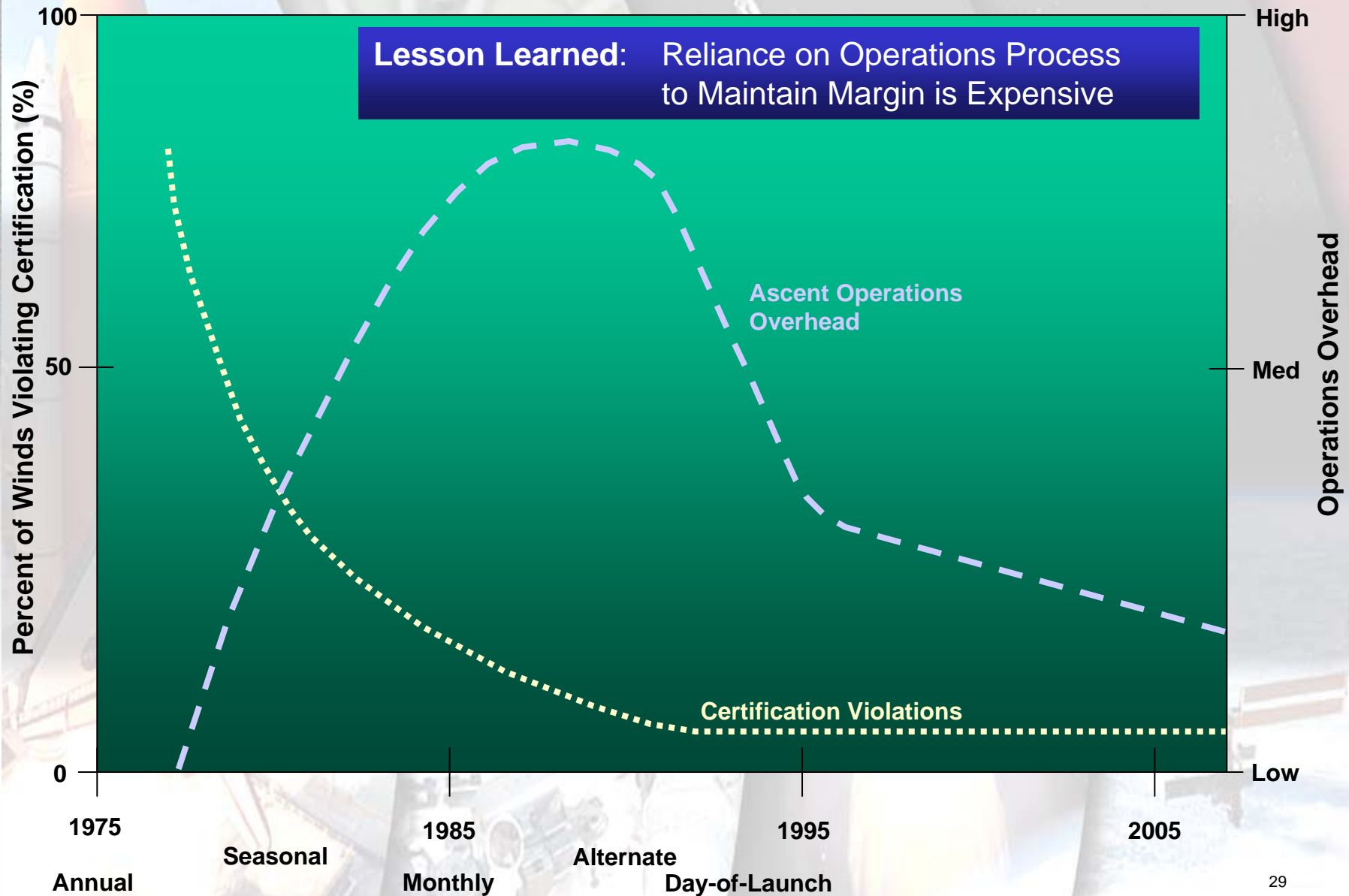
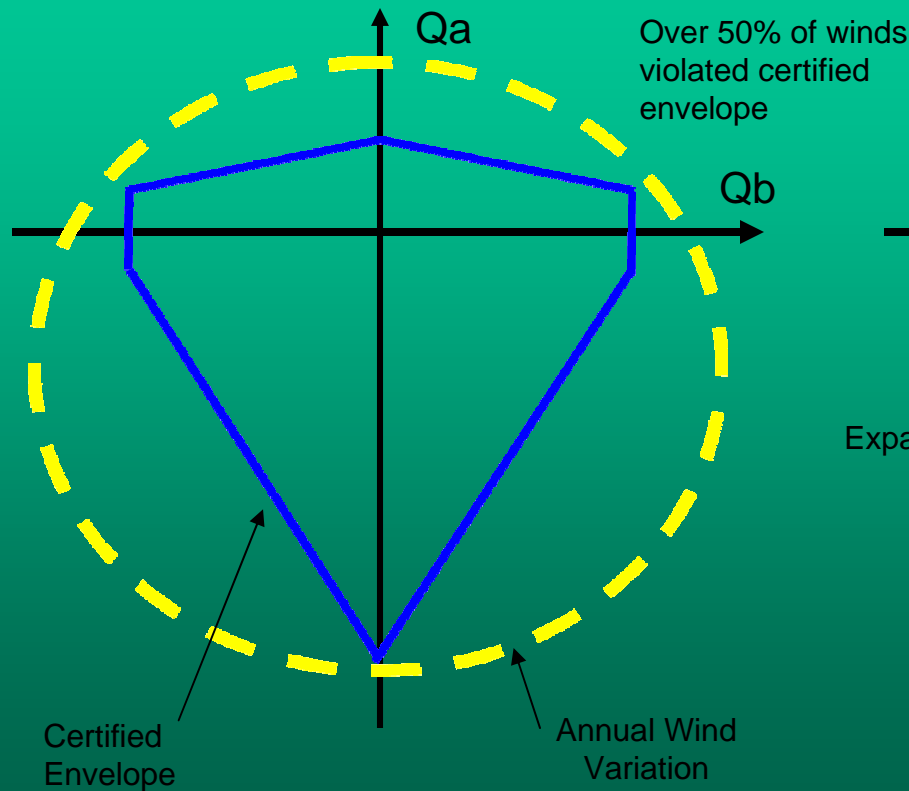
