

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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1. REPORT DATE (DD-MM-YYYY)		2. REPORT TYPE Technical Papers		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Research Laboratory (AFMC) AFRL/PRS 5 Pollux Drive Edwards AFB CA 93524-7048				8. PERFORMING ORGANIZATION REPORT	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory (AFMC) AFRL/PRS 5 Pollux Drive Edwards AFB CA 93524-7048				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited. MEMORANDUM FOR PRS (In House Publication) FROM: PROI (STINFO) 18 Apr 2001 SUBJECT: Authorization for Release of Technical Information, Control Number: AFRL-PR-ED-TP-2001-091 J.S. Shelley; R. LeClaire; J. Nichols; and D. Miracle (MLLM), "Yes this is Rocket Science: MMCs for Liquid Rocket Engines" TMS Fall Meeting (Statement A) (Indianapolis, IN, 05 Nov 2001) (Deadline 11 May 2001)					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT A	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Leilani Richardson
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (include area code) (661) 275-5015

20020827 081

41 items enclosed

YES - This is Rocket Science: MMCs for Liquid Rocket Engines

04-08 Nov 01



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PRSE (Liquid Rocket Engines)
Air Force Research Laboratory



Overview



- What is Affordable?
- Affordability goals and IHPRPT
- IHPRPT Phase II Technologies
- MMC projects for IHPRPT Phase II
- Summary



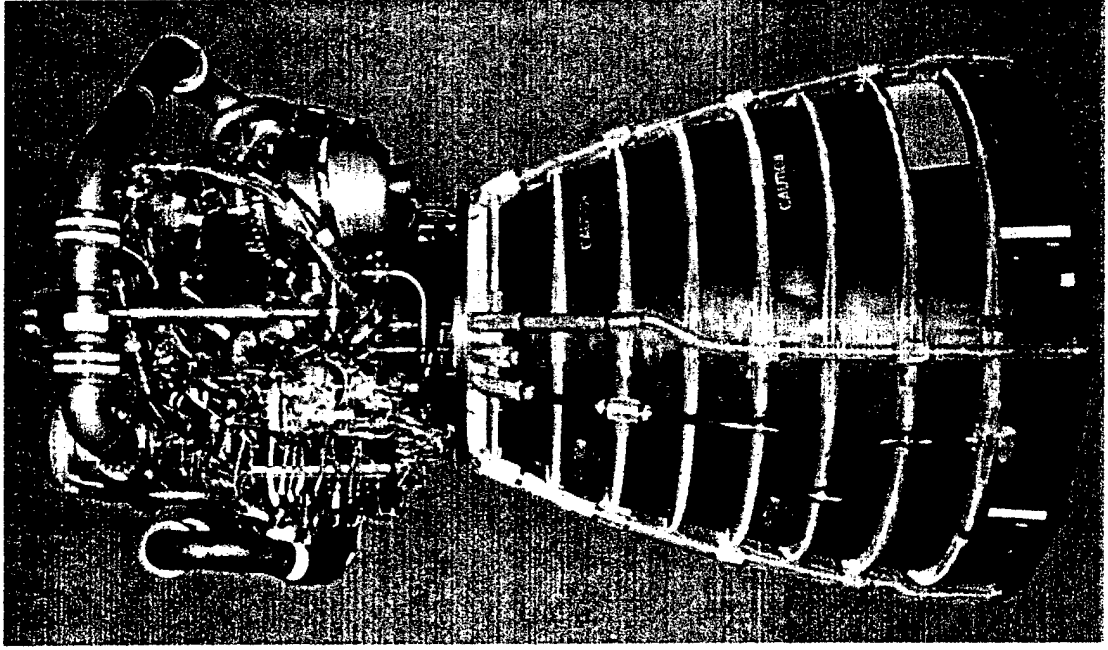
What is Affordable?



- Low production rates
 - 1 SSME produced per year, 50 total
- 3 major upgrades since 1980 (1988, 1995, 1999)
 - Over 6400 P&W F100 engines produced and in-service since 1974 in 3 models, 250/year
 - engine development cycle roughly 10-12 years
 - In 1996, US auto makers produced 11.8 M cars
 - new model development cycle 3-5 years
- Highly specific sub-components designs
 - few modular parts
 - labor-intensive assembly, refurbishment
- Performance cannot be sacrificed.



