National Aeronautics and Space Administration

Lessons in Systems Engineering –

The SSME Weight Growth History

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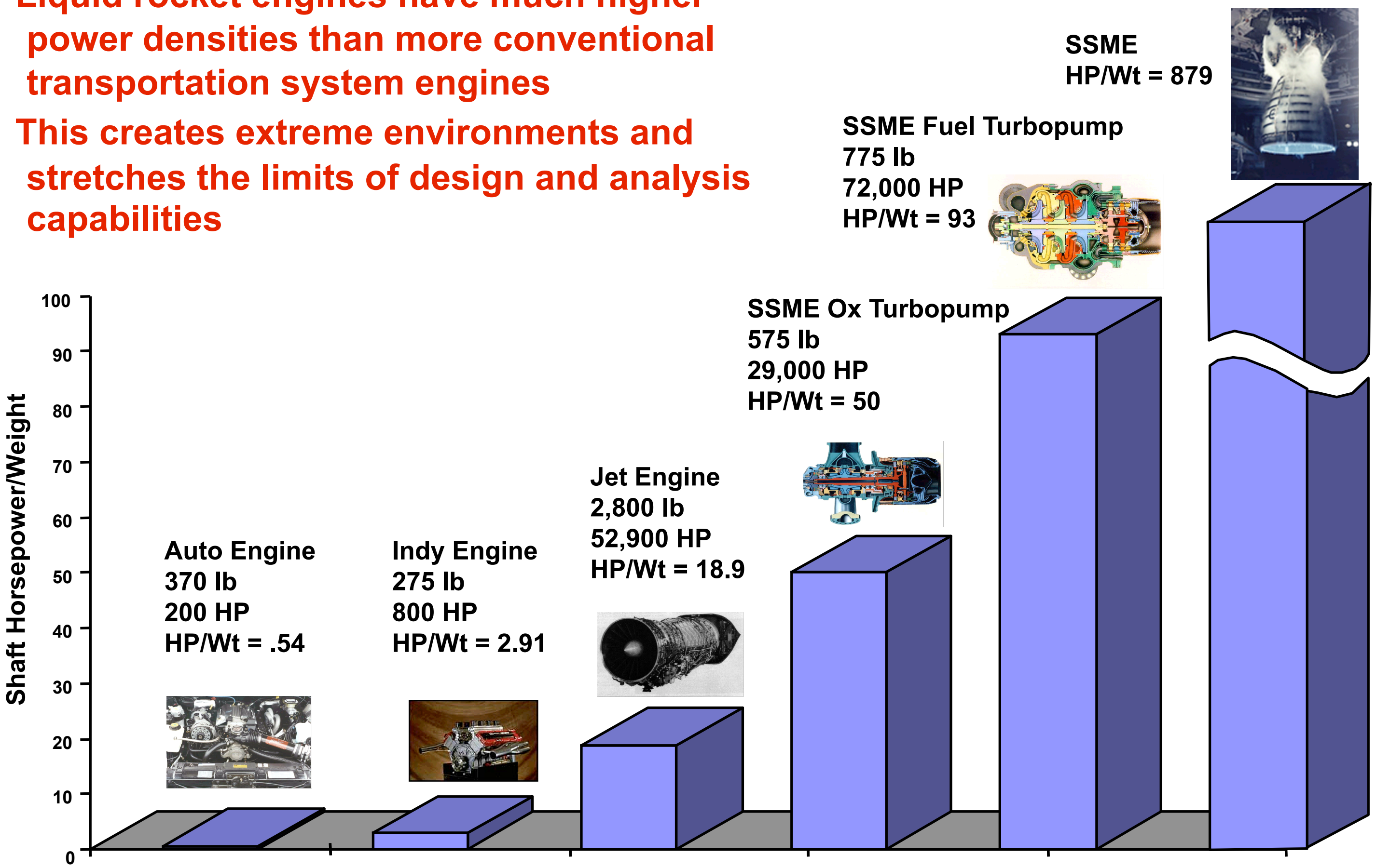
Liquid Pump-fed Main Engines

- 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, but
  - 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

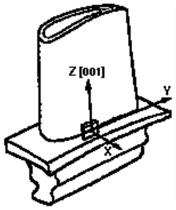


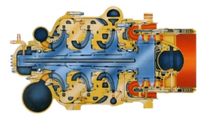
Difficulty and Complexity of Liquid Rocket Engines Are Reflected in Turbomachinery Design

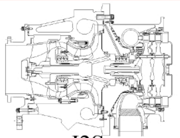
- **Turbopumps differ from conventional gas turbine engines in significant ways**

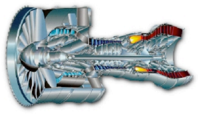
Difficult Propellants
Material compatibility issues, cavitation, bearing stresses, high heat fluxes, heavier flanges, tighter complex seals