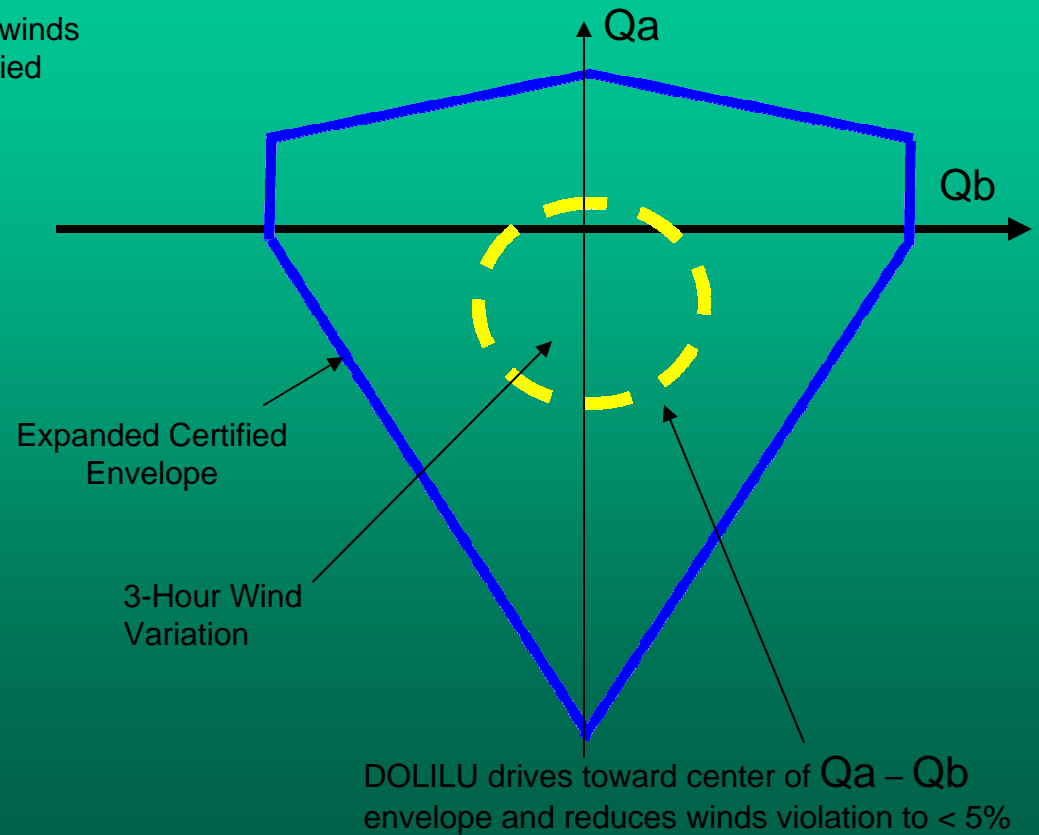


