National Aeronautics and Space Administration

Lessons in Systems Engineering –

The SSME Weight Growth History

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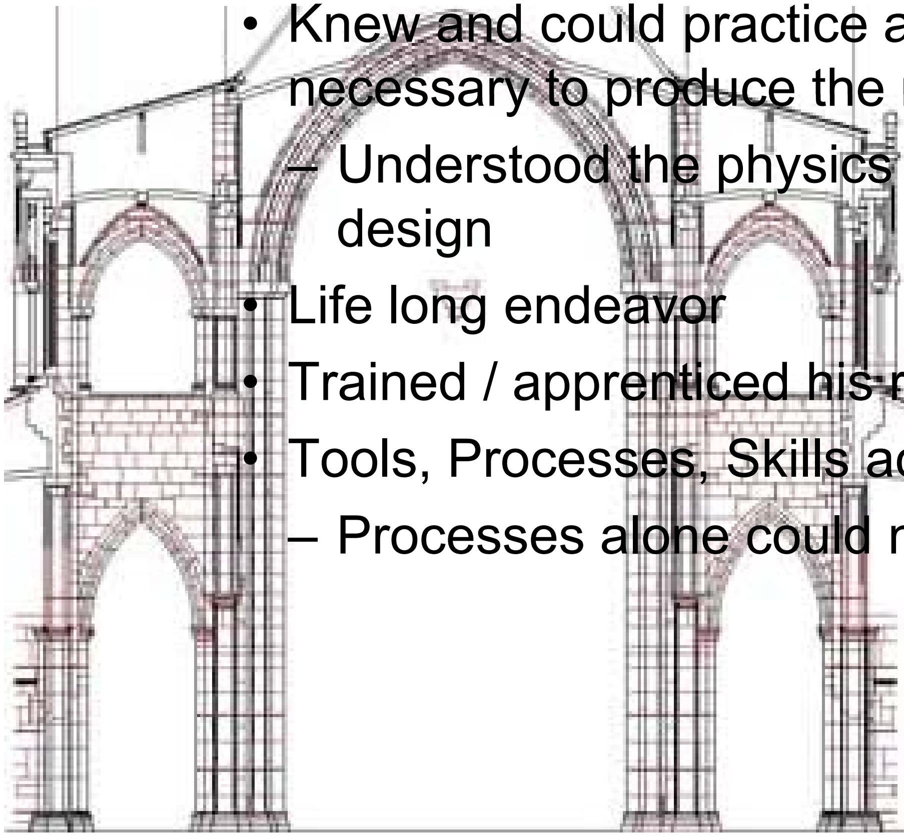
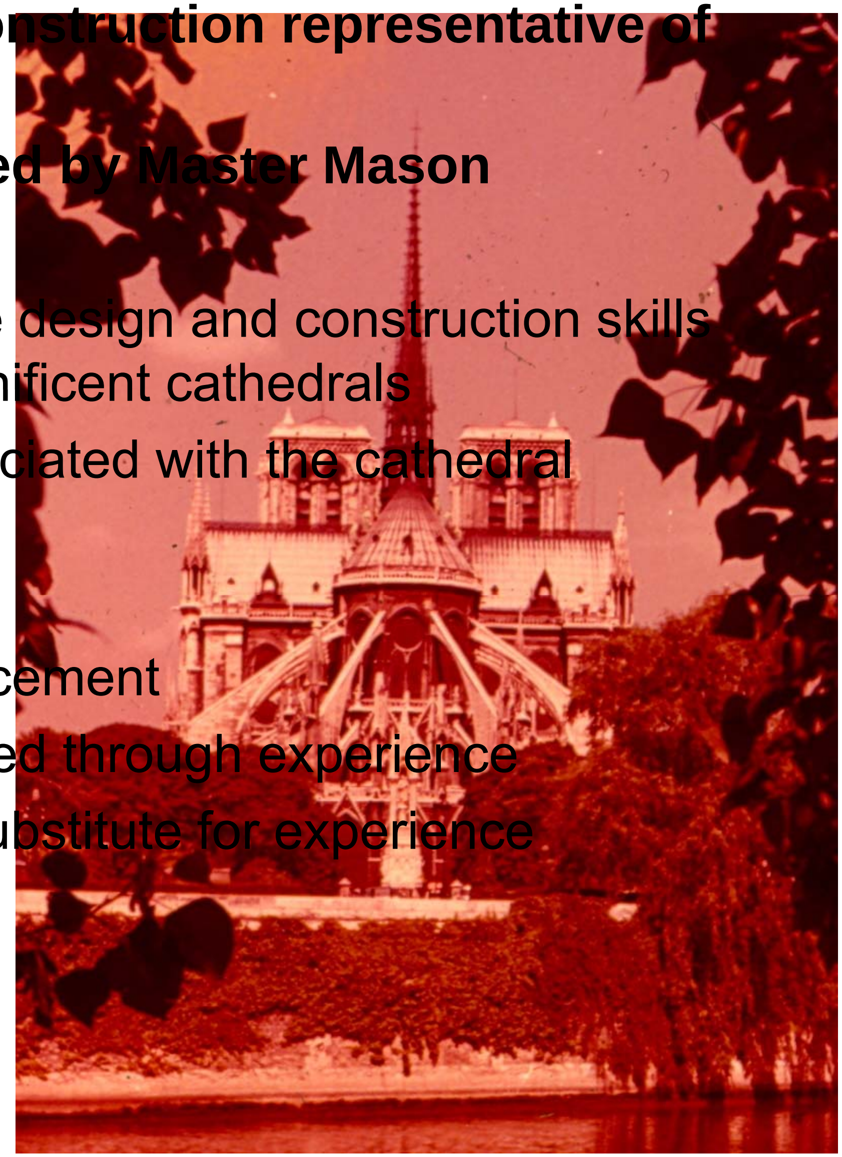
History of Design: Pre-Industrial Revolution

