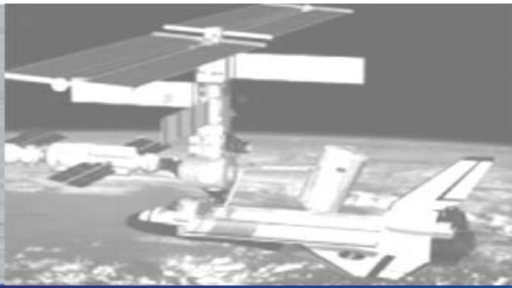

ARE WE LEARNING FROM PAST PROGRAMS?

ARE WE APPLYING LESSONS LEARNED ?

Bo Bejmuk

EXAMINE SELECTED SHUTTLE LESSONS LEARNED AND THEIR UTILIZATION IN CONSTELLATION

- STRUCTURES AND LOADS ANALYSES
- AVIONICS
- DESIGN FOR OPERATIONS
- MARGIN MANAGEMENT

PRVIDE CONCLUSIONS

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Introduction

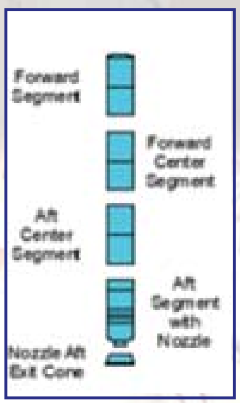
- **Two types of Shuttle Program Lessons Learned are addressed**
  - **<u>Problems</u> – How they were resolved and their applicability to Ares I**
  - **<u>Success Stories</u> – How they were achieved and their applicability to Ares I**
- **Lessons Learned are presented at a fairly high level**
  -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

Shuttle Elements

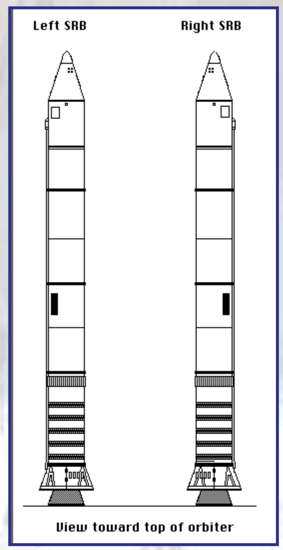
Ground Systems

External Tank

Shuttle System Main Engines



Solid Rocket Motor (SRM)



Solid Rocket Boosters (SRB)

Orbiter*

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

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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)

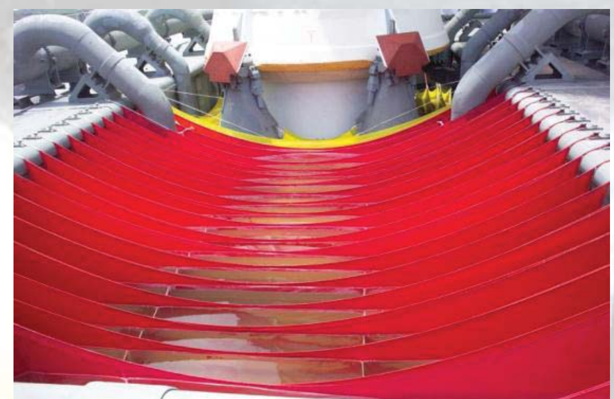
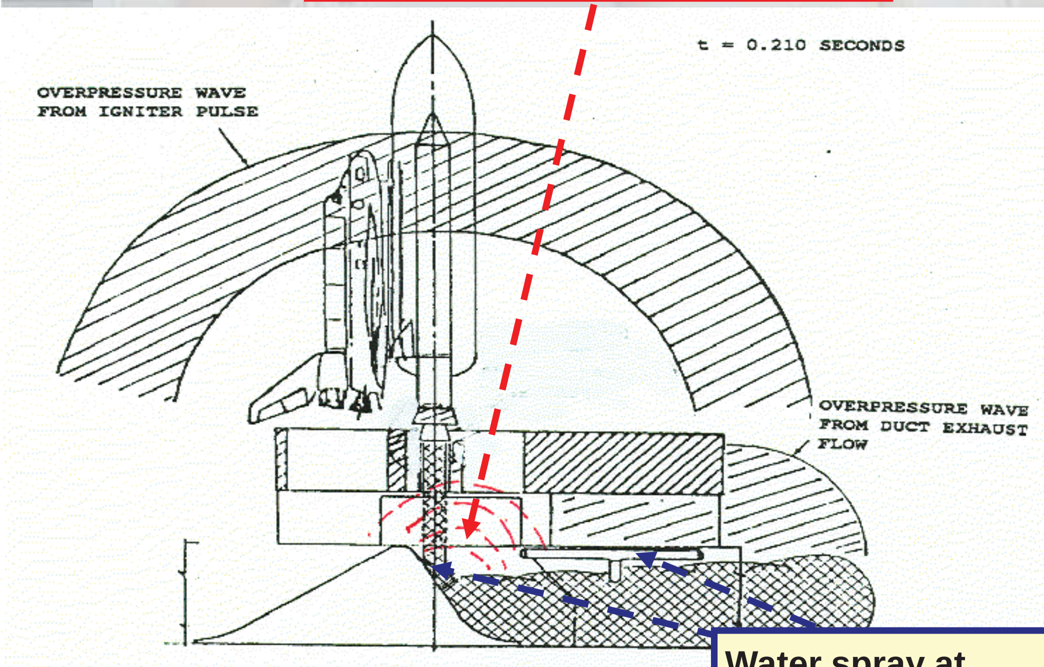


