REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE
10 July 2018

2. REPORT TYPE
Briefing Charts

3. DATES COVERED *(From - To)*
01 June 2018 - 30 July 2018

4. TITLE AND SUBTITLE
Advances in Turbopump Technology (Briefing Charts)

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Alan Sutton

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
P0D9

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory (AFMC)
AFRL/RQRE
4 Draco Drive
Edwards AFB, CA 93524-7160

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/RQR
5 Pollux Drive
Edwards AFB, CA 93524-7048

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

AFRL-RQ-ED-VG-2018-218

12. DISTRIBUTION/AVAILABILITY STATEMENT
Distribution Statement A: Approved for Public Release; Distribution is Unlimited. PA Clearance Number: 18400 Clearance Date: 25 June 2018.

13. SUPPLEMENTARY NOTES
For presentation at AIAA JPC 2018; Cincinnati, OH, USA; 09 - 12 July 2018.
The U.S. Government is joint author of the work and has the right to use, modify, reproduce, release, perform, display, or disclose the work.

14. ABSTRACT
Viewgraph/Briefing Charts

15. SUBJECT TERMS
N/A

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON / 19b. TELEPHONE NUMBER *(Include area code)*
Unclassified	Unclassified	Unclassified	SAR	15	Jamie Malak / N/A

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

AIAA JPC

Advances in Turbopump Technology

10 Jul 2018

Alan M. Sutton

AFRL/RQRE
Air Force Research Laboratory
Space & Missile Propulsion Division

Integrity ★ Service ★ Excellence

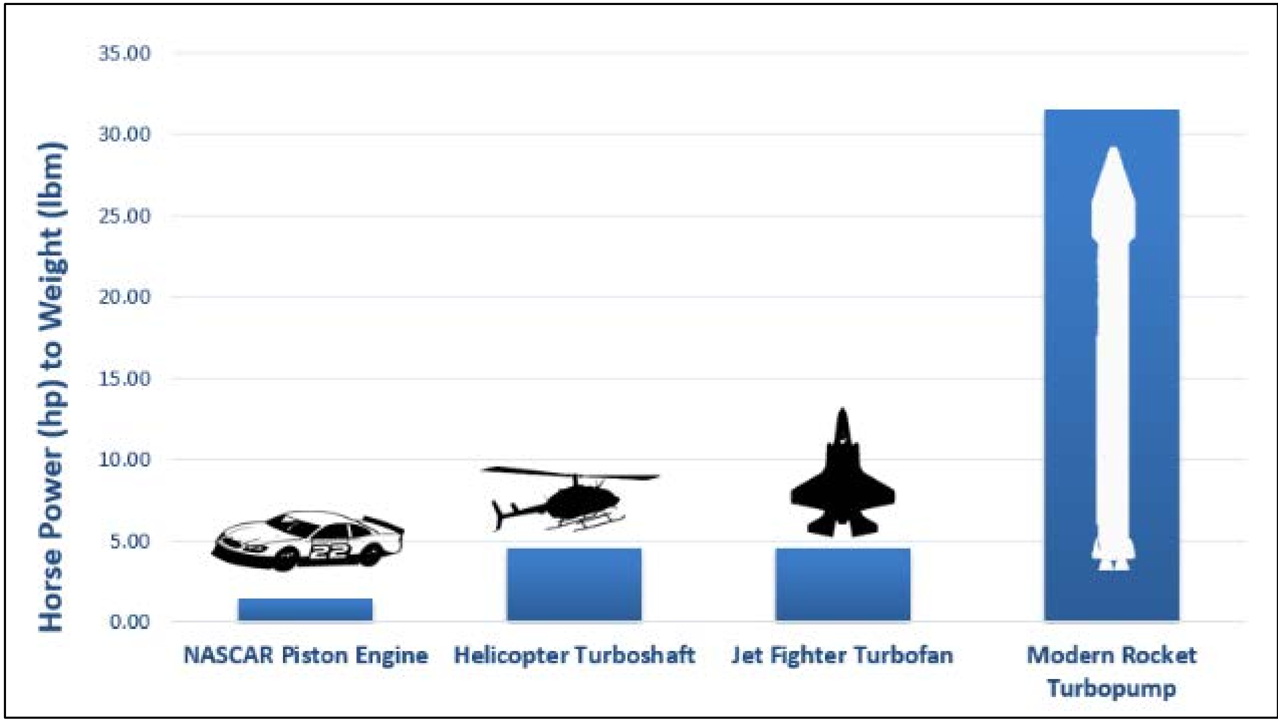
Outline

Turbopump Assembly

- Turbopump Introduction
- Turbopump Beginnings
- Heritage
  - 1950's, 1960's, 1980's, Today
- Turbopump Cavitation Limits
- Multi-Speed Shaft Design
- Historical Trends
- Summary