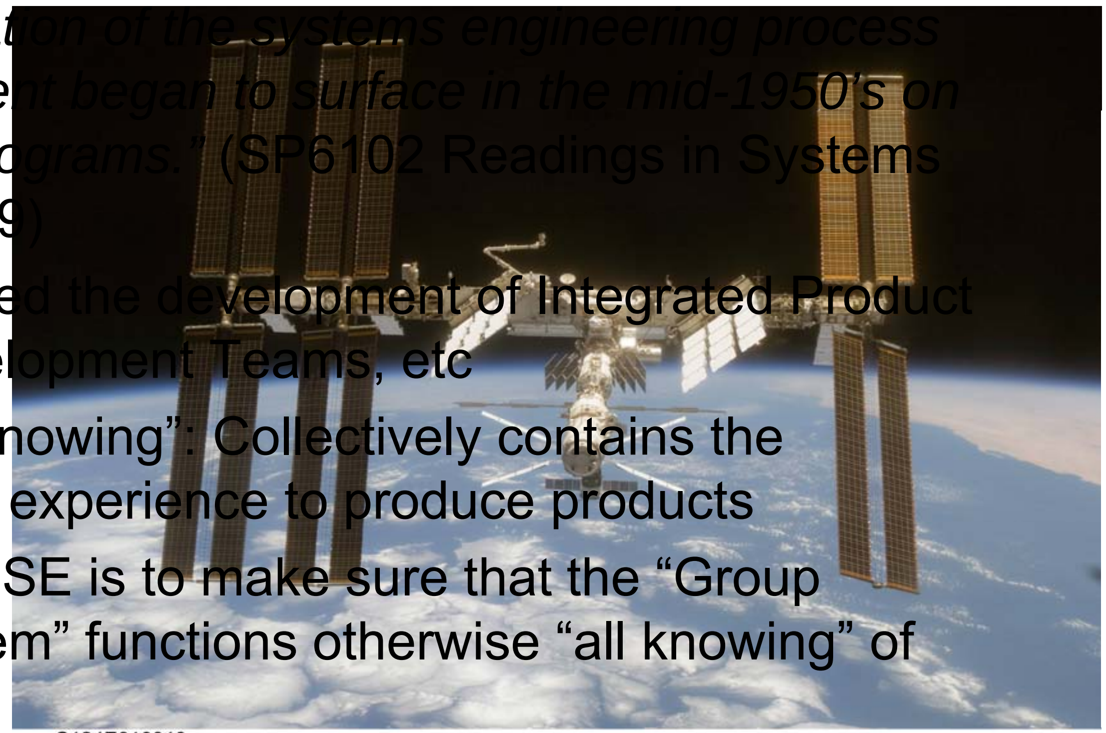
- **Classic Cathedral Design and Construction representative of the complexity of the era**
- **Design and construction managed by Master Mason**
  - All Knowing
    - Knew and could practice all the design and construction skills necessary to produce the magnificent cathedrals
      - Understood the physics associated with the cathedral design
    - Life long endeavor
    - Trained / apprenticed his replacement
    - Tools, Processes, Skills acquired through experience
      - Processes alone could not substitute for experience