Space Shuttle Main Engine



Thrust 470,000 lbf
Weight 7,289 lb
Mission Duration 9 minutes
MTBO 7.5 hrs
Designed to 10 mission MTBR

105 in diam by 167 in long

3 SSMEs on Space Shuttle

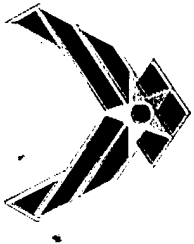


What is Affordable?



- Most turbomachinery components machined from forged billets
 - 51% total engine weight, 42% total engine cost
 - high performance properties with low Cv, tight tolerances
- Thrust chamber jacket Electrodeposited Nickel
 - 18% of C&ECD weight, 6.6% engine weight
 - 28% of C&ECD cost, 11% engine cost
 - 6 months to 1.5 year lead time
 - optimize shape, maximize liner/jacket bond integrity⁵

Good review for 2000



Affordability Goals



- Integrated high Performance Rocket Propulsion Technology Program (IHPRPT) has established goals based on total system affordability
 - Engine performance
 - Reusability
 - Engine cost
- System level goals flowed down to component level goals
 - component goals can be traded off



IHPRPT



- Integrated High-Payoff Rocket Propulsion Technology program
 - framework for guiding and tracking performance improvements
 - DoD and NASA, headed by Air Force, 1995
 - “materials” requirements tracked through IMWG (IHPRPT Materials Working Group), 1997
 - 5 years into a 15 year program
 - 3 phases planned, 5 years each
 - each phase culminates in an engine demonstration

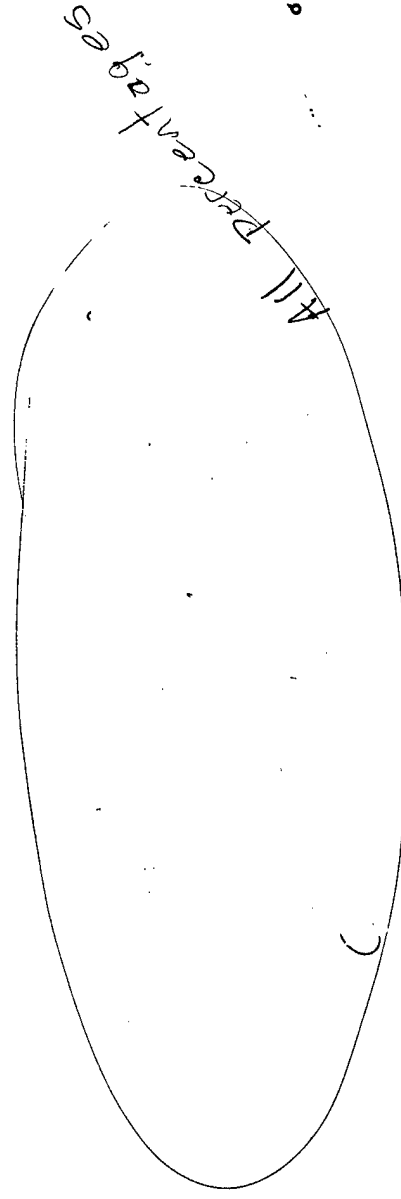


IHPRPT Goals



Cryogenic Boost and Orbit Transfer

	<u>Phase I</u>	<u>Phase II</u>	<u>Phase III</u>
Reduce Stage Failure Rate	25%	50%	75%
Improve I_{sp} (sec)	1%	2%	3%
Reduce Hardware Costs	15%	25%	35%
Reduce Support Costs	15%	25%	35%
Improve Thrust to Weight	30%	60%	100%
Mean Time Between Removal (Mission Life-Reusable)	20	40	100





IHPRPT Phase II Technologies



- Accomplish goals by enabling engineering design changes
 - Full-flow engine cycle (closed)
 - Reduced number of pump stages
 - Increased combustion pressures
 - Higher area ratio nozzles