Power Density of Various Machinery

- **The high power to weight ratio created challenges:**
  - – Rotordynamics
  - – Thrust balance
  - – Structures
  - – Thermal
  - – Hydrodynamics
  - – Aerodynamics
  - – Bearings & seals



Rocket Turbopumps Highest Horsepower to Weight of Any Machine

Note: Ranges are approximate based on generally available information

First Generation of Turbopumps

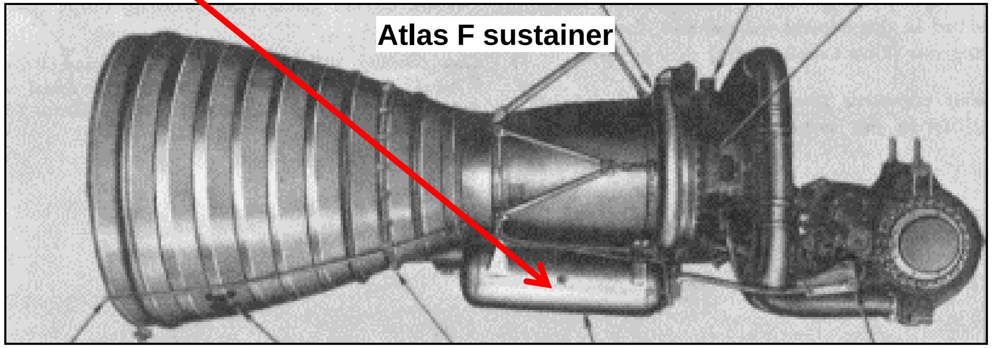
- "Boilerfeed" turbopumps have been utilized in steam systems for over a century
- Robert Goddard created the first rocket turbopump based on "boilerfeed" design
  - Classic design includes a centrifugal pump and axial turbine
  - This basic configuration continues today with the addition of more pump and turbine stages

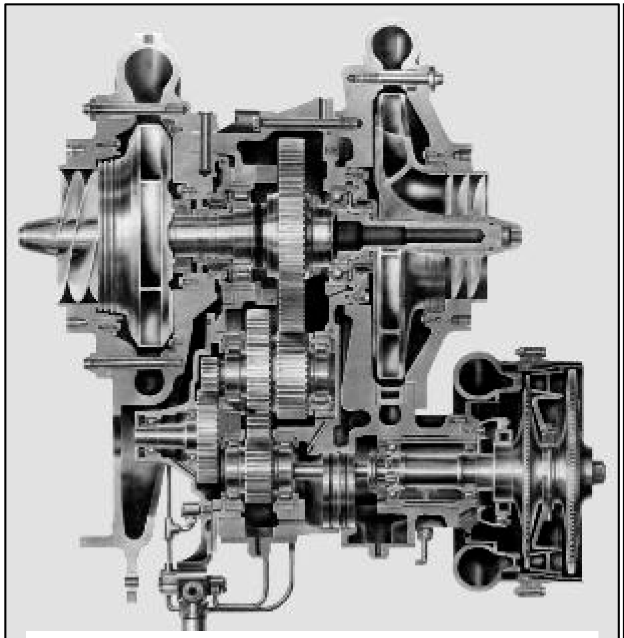
Robert Goddard's First Generation Turbopump

- Early designs were derivatives of water pumps or gas turbines
  - Poorly optimized for real propellant proper

1950's Turbopump Heritage

- **1950's Atlas & Thor Turbopump**
  - **Challenge with bearing lube freezing during LOX chill-in**
    - Not a major issue for liquid ICBM version
    - Limited Launch Vehicle hold times
  - **Gas Generator Cycle**
    - Extremely sensitive to TP efficiency
  - **Two Shaft design**
    - Oxidizer & fuel pumps on one shaft
    - Turbine & auxiliary drive another shaft
  - **Different speeds achieved via a complex gear box**
  - **Separate lube tank**