History of Design: Post-Industrial Revolution

- **The complexity system designs increased and became too much for one person to know**
- **Systems engineering developed in an attempt to manage these complex designs**
  - *"…the initial formalization of the systems engineering process for military development began to surface in the mid-1950's on the ballistic missile programs."* (SP6102 Readings in Systems Engineering, 1993, p.9)
  - Later evolution included the development of Integrated Product Teams, Product Development Teams, etc
  - Group becomes "all knowing": Collectively contains the knowledge, skills and experience to produce products
  - Biggest challenge for SE is to make sure that the "Group Communication System" functions otherwise "all knowing" of the team fails



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Systems Engineering: What Is It?

- **From SP-6102**
  - “Systems engineering is the management function which controls the total system development effort for the purpose of achieving an *optimum balance of all system elements.* It is a process which transforms an operational need into a description of system parameters and integrates those parameters to *optimize the overall system effectiveness.*”

- **Purpose of SE then is to create a complex product that meets all requirements through a methodology that focuses on an integrated design that emphasizes balancing risk between all subsystems and components**
  - The effect should be an optimized system but made up of sub-optimized subsystems and components

Systems Engineering Functions

- **SE Functions can be grouped into three categories**
  - Classical Systems Engineering focused on processes, procedures, configuration and data management control, etc
  - Project control focused on cost and schedule
  - Technical Integration focused on the interactions among all the compartmentalized hardware, design, and discipline areas reintegrating them into a verifiable and operable system that meets requirements in a balanced state.
- **Master Mason was responsible for all three**
- **Today, there is a tendency to focus only on the first two assuming that the processes and procedures can compensate for lack of experience, training and the complex interactions between subsystems / components**

Systems Engineering: Why We Ignore Technical Integration

- **Strong tendency to view systems engineering as only the processes that bring the designed parts together (integration) rather than creating "Integrated Designs"**
  - It is based on an assumption that the system can be broken apart expecting linearity and handle everything by defining pertinent requirements, defining and managing interfaces, design data flow and then designing the parts (Classical SE).
    - Then when the system is put back together it will perform ok.
    - It is a false assumption because there are many interactions, linear and nonlinear, in a complex "system" causing the parts to perform different together than apart.
  - It also assumes design development is serial and not iterative in nature
  - This approach also tends to neglect the communication needs of the "Group Knowledge"

Systems Engineering: Achieving a Balanced Integrated Design

- **So, the systems engineer for an integrated design is responsible for and concerned with getting all interacting disciplines into a balanced state using uncertainties, sensitivities, risks, and programmatics (cost and schedule)**
  - Part of that task is to also insure that all the discipline models, simulations, technology base, etc are at the appropriate maturity level so that an accurate trade space can be determined
  - Systems engineer does not replace the Master Mason but ensures that the necessary communication takes place in the SE process along with the necessary skills and tools to utilize the “Group Knowledge” in creating a balanced integrated design
  - The “Group Knowledge” provides the needed “understanding of the physics” associated with the complex system design

A Balanced Design

- **Achieving a balanced design is about "spreading the pain"**
- **Balance needs to be achieved early in the design process usually by the conceptual design review because the impact is almost always already set**
- **Metrics for balanced design**
  - Risk: cost, schedule, technical
  - Margins
  - Uncertainties
  - Sensitivities of design parameter
  - Technology maturity level
    - If low it is difficult to impossible to quantify the others above
- **If balance not achieved programs / projects will experience cost overruns, schedule slips or even failure**

SSME Weight Story is a good example of what can go wrong if the requirements, technology base and final systems design do not balance early

Background: Elementary Rocket Science

- **To fully appreciate the SSME weight growth story and the lessons it teaches us about proper systems engineering we need to understand some of the challenges of rocket design**

- **The vehicle must impart orbital energy to the payload.**
  – (Orbital energy is large -- h ~ 160 n.m. altitude, ΔV ~25,300 ft/s

- **With current technology, this pushes propulsion, structures, and systems capability to the limit.**