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

Requirements, Technology Capability and Design Must Balance Early in Development Cycle

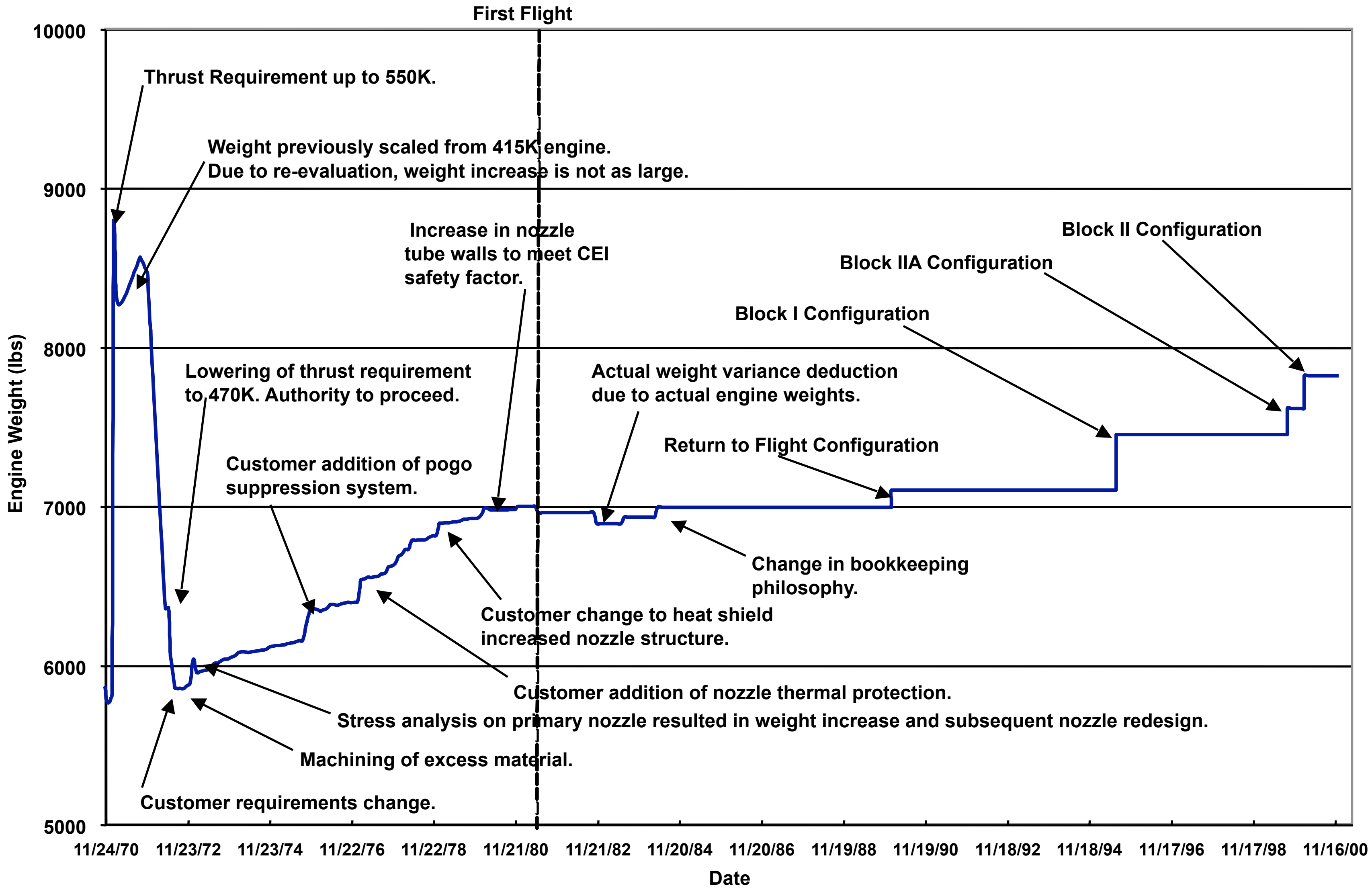
- **Strong tendency to view systems engineering as the processes that bring the designed parts together (integration) rather than creating "Integrated Designs"**
  - Based on the assumption that you can break the system apart assuming linearity and handle everything by defining pertinent requirements, defining and managing interfaces, design data flow, then designing the parts
    - When the system is put back together it will perform ok.
  - This is a false assumption because there are many nonlinear interactions 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

Requirements, Technology Capability and Design Must Balance Early in Development Cycle