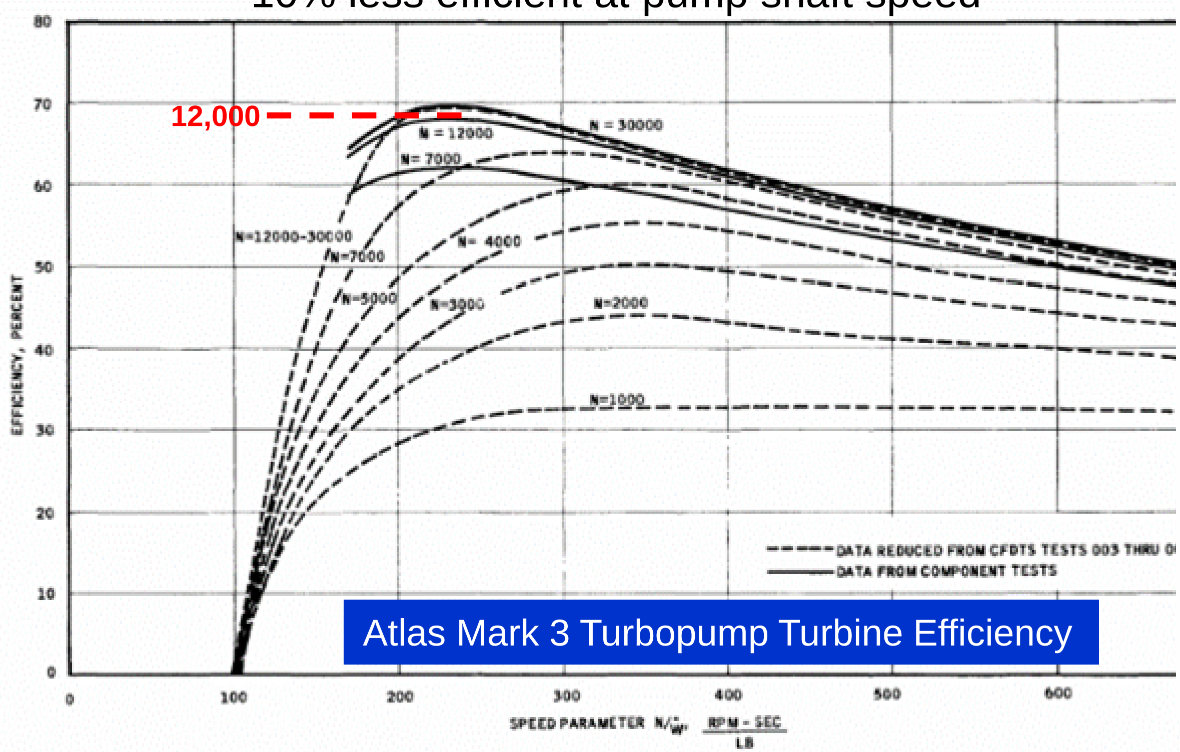


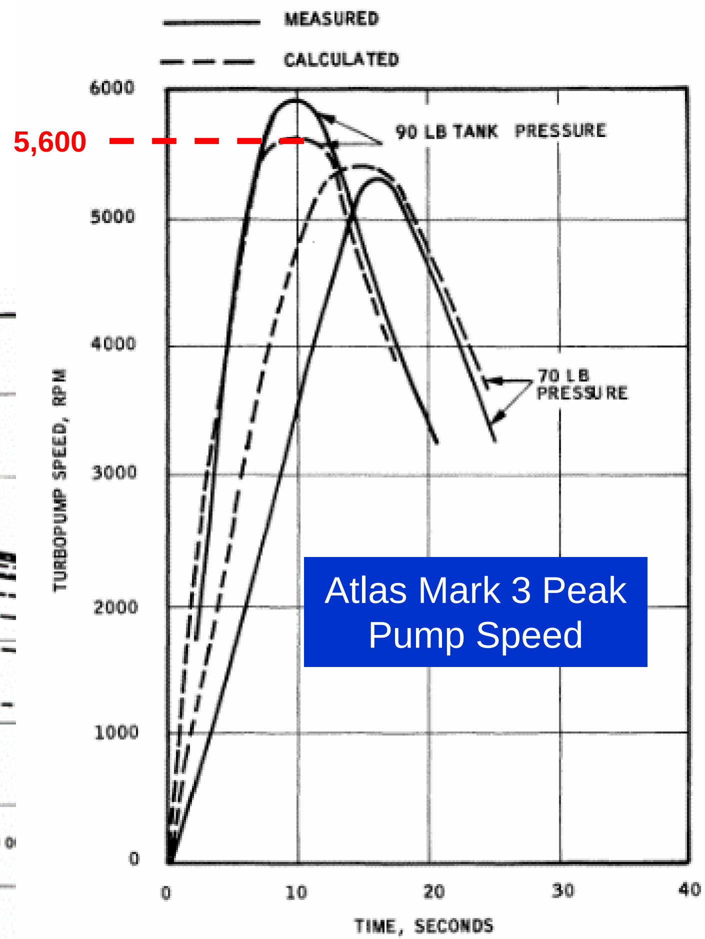

Mark 3 turbopump for the Atlas F Engine


Atlas Launch Vehicle

Atlas & Thor Turbopumps

- **Early turbopump gear box allow pump & turbine to operate at different speeds**
  - **Pump speed limited by suction performance NPSH 5,600 RPM**
  - **Turbine speed over 12,000 RPM**
    - 10% less efficient at pump shaft speed