- **Payload size and mass drives launch vehicle performance requirements.**

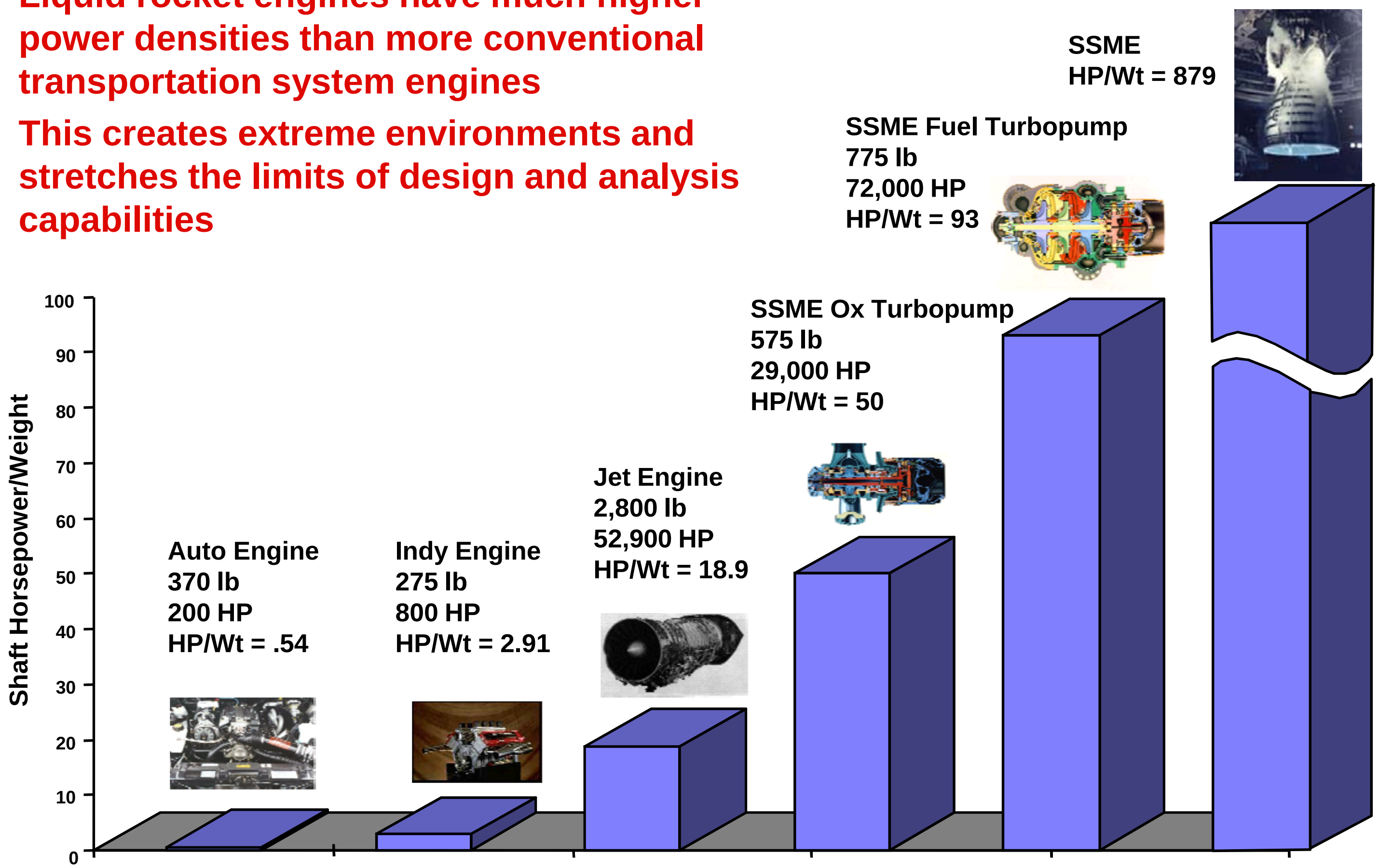
Background: Elementary Rocket Science

- **Propulsion:**
  - Efficient conversion of chemical potential energy to kinetic energy (The Space Shuttle Main Engine has an Isp of 452 s out of a potential 460 s)
  - Vehicle Thrust to weight ratio at liftoff greater than 1.1
- **Structures:**
  - Efficient/lightweight strong structures. Vehicle mass fraction around .90
    - The ratio of the average skin thickness to the diameter of the Shuttle External Tank is a factor of 3 less than that of an aluminum drink can.
- **System Effects:**
  - Minimize losses during mission (Understand, quantify, control, and manage)

All system elements being pushed to their limits creates a constant "tug of war" that, if not carefully monitored, leads to unbalance in the design

Liquid Pump-fed Main Engines

- **Pump-fed liquid engines are one of the most complex and challenging subsystems on the entire launch vehicle and present many systems engineering challenges**
- **Pump-fed liquid engine design requires many of the same design functions and analysis disciplines that the vehicle design uses**
  - **Liquid rocket engines have much higher power densities than more conventional transportation system engines**
  - **This creates extreme environments and stretches the limits of design and analysis capabilities**