Figure 4: Day-of-Launch I-Loads Evolution (10 years +)

Early Flights Single I-Loads



Present Flights DOLILU



SDLV can benefit by starting with DOLILU or Adaptive Ascent Guidance

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- Main Propulsion
- Software
- **Lightning**
- Flight Instrumentation
- RCS Thrusters
- Materials and Processes
- Risk Management
- Operational Cost Drivers
- Margin Management
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Lightning Requirements

Problem

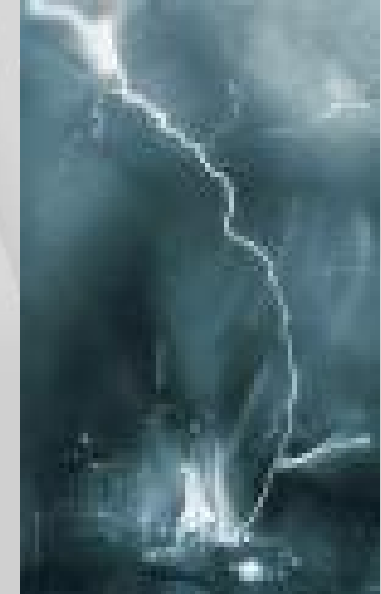
- **The Shuttle started with strict requirements**
 - TPS could not be certified
 - Avionics were difficult

Corrective Actions

- **Decision was made to transition to operational restrictions**
 - Field Mills & catenaries on ground
 - Cloud cover restrictions before launch
- **Years of unnecessary cost and effort prior to decision**

Lesson

- **Starting with a “fair weather” vehicle may be a cost effective approach**
 - Some avionics hardening could be worthwhile
 - Crew escape should be considered for hardening



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- Software
- Lightning
- Flight Instrumentation
- RCS Thrusters
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- Risk Management
- Operational Cost Drivers
- Margin Management
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Risk Management

Problem

- Although risk was managed by good engineering practices, very little formal risk classification and management was employed
- Probabilistic Risk Analysis (PRA) was rarely used on the Shuttle Program
 - Distrust of the methodology, lack of suitable data, Apollo experience
- Frequently funds were expended pursuing corrective action for extremely low probability threats – no means to measure effectiveness of a corrective action on the overall system reliability or safety

Corrective Actions

- A 5X5 matrix risk classification was implemented on the Shuttle Program
 - Up and down the organization, from individual technical disciplines to the Program Manager (Figure 5)
- PRA implemented on several technical projects
 - Orbiter windows, debris, Kevlar Overwrapped tanks, MMOD
- Response to CAIB criticism

Risk Management (continued)

Lesson

- **Formal risk management, including PRA, early in development could produce many cost savings features such as:**
 - Ensuring that system reliability drives redundancy requirements
 - Prioritizing safety and reliability enhancements
 - Identifying “highest value” initiatives
- **Use competent PRA analysts**
 - Must have the data
- **PRA does not replace good engineering**

Figure 5: Risk Rating Developed Since the Columbia Accident (Program View)

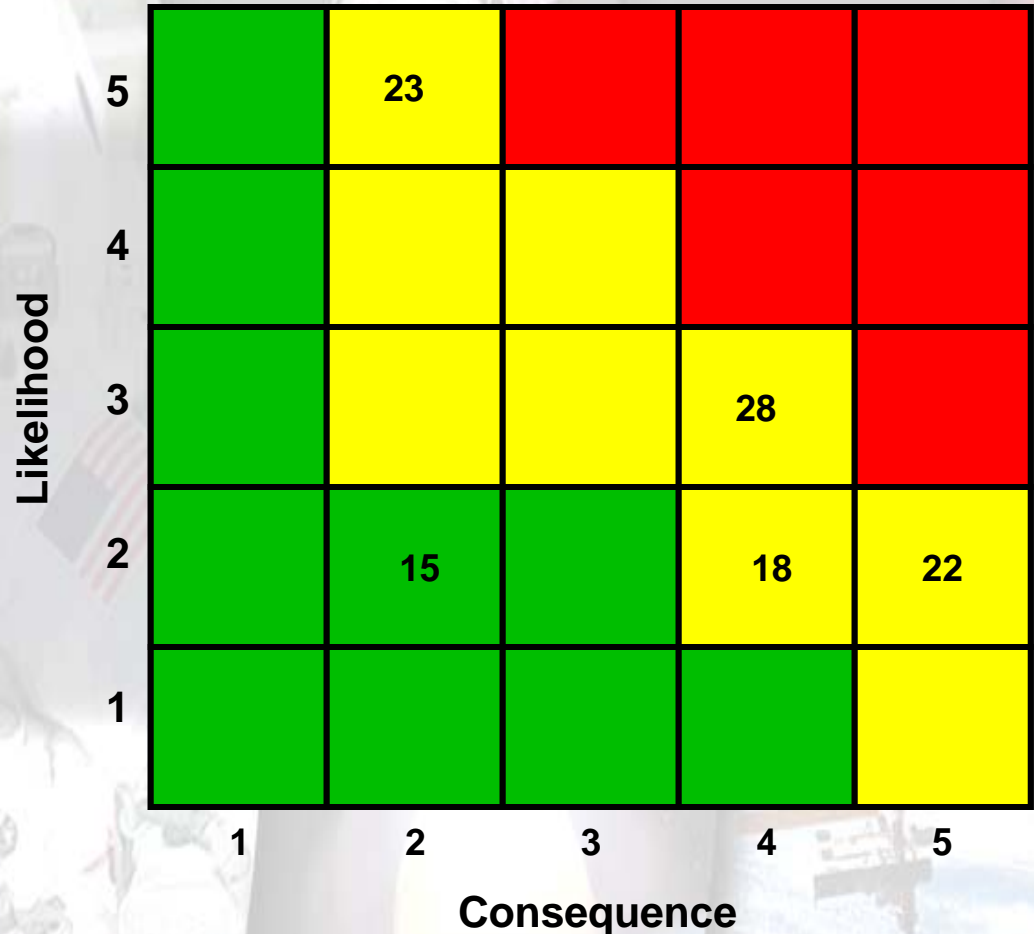
15 – Redesign of FRCS Paper Covers
Using Tyvek (Completed design/drawings)