COMPARISON OF CALCULATED AND MEASURED PUMP SPEED

Reference 4

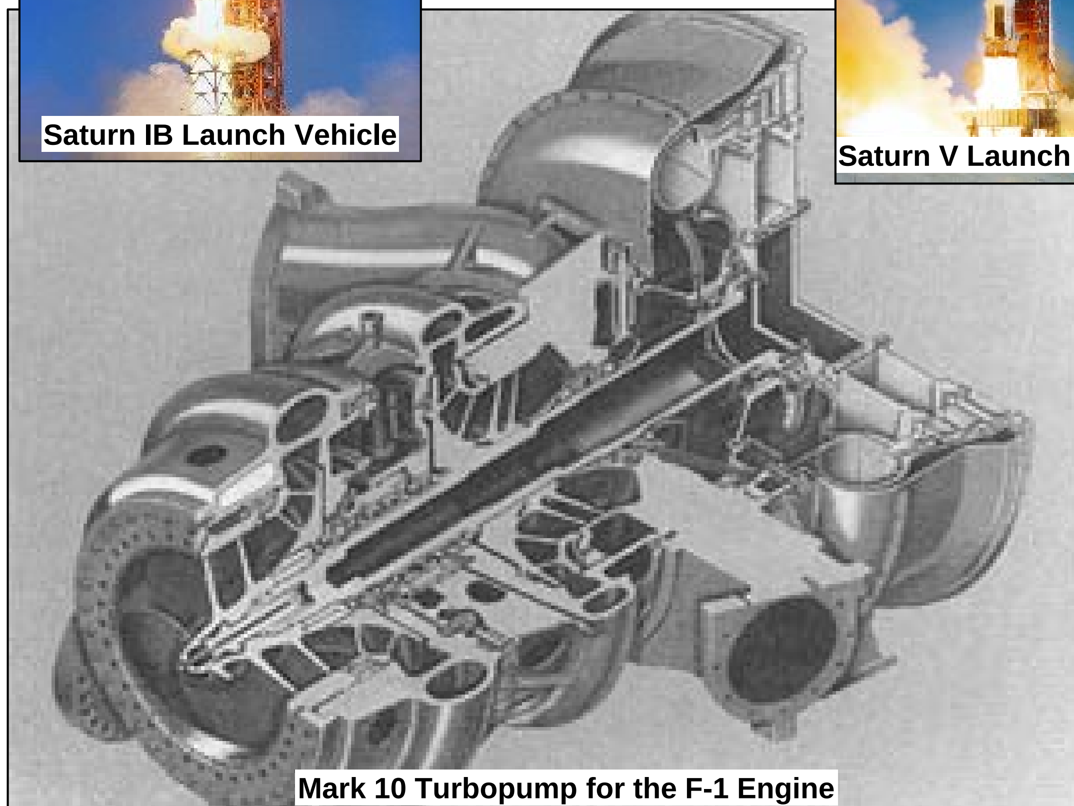
1960's Turbopump Heritage

- **1960's H-1 & F-1 Turbopump**
  - **Gas Generator Cycle**
  - **Single shaft with oxidizer, fuel pump, and turbine mounted same shaft**
  - **New bearing materials allowed fuel to be used as lubricant on all bearings**
  - **Fuel lubricated bearings still had freezing problem**
    - Ground powered heater added to mitigate fuel bearing freezing