- **Rather, 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

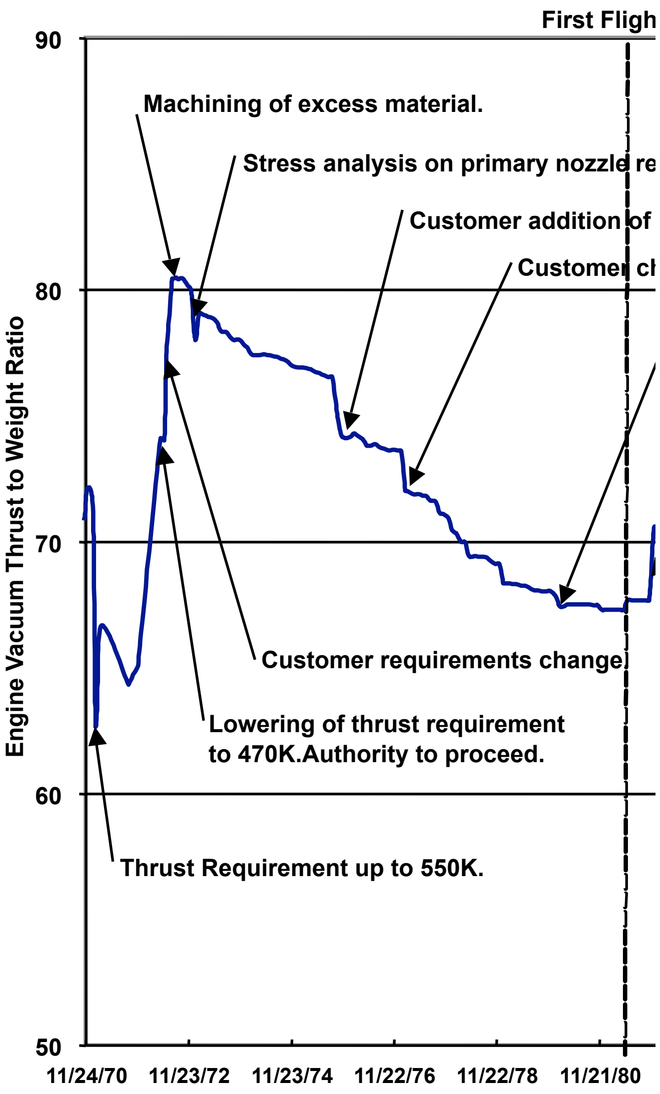
SSME Weight Story is a good example of what can go wrong if the requirements, technology base and final systems design do not balance early

SSME Weight Growth History



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

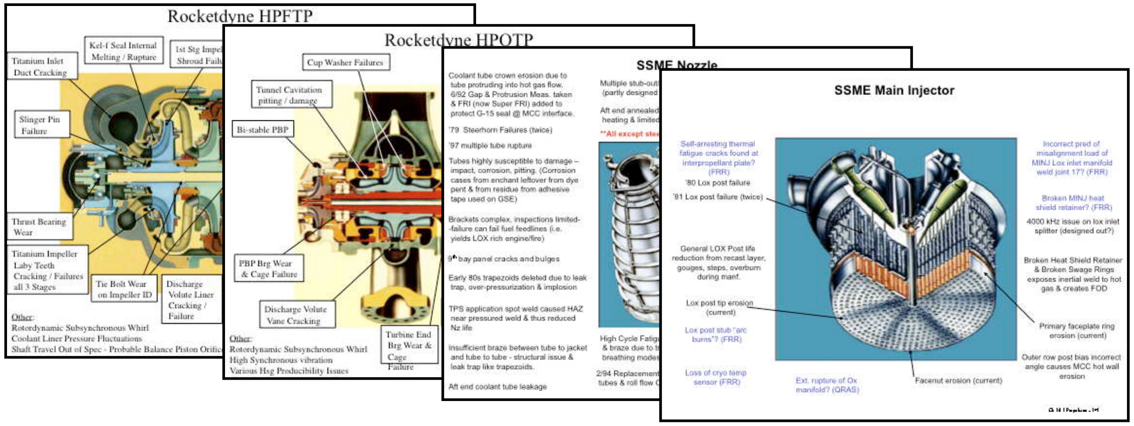
SSME Vacuum Thrust to Weight Ratio History



- **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**


Rocketdyne HPFTP

Other:
Rotordynamic Subsynchronous Whirl
Coolant Liner Pressure Fluctuations
Shaft Travel Out of Spec - Probable Balance Piston Orifice

Rocketdyne HPOTP

Other:
Rotordynamic Subsynchronous Whirl
High Synchronous vibration
Various Hsg Producibility Issues

SSME Nozzle

Coolant tube crown erosion due to tube protruding into hot gas flow. 6/92 Gap & Protrusion Meas. taken & FRI (now Super FRI) added to protect G-15 seal @ MCC interface.