18 – Orbiter Processing Issues – Hardware
(Numerous processing issues at KSC)

22 – Water Spray Boiler Freezing
(Mitigation design in work, on-orbit testing planned)

23 – MPS Surface Mounted GO2 Temp
Sensor Mod (Complete design drawings/
MASR II database update)

28 – Cold Plate Manufacturing Issues

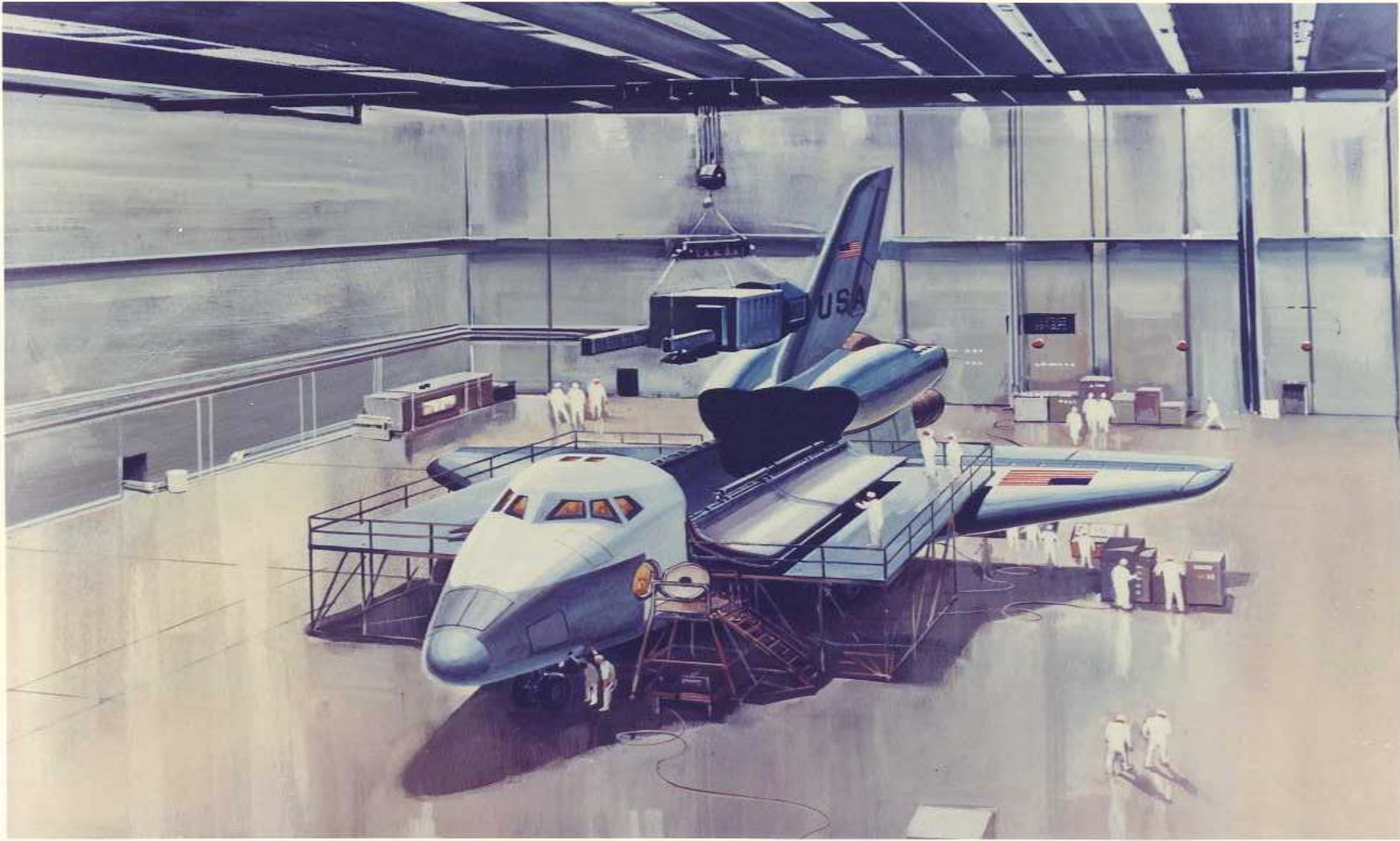


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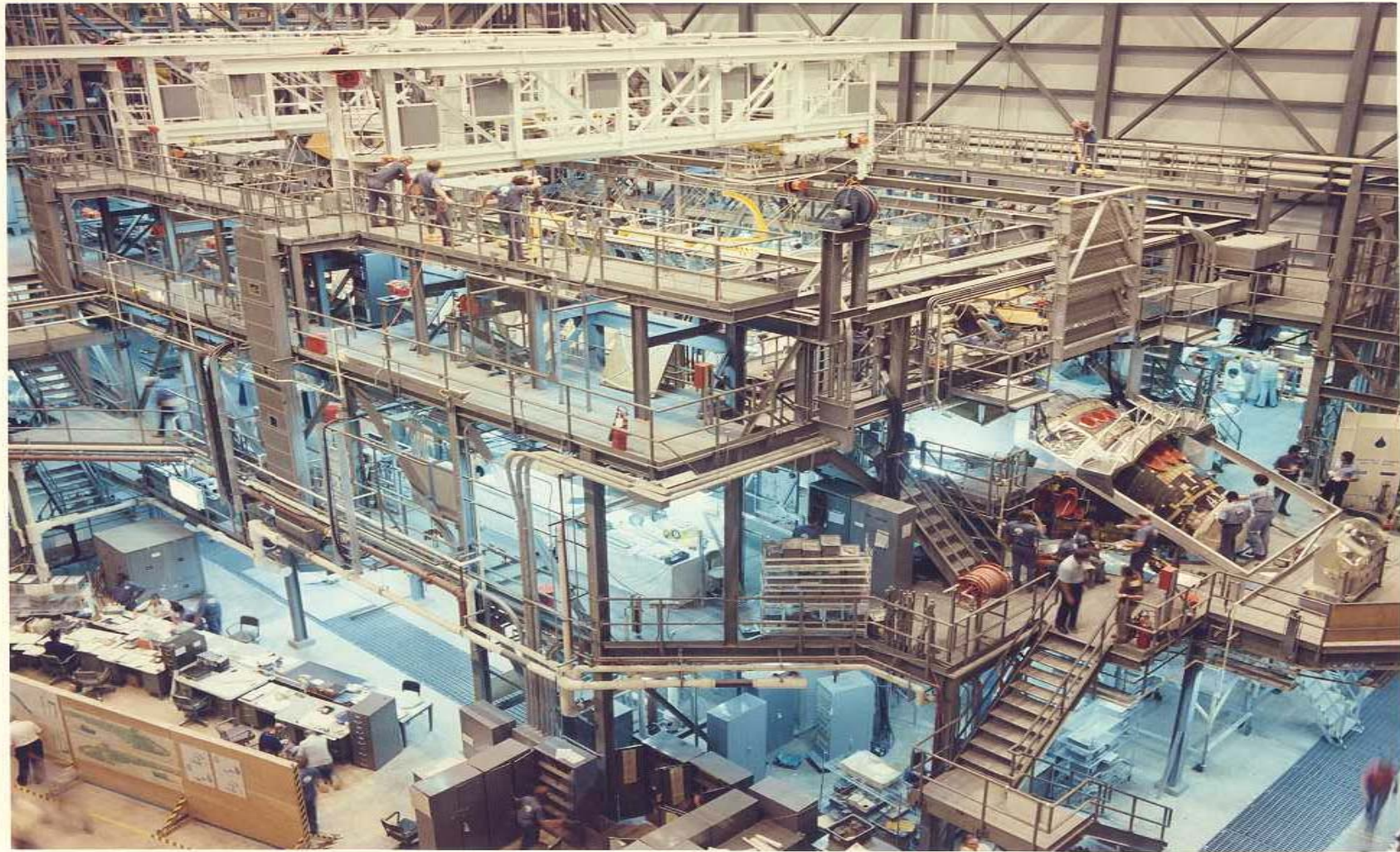
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- Liftoff and Ascent Aerodynamics
- Structures
- Ascent Flight Control System
- Day-of-Launch I-Loads Evolution
- Avionics Architecture
- Main Propulsion
- Software
- Lightning
- Flight Instrumentation
- RCS Thrusters
- Materials and Processes
- Risk Management
- **Operational Cost Drivers**
- Margin Management
- Significance of Lessons Learned
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Initial Naive Concept of Operations



Operational Reality



NASA, KSC Photo, dated September 25, 1979, index number "KSC-79PC-500"