Figure 1: STS-1 and STS-2 SRB IOP Suppression Configuration

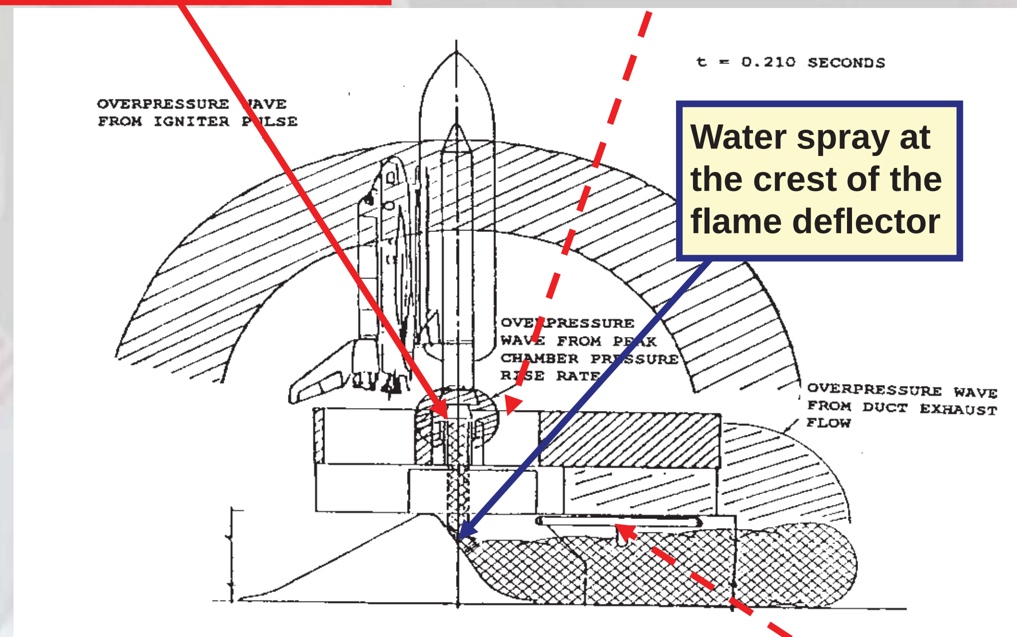
Water spray for STS-1 was designed for IOP Source at flame deflector