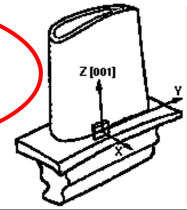


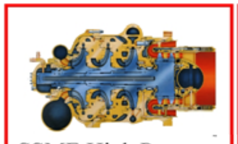
Difficulty and Complexity of Liquid Rocket Engines Are Reflected in Turbomachinery Design

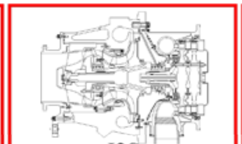
- **Turbopumps differ from conventional gas turbine engines in significant ways**

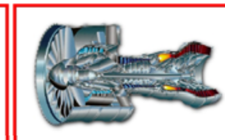
Difficult Propellants
Material compatibility issues, cavitation, bearing stresses, high heat fluxes, heavier flanges, tighter complex seals

Extreme Blade Loading
Up to 550 hp per blade




SSME High Pressure LH2 Turbopump


J2S LH2 Turbopump


State of the Art Gas Turbine

Item	Typical Pump Fed Rocket Engine Hydrogen Turbopump Parameters (range depends on engine cycle and application)	Jet Engine
Fuel	Hydrogen	Petroleum distillate
Oxidizer	Oxygen	Air
Operating speed (RPM)	20,000 to 36,000	15,000
Turbine blade tip speed (ft/sec)	1400 to 1850	1850
Turbine power density (HP/in^2)	2000 to 3200	394
Turbine inlet temperature (deg F)	1000 to 1600	2400
Turbine heat transfer coef. (BTU/ft^2- hr-degF)	20,000 to 54,000	500
Turbine thermal start/stop transients (deg F/sec)	1000 to 32,000	100
Pump/compressor pressure rise (psi)	2000 to 7000	400 - 600
Pump dynamic pressure (psi)	500 to 2000	50 - 200

High Speeds
Bearing life, rotordynamics issues

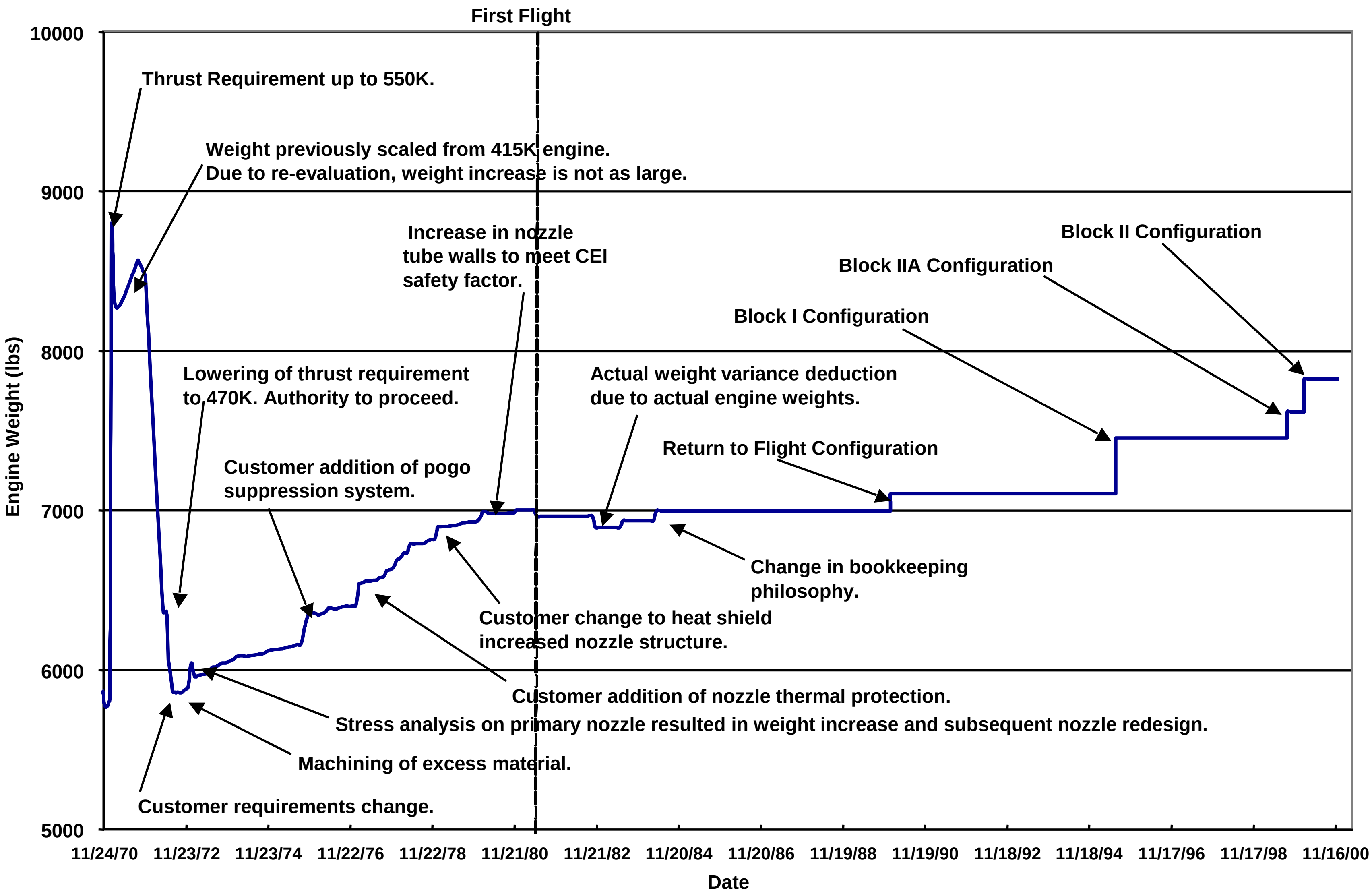
High Power Density
High power bending stress, high work per unit area, tight manufacturing tolerances