39

Operational Cost Drivers

Problem

- **Insufficient definition of operational requirements during development phase**
 - Concentration on performance requirements but not on operational considerations
 - Shuttle design organizations were not responsible for operational cost
 - Very few incentives for development contractors

Corrective Actions

- **Very labor intensive (high operational cost) vehicle was developed and put into operations**

Lesson

- **Must have the Concept of Operations defined**
- **Levy the requirements on contractors to support the Concept of Operations**
- **Must have continuity and integration between designers, ground operations, and flight operations requirements during the developmental phase**

Operational Cost Drivers (Continued)

Problem

- **The cost of reusability of complex, multifunctional, aging vehicle**
 - Every Orbiter function whether used or not on a given mission must be verified and checked out prior to flight
 - Every function must also be monitored and failures managed to avoid a catastrophic event
 - Reusability of aging complex systems requires ever increasing attention to maintain performance and safety
 - Complex paper system “touched” by too many organizations governs every step of the operation
 - Early 1980’s heritage
 - Only limited streamlining over the life of the Program

Lesson

- **Complexity creates flight operational cost**
 - Minimize complexity
- **Manual approach adds to operational cost**
 - Automate
- **Realistically define operational life prior to development**

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- Software
- Lightning
- Flight Instrumentation
- RCS Thrusters
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- Risk Management
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Structural and Ascent Performance Margin Management

Problem

- **Unrealistic ascent performance requirements eliminated the possibility of effective margin management**
 - DOD insisted on 32K lbs polar orbit capability
 - Equivalent to 65K lbs due East
 - NASA needed DOD support of the Shuttle Program
- **Continuous pursuit of the elusive 65K lbs due East ascent capability precluded the possibility of holding back some structural margin to avoid costly redesign changes as Program development matured**
- **Prior to performance enhancement program the Shuttle had an ascent performance shortfall of ~10K lbs**

Actions Taken

- **All priorities were subordinated to the quest for ascent performance**
 - Very few features supported effective operations
 - Costly structural modifications to maintain the required factor of safety were made

Structural and Ascent Performance Margin Management (continued)

Lesson

- **Set realistic ascent performance requirements**
 - Hold back some margin to be used for problem areas
- **Use factors on “not well understood” environments to protect against costly design modifications as Program knowledge matures**
- **Transition to operations should be made consistent with vehicle operational capabilities imbedded in the design**

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Significance of Shuttle Lessons Learned

Greater ↑

5

4

3

2

1 ↓

Less

		2-Fault Tolerant Avionics	Margin Mgmt.	SRB IOP
		Risk Management	Instrumentation	
			RGAs in GVT	Ops Cost Drivers
	S/W Verification Facilities	Lightening	Liftoff Loads	Engine Inlet Screens
		Slosh Baffles	GVT	STA as Flight Article
			DOLILU	
		Flex Modes Effects on FCS	Buffet	Ascent Aero Anomaly
			Software Reliability	MPS Pressure Oscillations
		RCS Seat Extrusion	RCS Combustion Instability	
			RCS Inter-granular Cracking	
			Flex Hoses	