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



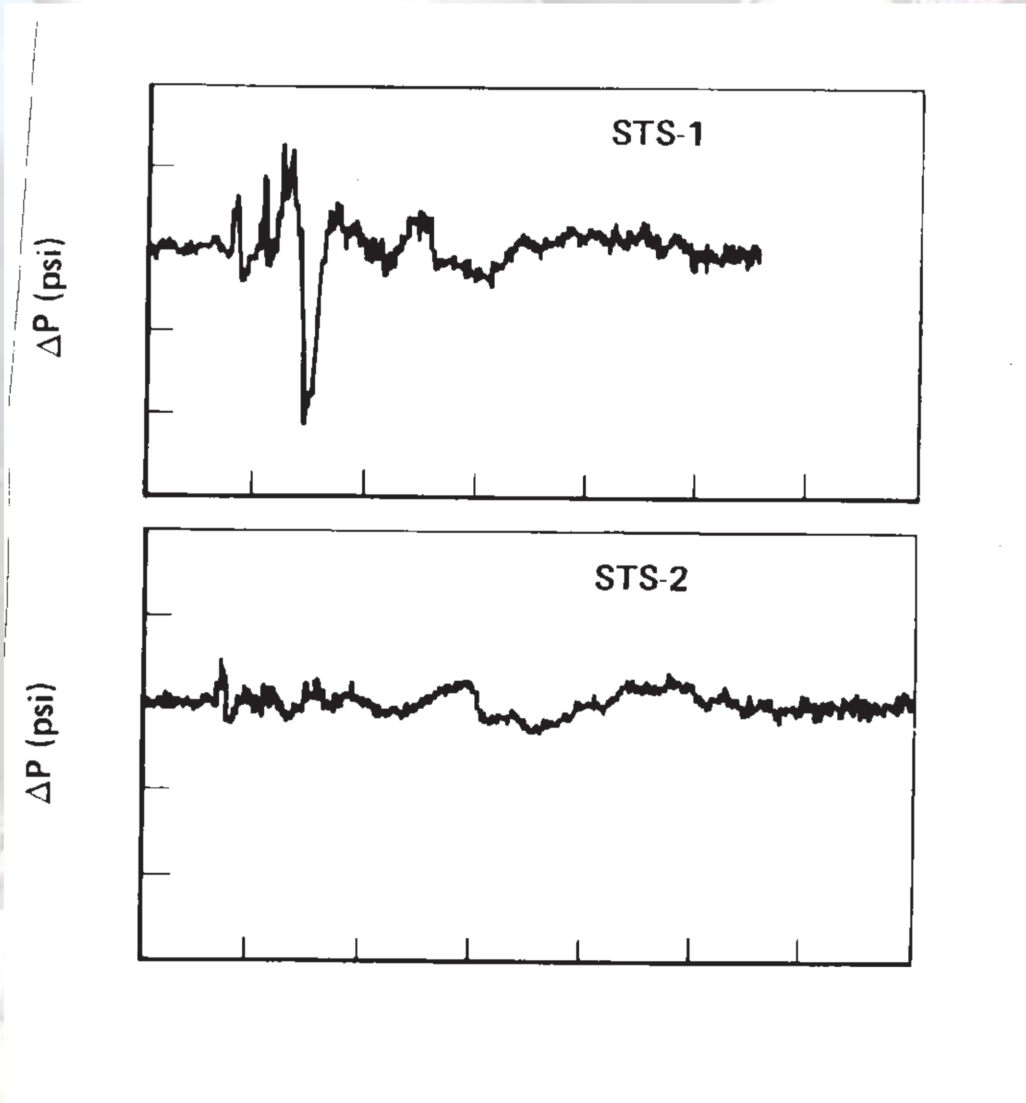
Water spray at the crest of the flame deflector

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 Ares I 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**

DIRECT BENEFIT TO ARES LIFTOFF

- BROAD INVOLVEMENT OF STRUCTURES/AERO COMMUNITY DURING SHUTTLE DEVELOPMENT- CONTINUITY OF MSFC INVOLVMENT
- UTILIZATION OF LEGACY HARDWARE IN ARES FIRST STAGE

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**

DIRECT BENEFIT LESS VISIBLE

- **SIMPLER AXISYMETRIC CONFIGURATION IN ASCENT**
- **MSFC LESS INVOLVED IN SOLVING THIS ISSUE DURIND SHUTTLE DEVELOPMENT**
- **SOME HOT PLUME TESTING CONTEMPLATED**

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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**

STRUCTURAL MARGIN MANAGEMENT

- ARES IMPLEMENTED STRUCTURAL MARGIN MANAGEMENT
- ORION IS CHALLENGED BY MASS ISSUE-DIFFICULT TO HAVE ROBUST STRUCTURAL MARGIN MANAGEMENT-MASS GROWTH ALLOWANCE STILL IMPLEMENTED

Liftoff Loads Analyses

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

Shuttle

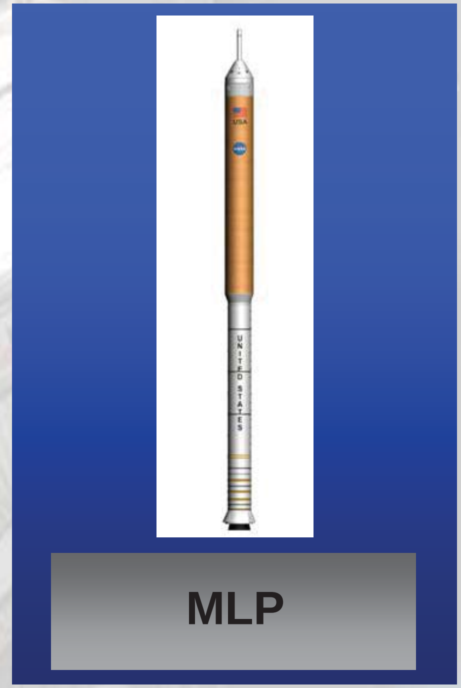
H2 Tank Compliance

SRB Growth

ET/Orbiter axial interface

Common Shuttle/Ares I

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



Ares I

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

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 Ares I, L/O loads may be a significant design issue due to direct load path between the SRB and the upper stage

ARES/ORION LIFTOFF ANALYSES BENEFITED FROM SHUTTLE EXPERIENCE

- MSFC INVOLVED IN LIFTOFF LOADS RESOLUTION – CONTINUITY OF KNOWLEDGE
- SENSITIVITY TO MLP STIFFNESS
- EXPERIENCE IN MODELING SRB IGNITION FORCING FUNCTION