Shaft Speed Still Limited by Suction Performance - NPSH

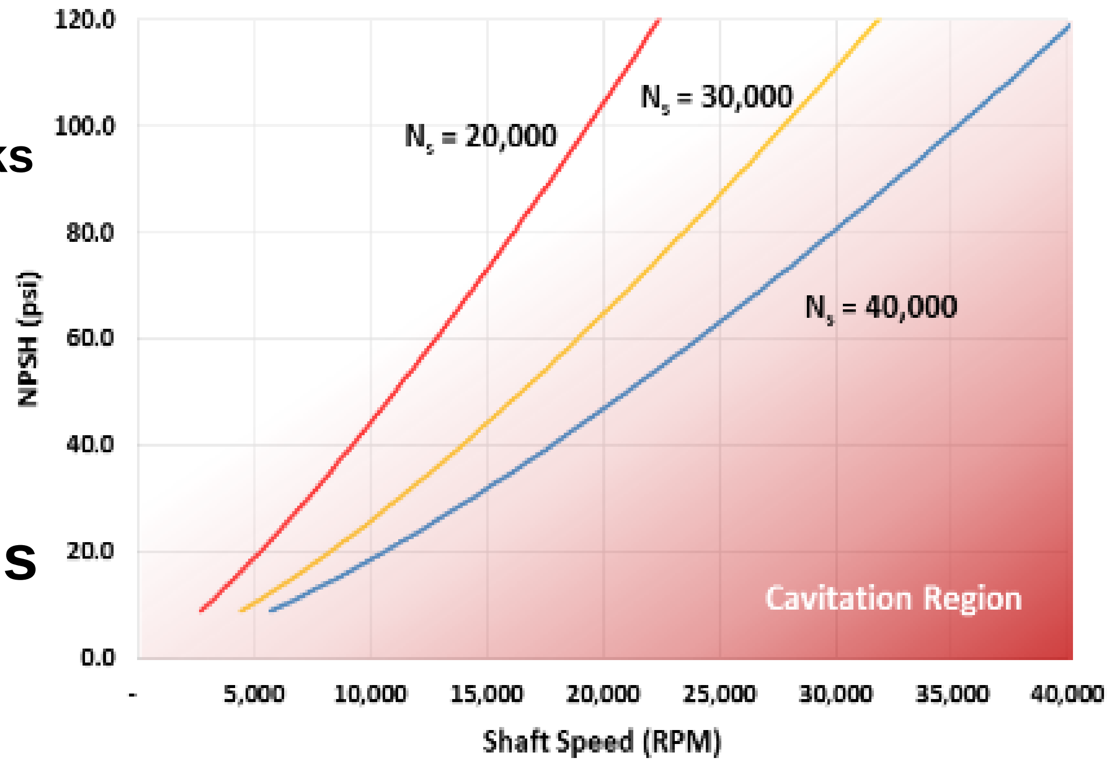

Saturn IB Launch Vehicle


Saturn V Launch Vehicle


Mark 10 Turbopump for the F-1 Engine

Cavitation is a Limit to Rotational Shaft Speed

- High tank pressure drivers down vehicle mass fraction and increases weight of Launch
  - Thicker wall propellant tanks
  - More pressurant gas
- For a given Specific Speed (N_s) the cavitation limit is directly proportional to shaft speed