Risk of Crew/Vehicle Loss

Risk to Cost/Schedule

1 2 3 4 5

Less → Greater

Significance to Shuttle

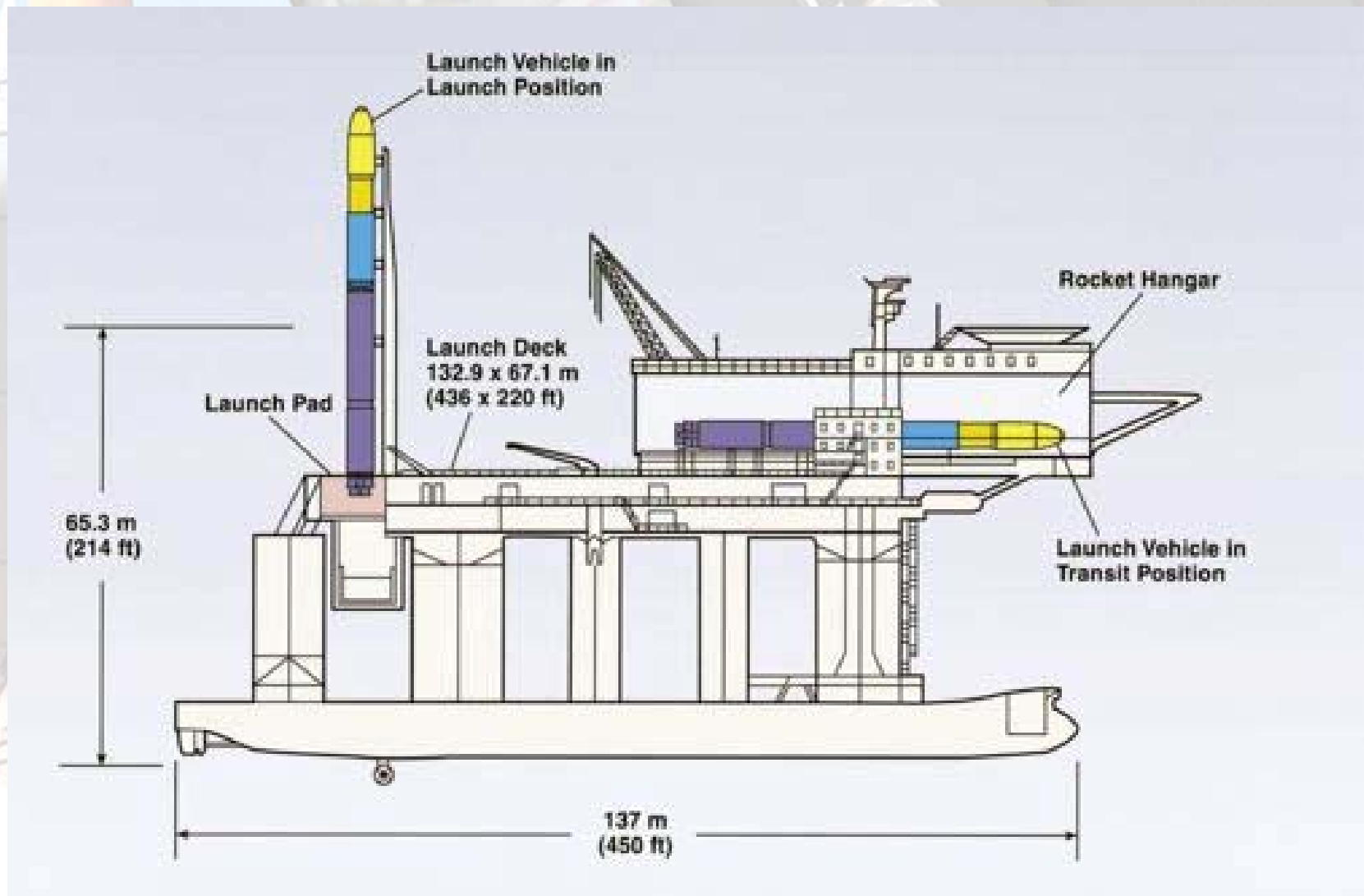


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- Software
- Lightning
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- RCS Thrusters
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- Risk Management
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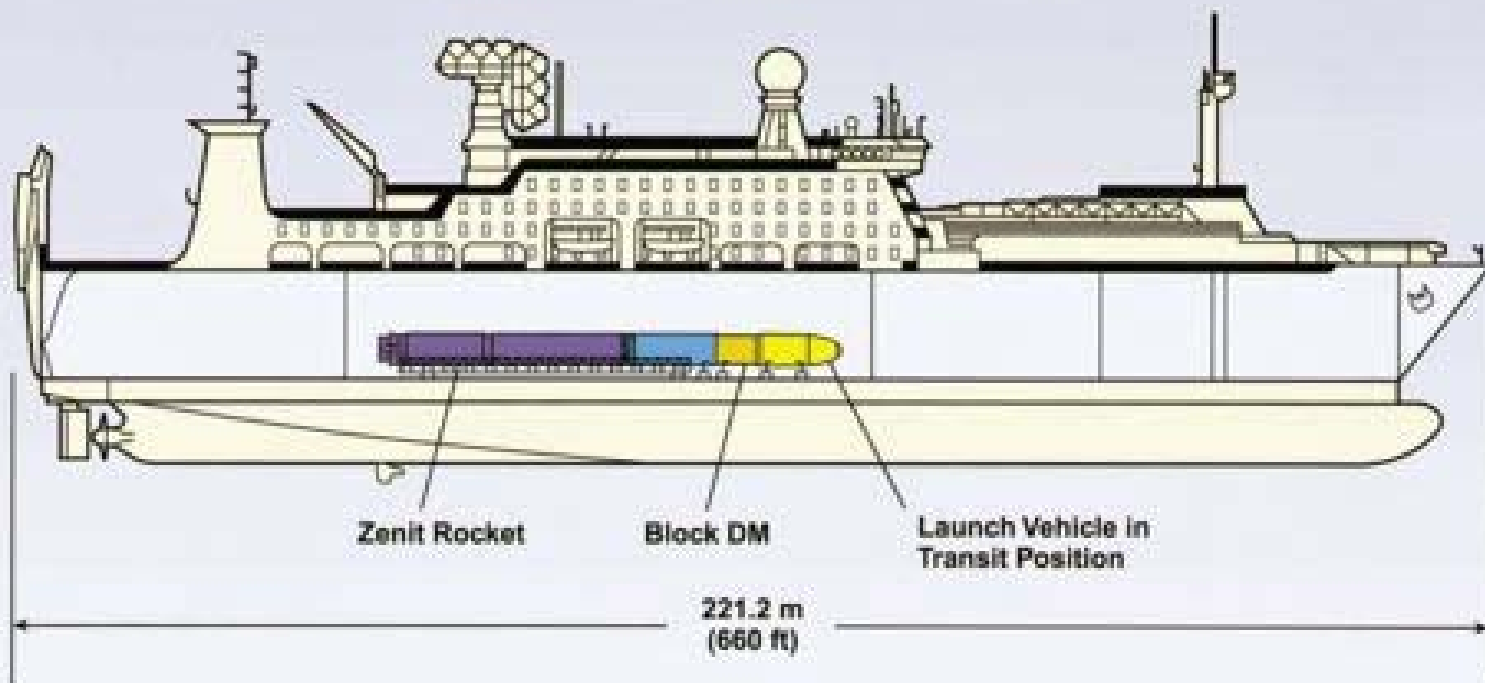
Lessons learned from Shuttle development & operations can reduce SDLV cost and development schedule and result in a more reliable and safer vehicle.