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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

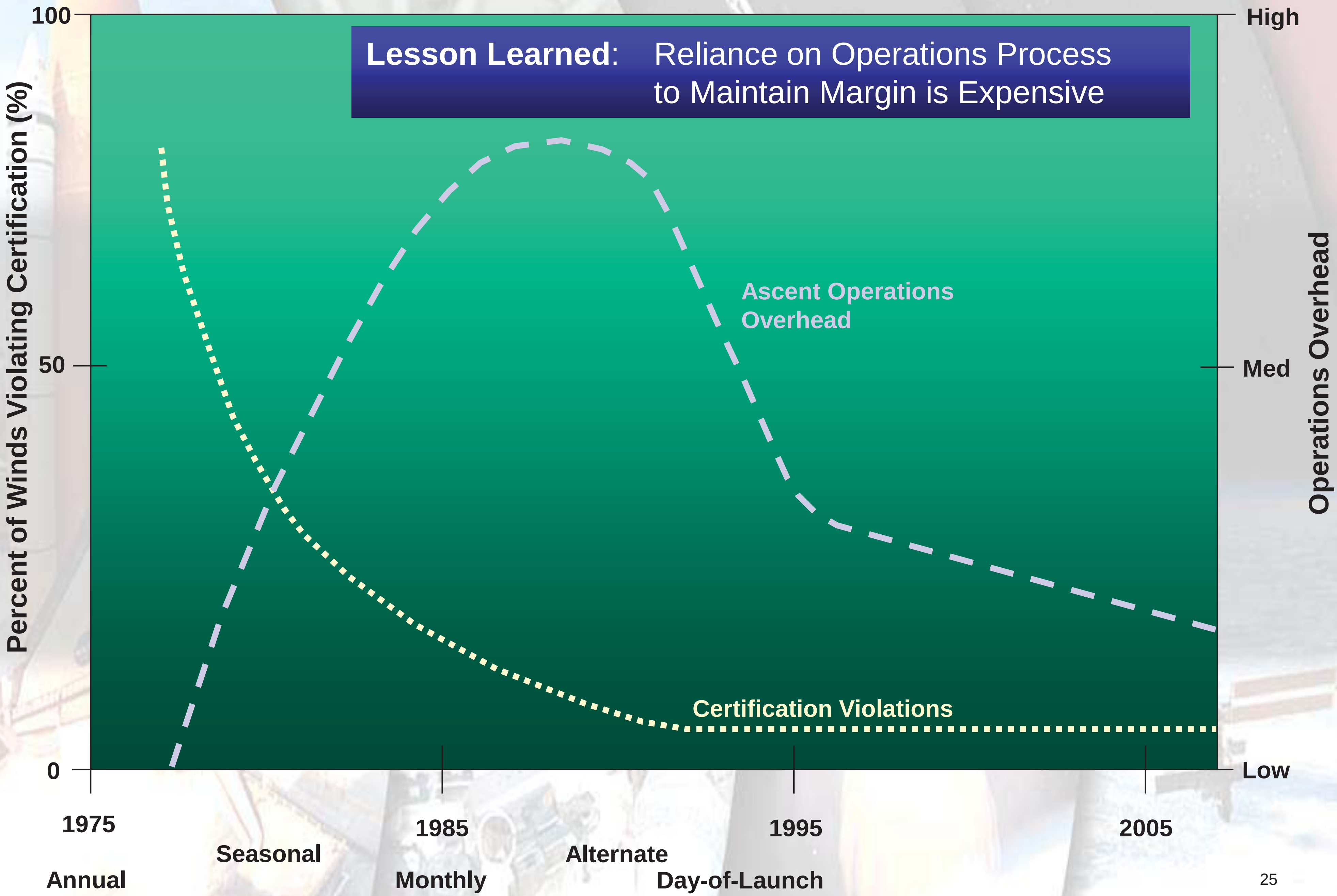
Corrective Actions

- 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



DAY OF LAUNCH I-LOADS METHODOLOGY IS STATE OF THE ART TODAY

- **PLANNED FOR CONSTELLATION ASCENT FLIGHTS**
- **WINDS ALOFT WILL HAVE LESS EFFECT ON STRUCTURAL WEIGHT**
- **MORE ROBUST VEHICLE**

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Avionics Architecture

Problem

- **Prevention of loss of vehicle/crew or mission due to avionics failures considering mission duration up to approximately 12 days**

Actions

- **Dissimilar solutions (primary, backup and two fault tolerance in avionics hardware/software)**
- **Establishment of SAIL – Simulation of hardware/software interaction**
- **Four LRU Mid Value Select (MVS) implemented with appropriate cross strapping to ensure two fault tolerance**
- **The Redundancy Scheme was required to be test verified**
- **Two fault tolerance became an avionics system "mainstay" on the Shuttle Orbiter**