Uncooled Blades
Limit inlet temperature, increase rotational speed and blade turning

High Pressures (static and dynamic)
High housing loads, instabilities, high-cycle fatigue

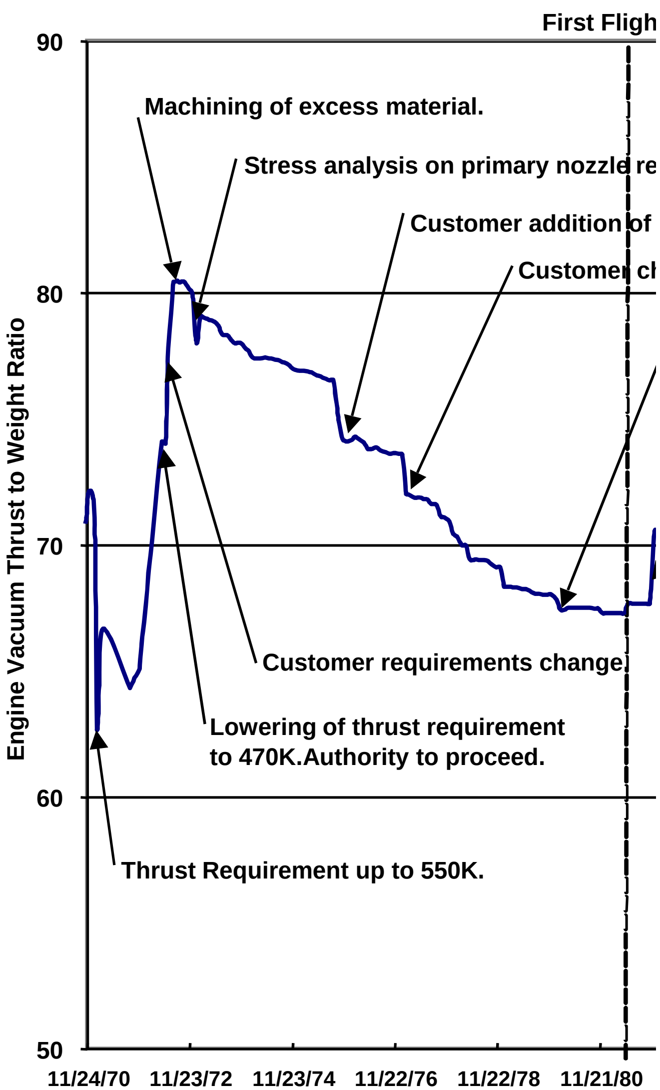
High Thermal Strains
Very high thermal stress, low cycle fatigue, material limitations

SSME Weight Growth History



Challenge and Problem better understood by looking at engine thrust to weight ratio