Launch Platform



Courtesy of the Sea Launch Company 48

Assembly and Command Ship



Courtesy of the Sea Launch Company

49

Launch



3/15/2006

Courtesy of the Sea Launch Company



Sea Launch – Zenit Derived Launch System



Courtesy of Boeing Sea Launch

- Major integration of existing and new elements
 - Two stage Ukrainian Zenit
 - 3rd stage Russian Block DM
 - New payload accommodation & composite fairing
 - Modified semi-submersible oil drilling platform into a launch pad
 - New command and control and rocket assembly ship
- System was built and brought to operational state in less than 3.5 years
 - 19 flights to date, 18 successful

Sea Launch Operations



Courtesy of the Sea Launch Company

- Integration of rocket stages and payload at home port in Long Beach, CA
- Launches performed from the Equator, 154 degrees west (south of Hawaii)

Small Team performs ground checkout and launch

	Ground Processing Team	Launch Team*
Americans	80	40
Russians	200	140
Ukrainians	50	50
Norwegians	75	70
Totals	405	300

* Launch Team is a subset of the Ground Processing Team; Ground Processing team members that are not required to participate in launch at sea are sent back to their companies and are off the Sea Launch payroll

Lessons Learned from Sea Launch

- **Zenit extremely automated launch vehicle**
 - Very little interaction with crew during checkout, pre-launch, and flight
- **Single string accountability, no duplications of effort (to some extent driven by export compliance restrictions)**
- **Low operational cost benefited from original design criteria of Zenit**
 - Rollout to pad, fuel and launch in 90 minutes
 - Allows very little time for ground or flight crew involvement
 - Imposes requirements for automatic processes

OUTLINE

- Introduction
- System Integration Approach
- Liftoff and Ascent Aerodynamics
- Structures
- Ascent Flight Control System
- Day-of-Launch I-Loads Evolution
- Avionics Architecture
- Main Propulsion
- Software
- Lightning
- Flight Instrumentation
- RCS Thrusters
- Materials and Processes
- Risk Management
- Operational Cost Drivers
- Margin Management
- Significance of Lessons Learned
- Other Applicable Lessons Learned
 - Zenit Derived Launch System – Sea Launch
 - Delta IV – Separate Briefing
- **The Big Lesson**

Lessons learned from Shuttle development & operations can reduce SDLV cost and development schedule and result in a more reliable and safer vehicle.

The Big Lesson

- **At least 2 critical design flaws existed in the flight system through design, testing and flight testing**
 - Not detected or acknowledged as major problems
- **A gap existed between actual and perceived state of vehicle robustness and safety**
- **Although strong indications were present, neither the design nor the operations team identified the problem**

The Big Lesson (continued)

Big Lesson

WE WERE NOT AS SMART AS WE THOUGHT WE WERE!

- **Develop and maintain a strong integration team throughout the program life cycle**
- **Empower integration to challenge the elements and program on issues of design flaws and interaction between the elements**
 - **Continuously monitor performance and safety throughout the transition to operations and the operations phase**
- **Integration and element engineering should be staffed with the best in their field...inquisitive by nature, respected by peers and management, and who have the courage to take on the Program regarding issues**
- **Transition to operations should be made consistent with vehicle operational capabilities imbedded in the design**



BACK-UP

3/15/2006

57

 **BOEING**

Seven Types of System Analyses will Define Interstage Stiffness Requirements



Interstage
Hardware

- 1.) Response to Ground Winds
- 2.) Liftoff Loads and Clearances
- 3.) Roll Control Authority
- 4.) Transonic Buffet
- 5.) FCS Flex Stability
- 6.) High Q static Elastic Loads
- 7.) High Q Response to Gust