Lesson

- **The Orbiter system provided a reliable avionics system. For a short duration, missions such as Ares I ascent suggested a tradeoff to be performed between one and two fault tolerance. Overall system reliability could be used in the evaluation.**

Avionics Architecture (Continued)

- **Establishing the Fault Tolerance Requirements is a Primary Avionics Cost Driver**

High Time Exposure

Low Time Exposure

- **Trade off study suggested: One vs. two fault tolerance on Booster**
- **A "tailored" level of fault tolerance could emerge as the best solution**

- **The Shuttle approach of two fault tolerance* was robust, but may be excessive for a boost only vehicle. The overall system reliability (for example 0.999) should drive redundancy requirements.**

*** With some compromises**

CONSTELLATION IS USING “TAILORED APPROACH”

- **LOC/LOM DRIVES REDUNDANCY**
- **ORION MASS/ARES PERFORMANCE ISSUE CONSTRAINS REDUNDANCY**
- **SOME CONCERNS ABOUT ROBUSTNESS OF AVIONICS**
- **LIMITED REDUNDANCY EXPECTEDTO INCREASE LIFE CYCLE COST**

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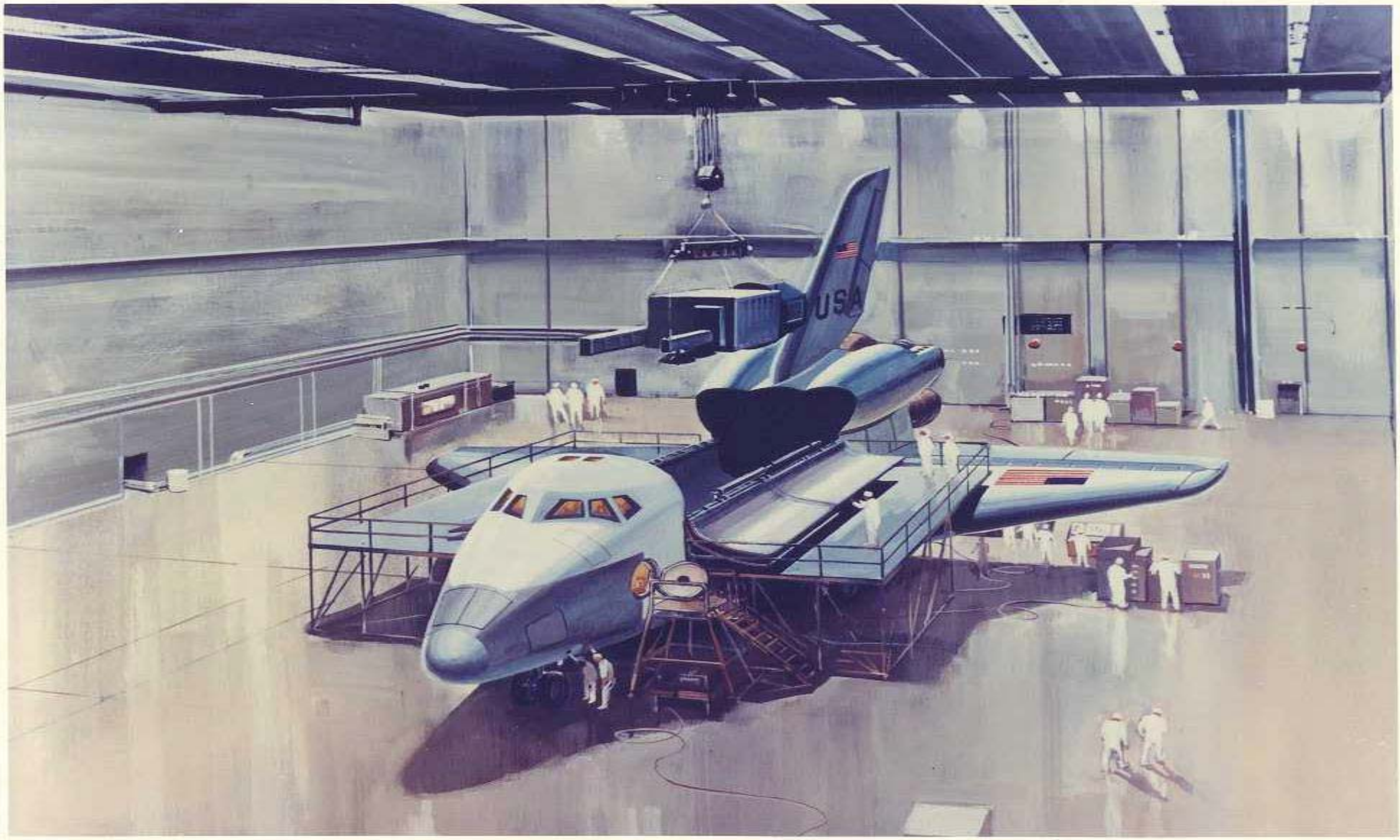
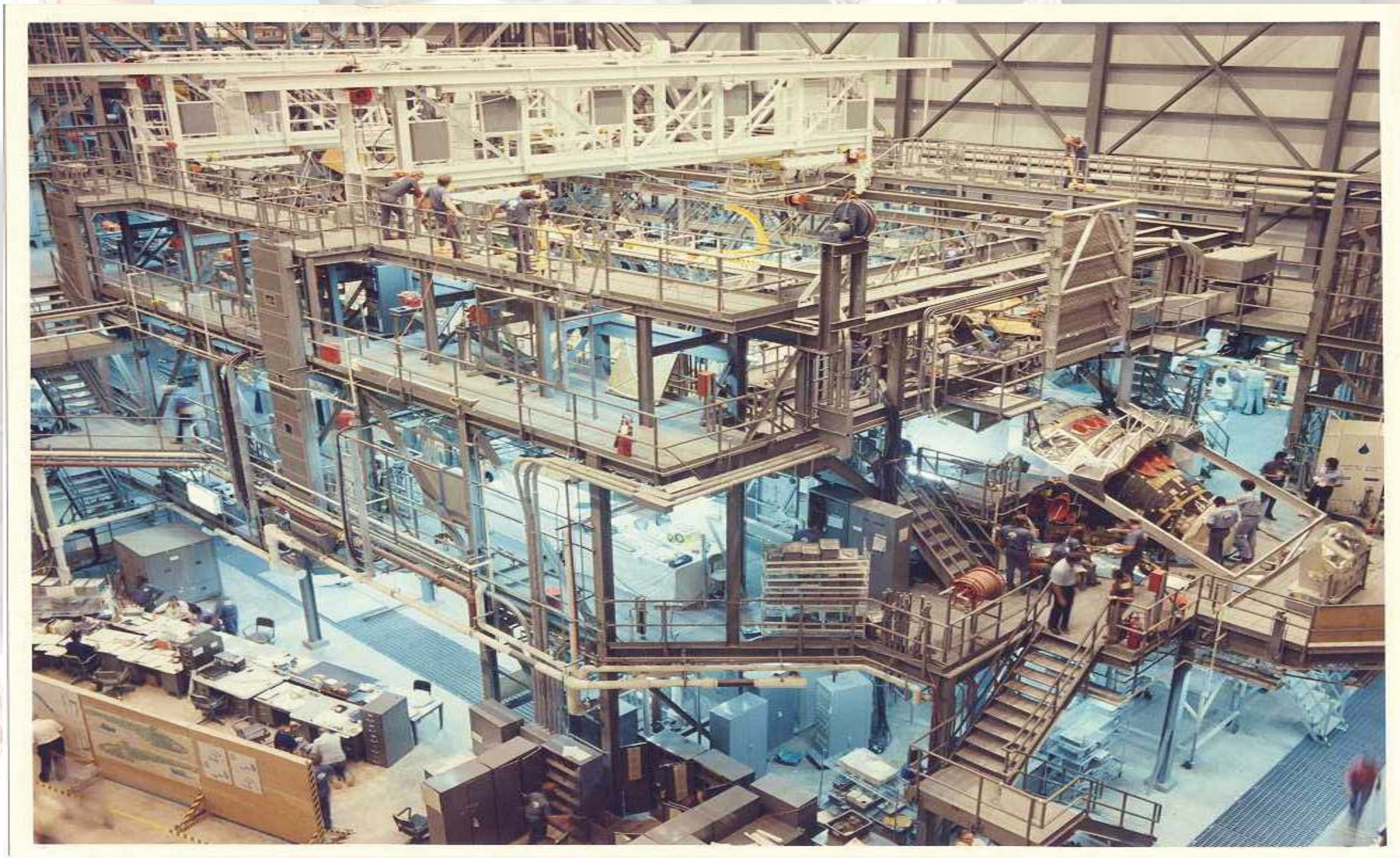
Initial Naive Concept of Operations