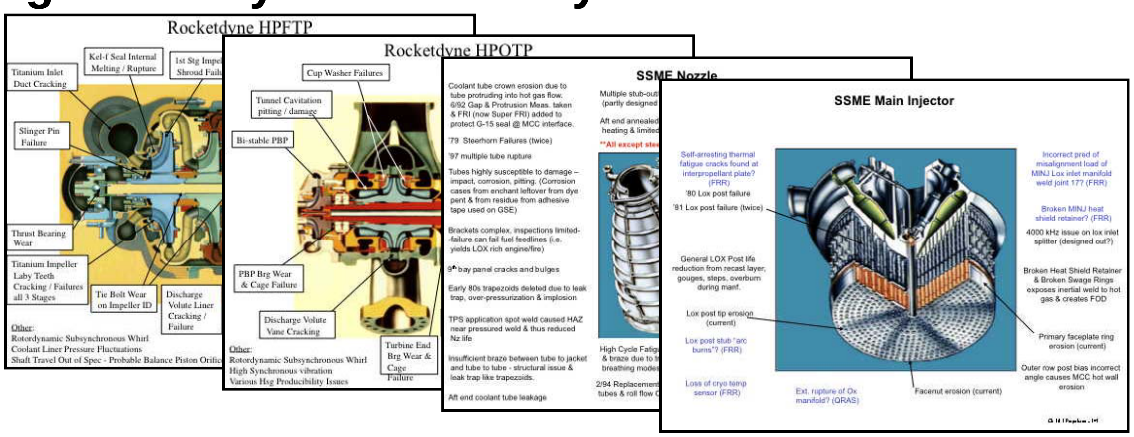
SSME Vacuum Thrust to Weight Ratio History



- **Early (1971) thrust to weight ratio predictions for the SSME concepts were around 65 to 1**
  - Based on J-2 and F-1 technology base and some advanced development with Air Force
  - Estimate was realistic and representative of achievable values
- **As the Space Shuttle System design concept matured, weight became a serious problem driving the thrust to weight ratio requirements of the SSME to 80 to 1**
  - The technology base did not support this requirement
  - Massive development effort required to cut weight out of the engine
    - All welded construction for most of the components
    - No weld lands
    - Machining off all excess material
  - Additional performance enhancements to meet system weight problem included trading engine life for increased power level
    - Increased engine thrust to 109% PL and cut design life from 100 to 55 missions

SSME Weight Problems

- **As consequence of weight cuts and power level increase, engine began experiencing many fatigue failures some resulting in catastrophic engine failures during ground testing**
  - High cost of hardware losses, design changes and schedule slips
  - In 1978, two alternating MSFC engineering teams of about 100 each were established at Canoga Park and worked with a large team at MSFC for 9 months to address these problems
  - Instituted a fracture control survey of engine and identified many problem areas
    - Engine originally not designed for fracture control
    - Fracture control team established permanently
- **Lack of robustness in design lead to increased operations costs to assure engine safety and reliability**