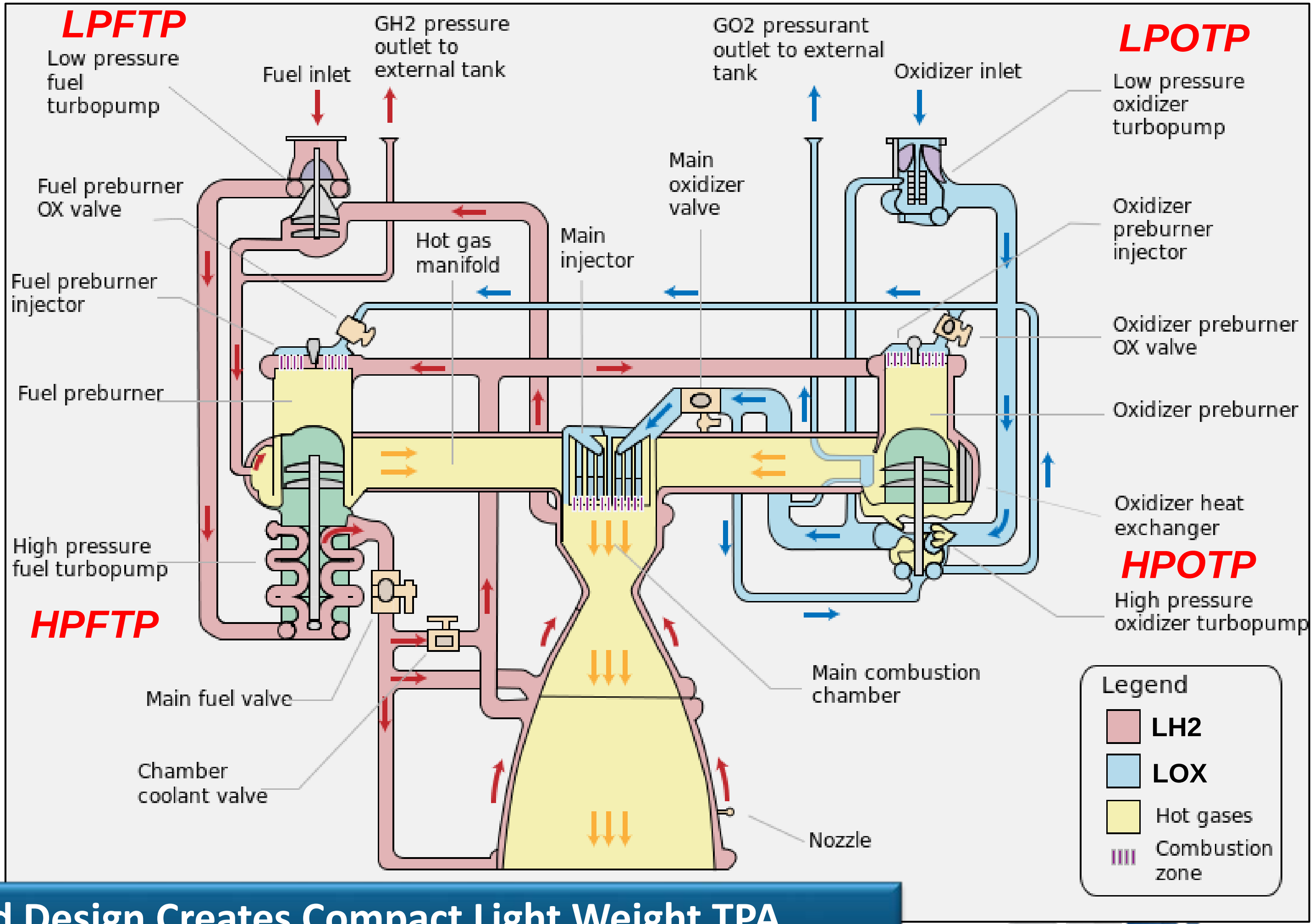


Reference 2 & 6

Current US LOX /Hydrogen Stage Combustion Engine Technology

- 1980's Space Shuttle Main Engine

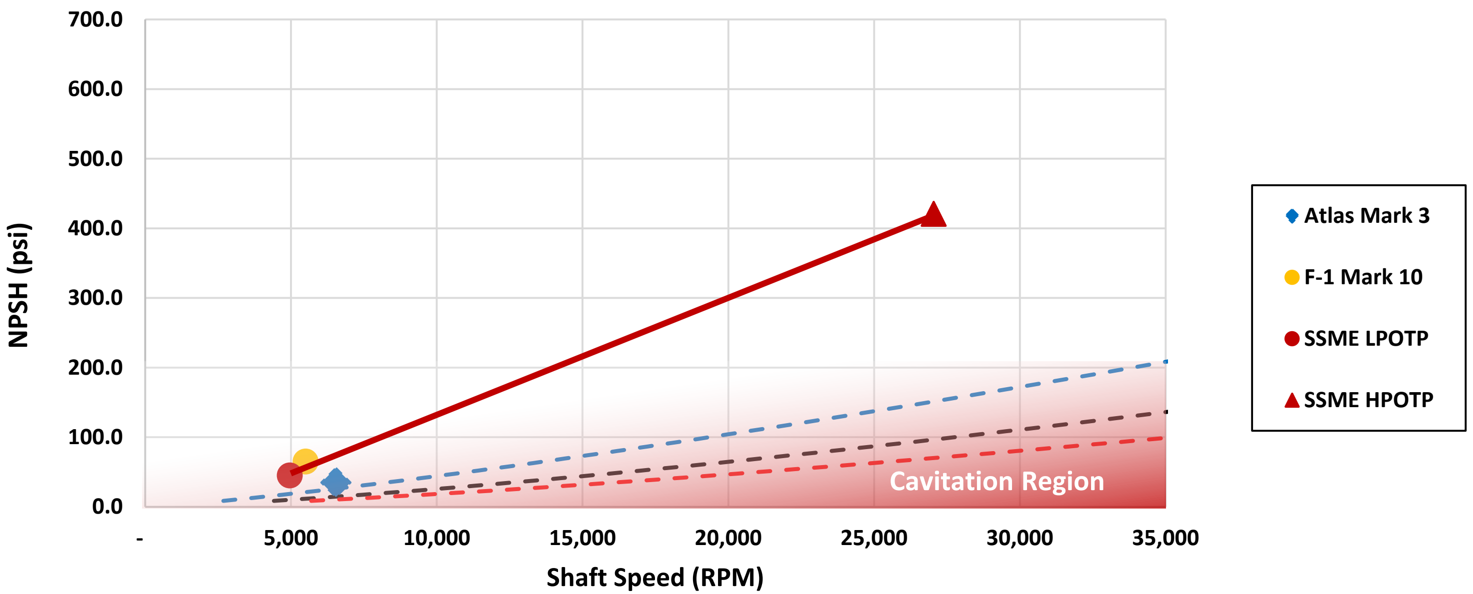
- **Separate low speed fuel & oxidizer inducer / pumps**
  - *Excellent cavitation performance*
- **Separate high speed main pumps**
  - *Speed increase pump & turbine efficiency and reduced size*
- **LOX & LH_2 used as lubricants**
- **Freezing problem eliminated with LOX cooled bearings**



Multi – Speed Design Creates Compact Light Weight TPA

Overcoming Cavitation Limits

- Cavitation performance and shaft speed limits overcome by the use of a multi-speed turbopump designs