Operational Reality



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

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

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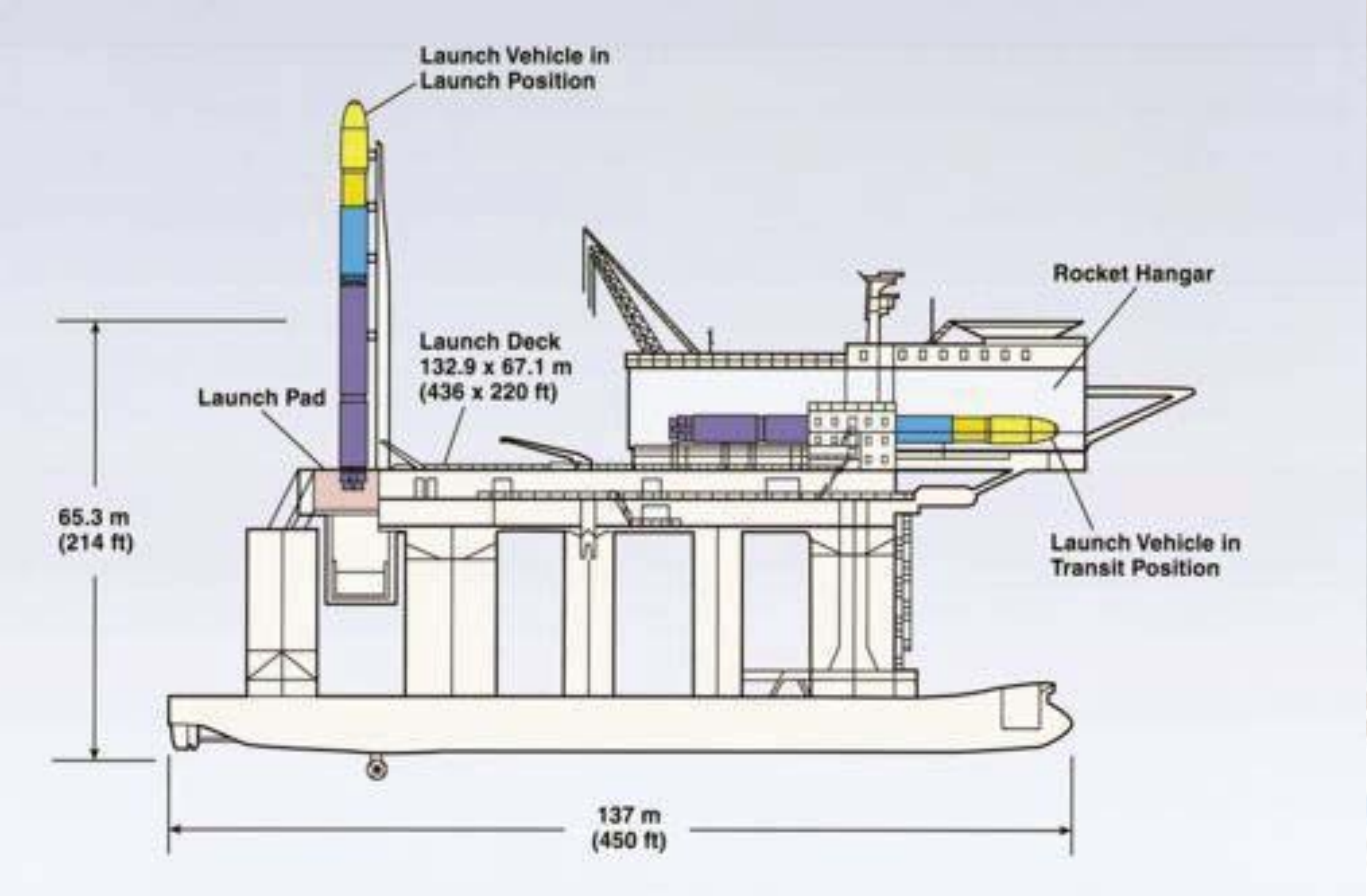
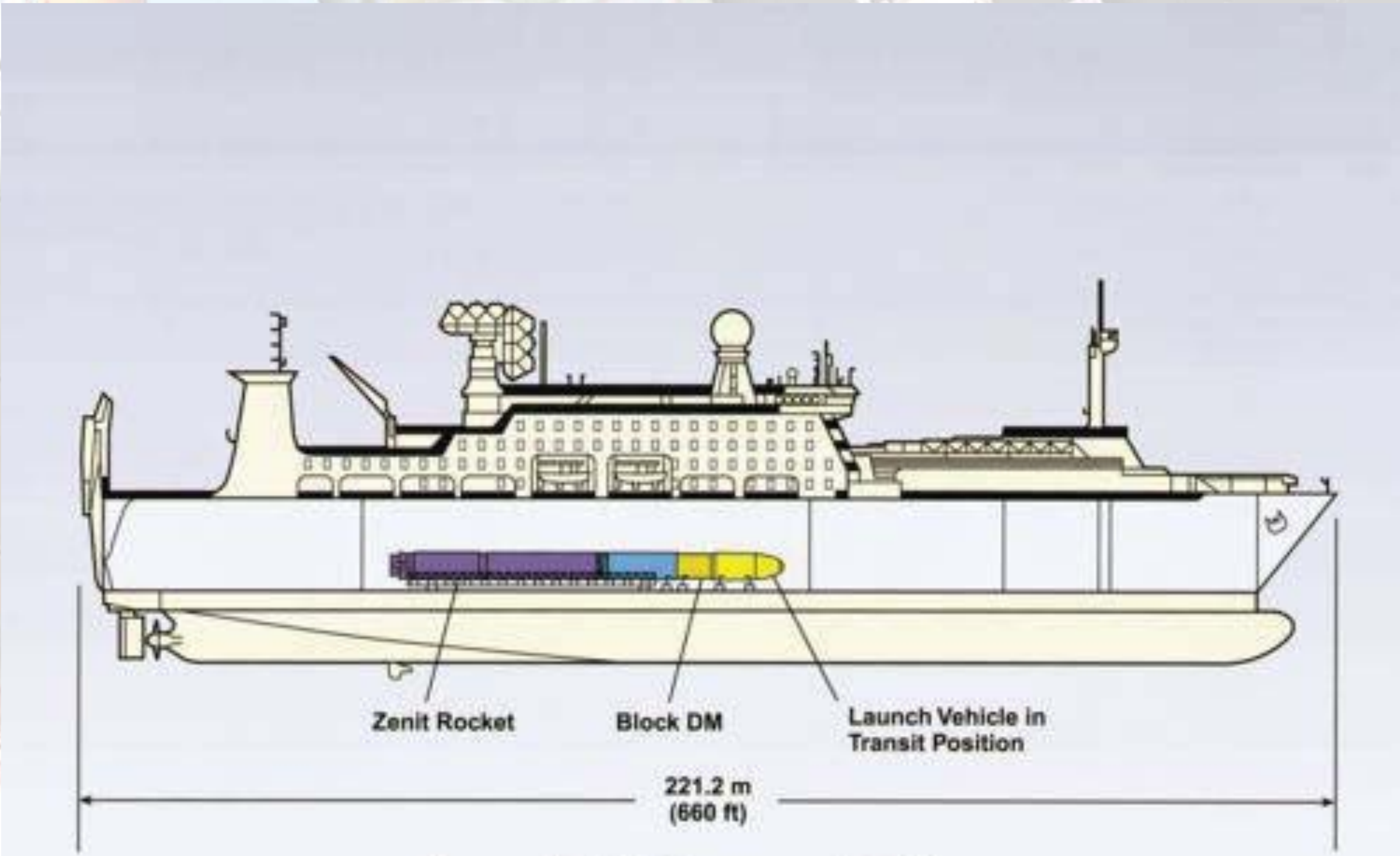
Launch Platform