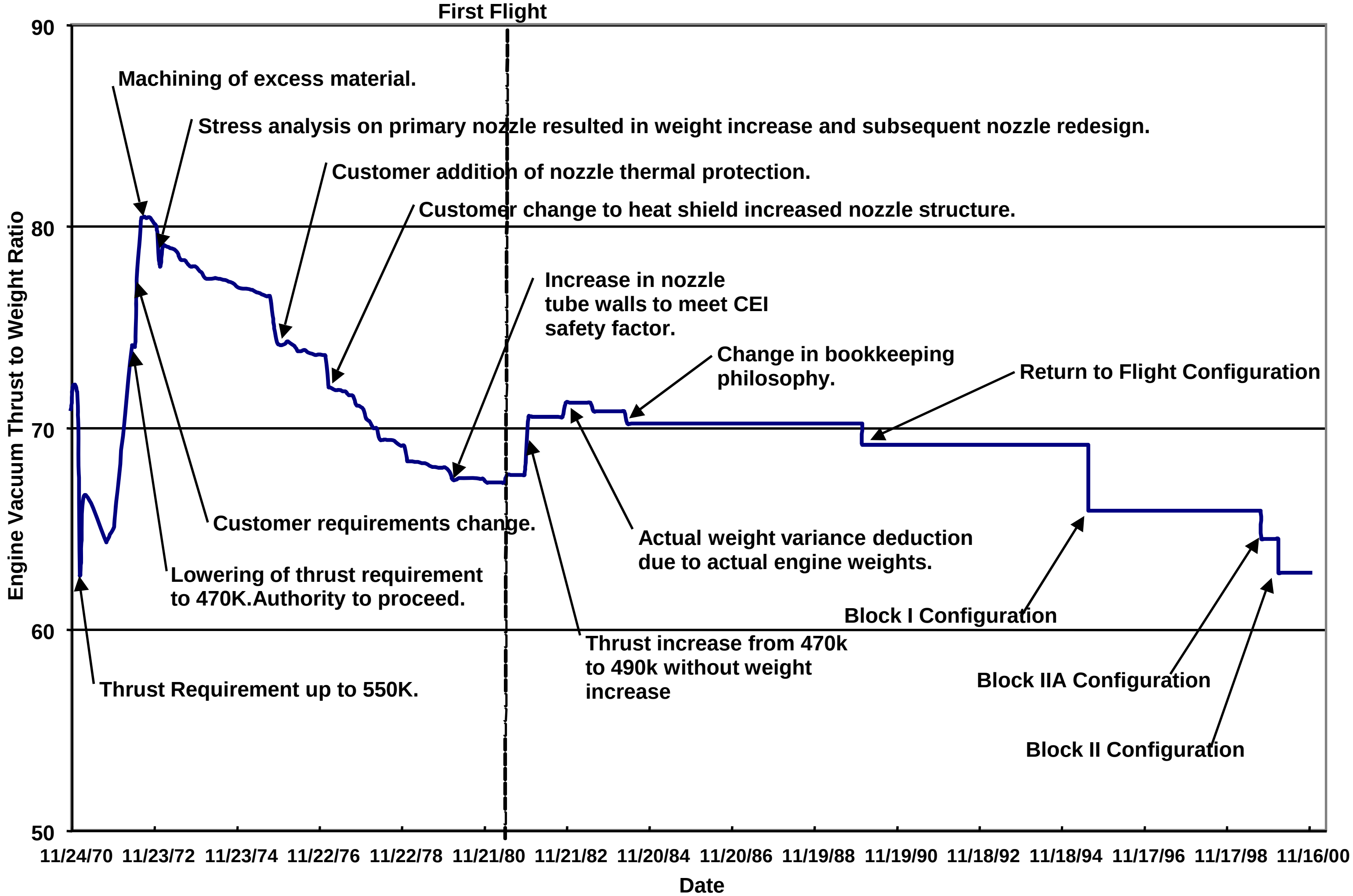


SSME Solutions and Weight Growth

- **In late 70's as Shuttle System design began to solidify, weight was offered up to the SSME project manager to fix problems by Shuttle program manager**
  - SSME project manager put off weight increases to support first flight date using current engine design with limited life and performance
    - Believed that it was better to be flying at lower capability than to wait until all capability was available (balancing political concerns)
  - Weight was increased as new redesigned components were added as block upgrades beginning in the mid to late 80's and into the 90's
    - Major examples are Two Duct Hot Gas Manifold, Large Throat Main Combustion Chamber, ATD High Pressure Oxidizer Turbopump, ATD High Pressure Fuel Turbopump
- **Weight could be added without impacting performance because the Orbiter had to fly ballast in the back to offset a heavy nose section**
  - Increased engine weight just off loaded ballast

SSME Vacuum Thrust to Weight Ratio History

- **Final engine T/W ratio essentially same as originally estimated but final design was compromised because unrealistic requirements set stage for constrained engine design**



Lesson Learned

- ***Absolutely critical*** **that someone be responsible for the *Integrated Vehicle System Design* (not just "integrating" pieces together) to adequately *balance* the risks across all elements while decomposing the requirements down to each element taking into account the varying maturity levels of the technology base, the design of each and the intricate interactions**
  - That "someone" is not a master mason but ensures that the "Group Knowledge" of the design team provides the same function
- **Shuttle system was designed with an immature technology base for many of the subsystems**
  - Made it impossible to adequately balance risk by properly flowing down requirements to these subsystems such as the SSME
  - Cannot adequately measure risk, uncertainties, sensitivities, cost or schedule if technology base is not demonstrated and understood
  - Must fight external pressures to compromise on technical credibility

Lesson Learned Continued

- **Pushing the envelope *without margin* or a *robust design* will result in increased problems and non-optimum designs at *significant* cost**
  - SSME, while a magnificent machine, is not robust
  - It took numerous design block changes with increased weight and operations costs to reach the current level of maturity that is flying today
- **Anticipating *unknowns* is essential because they *will* occur during development no matter how mature the technology base or the design concept**
  - Minimizing these unknown unknowns is accomplished through diligently quantifying sensitivities, uncertainties and risks based on all identified potential failure modes