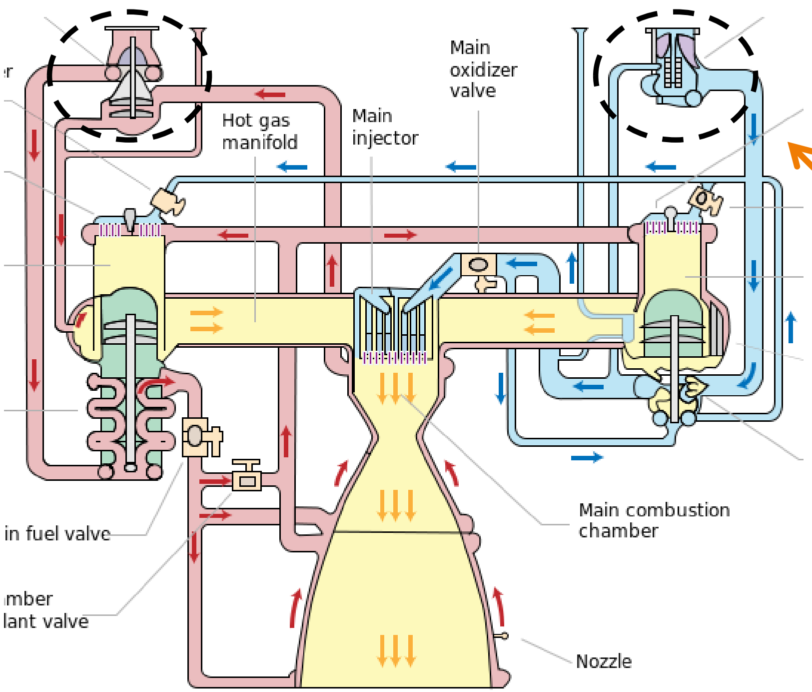
- The SSME solved this problem by separating the turbopump into two separate units

Multi-Shaft Speed Overcomes Cavitation Limit by Dividing the Turbopump

Beyond Space Shuttle Main Engine

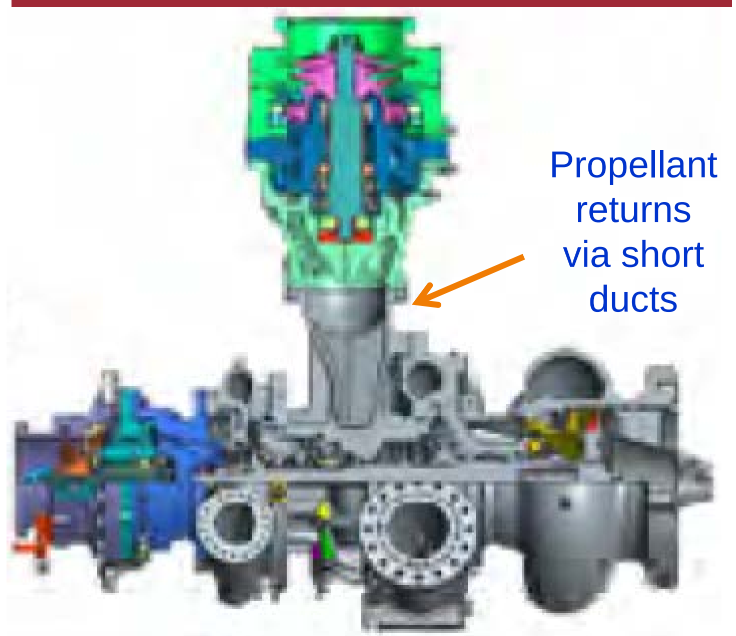
- **Further refinement of design**
  - **Closely coupling the boost pumps to the high speed turbopump**
  - **Single shaft high speed turbopump**