'79 Steerhorn Failures (twice)

'97 multiple tube rupture

Tubes highly susceptible to damage – impact, corrosion, pitting. (Corrosion cases from enchant leftover from dye pent & from residue from adhesive tape used on GSE)

Brackets complex, inspections limited- -failure can fail fuel feedlines (i.e. yields LOX rich engine/fire)

9th bay panel cracks and bulges

Early 80s trapezoids deleted due to leak trap, over-pressurization & implosion

TPS application spot weld caused HAZ near pressured weld & thus reduced Nz life

Insufficient braze between tube to jacket and tube to tube - structural issue & leak trap like trapezoids.

Aft end coolant tube leakage

Multiple stub-out
(partly designed

Aft end annealed
heating & limited

**All except ste

High Cycle Fatig
& braze due to t
breathing modes

2/94 Replacement
tubes & roll flow C

SSME Main Injector

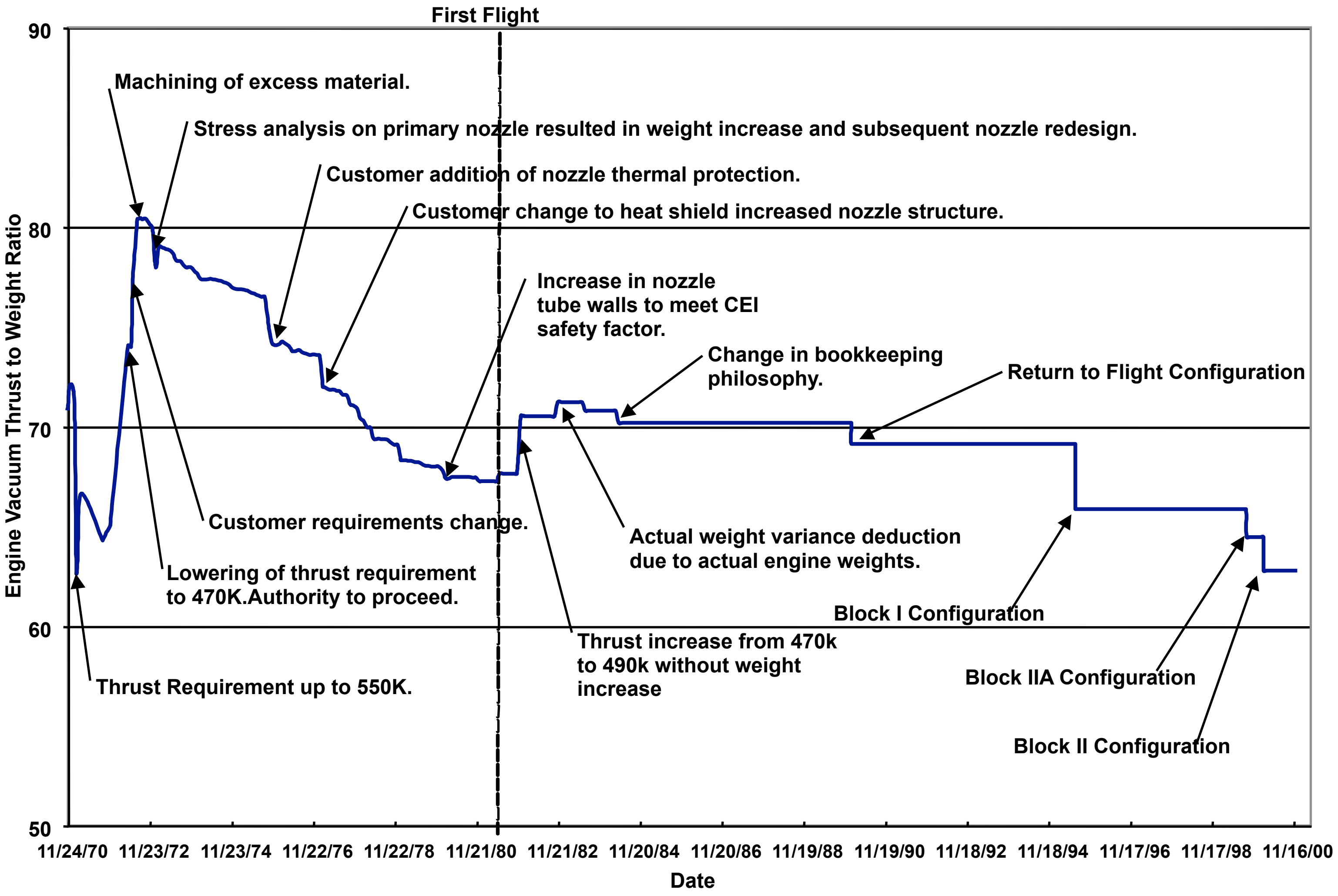
SSME Solutions and Weight Growth

- **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**
  - 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 if technology base is not understood
- **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**