Courtesy of the Sea Launch Company

Assembly and Command Ship



Courtesy of the Sea Launch Company

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

DESIGN FOR COST EFFECTIVE OPERATION ONLY PARTLY SUCCESSFUL

- **ATTEMPT TO DEVELOP "STRETCH GOALS"**
- **TIGHT ORION MASS/ARES PERFORMANCE ISSUE INHIBITED IMPLEMENTATION OF OPERATIONAL FEATURES**
- **NASA DOES NOT HAVE DESIGN-FOR-OPERATIONS ADVOCACY WITH STRENGTH EQUAL TO OTHER TECHNICAL DISCIPLINES**
- **OPERABILITY MUST BE ADDRESSED MORE VIGOROUSLY TO ENSURE VIABILITY OF THE VISION**

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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**

CONSTELLATION ONLY PARTLT BENEFITTED FROM SHUTTLE EXPERIENCE

- **ORION MASS/ARES PERFORMANCE SHOW VERY TIGHT MARGINS EARLY IN DESIGN CYCLE**
- **TIGHT MARGINS WILL CONTINUOUSLY BURDEN THE DESIGNERS OF FLIGHT SYSTEMS AS THE DESIGN MATURES**
- **VIGILANT MANAGEMENT OF MASS AND PRFORMANCE THREATS WILL BE REQIRED**
- **STRUCTURAL MARGIN MANAGEMENT IS MORE ROBUST**

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The Painful Reality

- At least 2 critical design flaws existed in Shuttle 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

Avoid Repeating History

- Learn about the past
- Develop and maintain a strong System Engineering & Integration team throughout the program life cycle
- Empower engineering to challenge the Projects 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
- Cultivate culture of respect for descending opinions
- Transition to operations should be made consistent with vehicle operational capabilities imbedded in the design

The Big Lesson

- We were not as smart as we thought we were
- Knowledge capture initiatives are helping – but should be practiced as a "contact sport"
- If we want simple and cost effective operations we must design for operations
  - Shuttle designed for performance and cost
  - Constellation needs more emphasis on design for operations
  - NASA is in control of operations destiny- short window of opportunity