SSME's Low Speed Pumps Separated via Long Ducts



Propellant returns via long ducts

HydroCarbon Boost Low Speed Pumps Closely Coupled

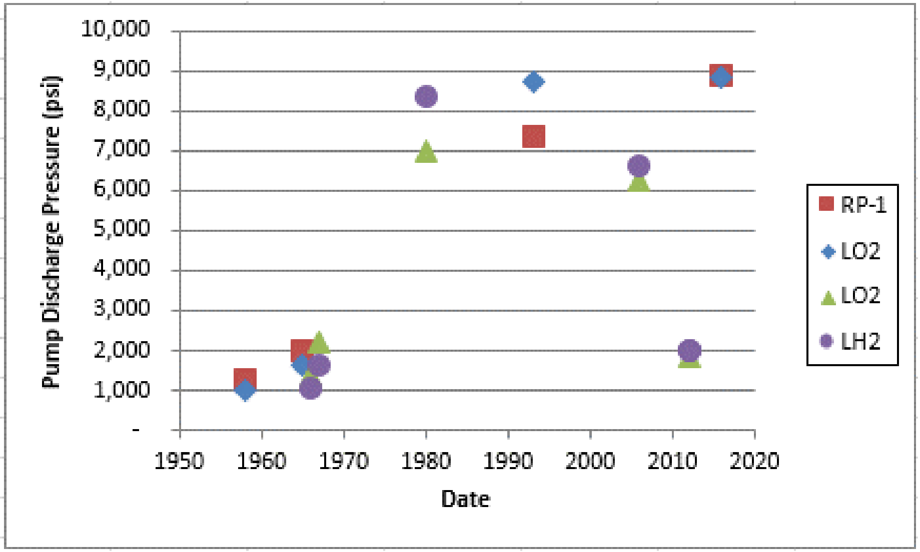


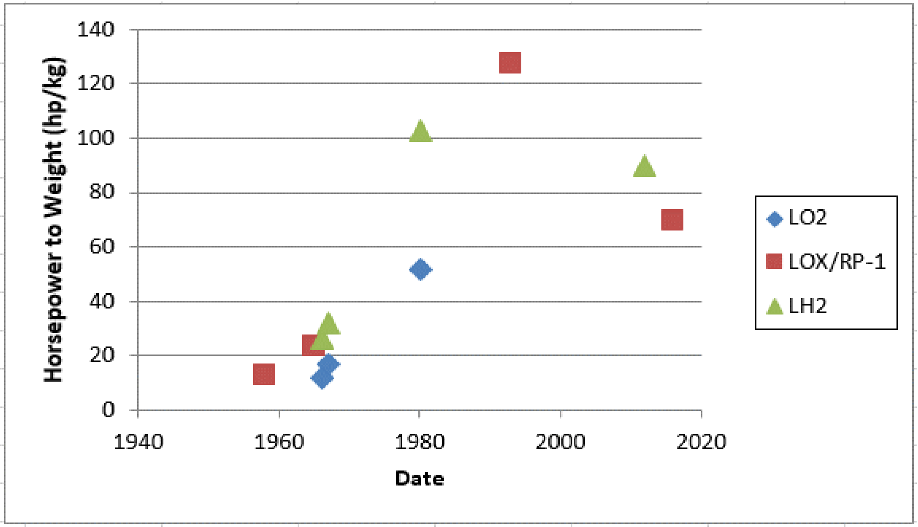
Propellant returns via short ducts

AFRL PA #17175

Historical Trends

- **Initially only low pump discharge & horsepower to weight turbopumps were possible**
- **Today a wide range of turbopumps are able to be designed**
  - **Mission dependent:**
    - **Low performance & cost for modest deltaV missions**
    - **High performance for large deltaV missions**





Summary

- Significant advances in rocket turbopump technology have been made over the past fifty years
  - Eliminated the need for separate lubrication systems
  - Multi-shaft designs have increased efficiency and decreased turbopump weight without sacrificing cavitation margin
  - Close coupled boost pumps to high speed pump
- Together increased pump discharge and horsepower to weight almost an order of magnitude

Resulting in launch vehicles with greater utility and performance

References

1. National Air and Space Museum Archives, Smithsonian Institution, "*Turbopump for Robert Goddard's P-series 'pump" rocke*t," circa 1938–41Catalog Number: NASM2014-04384.
2. D.K. Huzel, D.H., Huang, Design of Liquid-Propellant Rocket Engines, Progress in Astronautic and Aeronautics, AIAA Vol 147, ISBN: 1-56347-013-6, 1992.
3. Heroicrelics.org, "http://heroicrelics.org/info/h-1/mark-3-turbopump.html," contact: mikej@heroicrelics.org
4. AEC-NASA Space Nuclear Propulsion Office, "CFDTS Data Analysis," Nerva Program, Aerojet, RN-S-0250, Jan 1966.
5. D.E. Aldrich, "F-1 Engine," Astronautics 7, p. 69, Feb 1962.
6. E. Grist, *Cavitation and the Centrifugal Pump*, Taylor & Francis, USA, © 1999, ISBN: 1-56032-591-7.
7. Boeing, Rocketdyne Propulsion & Power, Space Transportation System, "*Space Shuttle Main Engine Orientation*," Training Data, BC98-04, June 1998.
8. I.J. Karassik, J.P. Messina, P. Cooper, C.C. Heald, *Pump Handbook*, 3rd Ed., McGRAW-HILL, New York, NY, © 2001, ISBN 0-07-034032-3.
9. C.E. Brennen, *Hydrodynamics of Pumps*, Cambridge Univers. Press, © 2011, ISBN: 978-1107002371.
10. G.P. Sutton, *Rocket Propulsion Elements*, 7 Ed., Wiley-Interscience Publ., p. 393, © 2001, ISBN: 0-47-32642-9.
11. G.P. Sutton, "Turbopumps, a Historical Perspective," 42nd AIAA JPC, 9 - 12 July 2006, Sacramento, CA, AIAA 2006-5033.