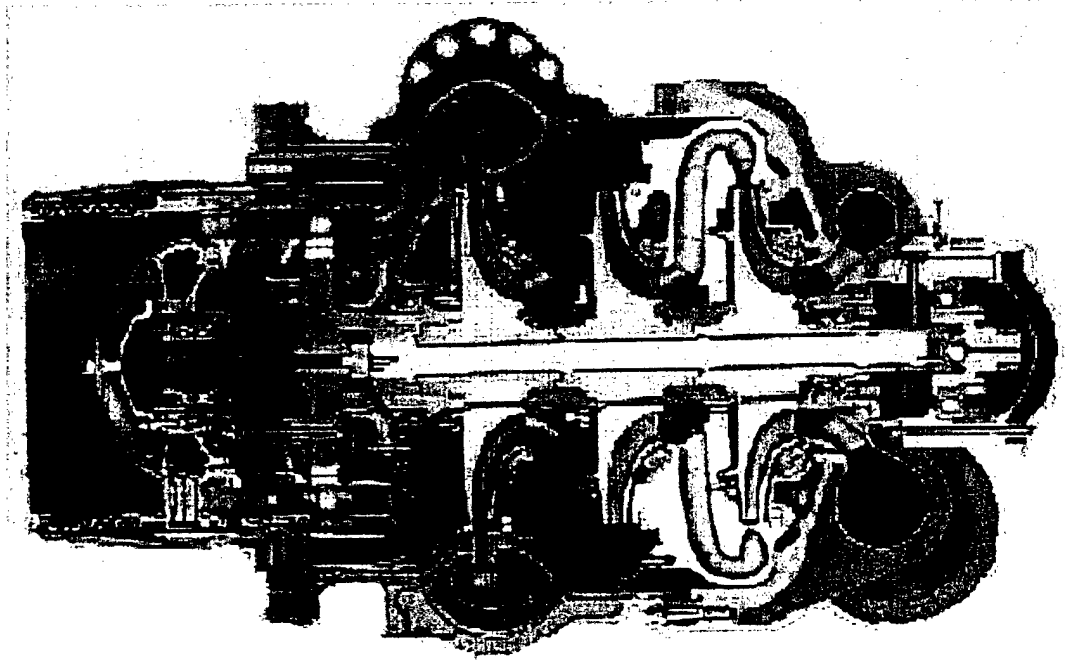


Phase II MMC Projects

- **PMD**
 - Near net shape processing
 - Al MMCs
 - “Nanostructured” Al
 - Oxygen compatible nickel alloys and MMCs
- **C&ECD**
 - Casting approaches to jackets
 - Transpiration cooling
 - Nozzle materials and design



SSME HPFTP



High Pressure Fuel Turbopump

75,000 Horsepower
178 lbs/sec fuel flow rate
6,900 psia discharge pressure
1,440 °F turbine temperature
37,000 rpm
3 stage pump/2 stage turbine
480 lbs (218 kg)
roughly 30 in diam by
41 in long



“Materials” Requirements for Pumps



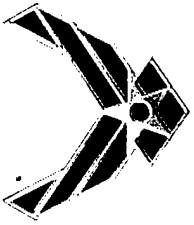
- High strength at cryogenic temperatures (125 ksi)
- LCF resistance and toughness at cryogenic temperatures
- Low density (0.14 lb/in²)
- Compatible with cryogenic propellants
- Amenable to deterministic design methods
 - generally requires ductility at temperature above 3%
- Near-net shape processing of complex geometries



Current Pump Projects



- Housings
 - particulate reinforced aluminum
 - 20 - 40% project weight savings, moderate risk, MRL = 3.5, PRL = 3
 - chopped fiber reinforced aluminum
 - 20 - 40 % $-\Delta W$, mod risk, MRL = 2.5, PRL = 2
- Rotating components
 - high-strength, compatible alloys
 - 10 - 20% $-\Delta W$, mod-high risk, MRL = 2, PRL = 5
 - ‘nanostructured’ Al
 - 0 - 10% $-\Delta W$, mod-high risk, MRL = 2.5, PRL = 1



Future Pump Efforts



- Future Efforts
 - ‘functionally graded’ MMCs with continuous fiber constituents
 - CMCs for rotating components
 - PMCs for housings



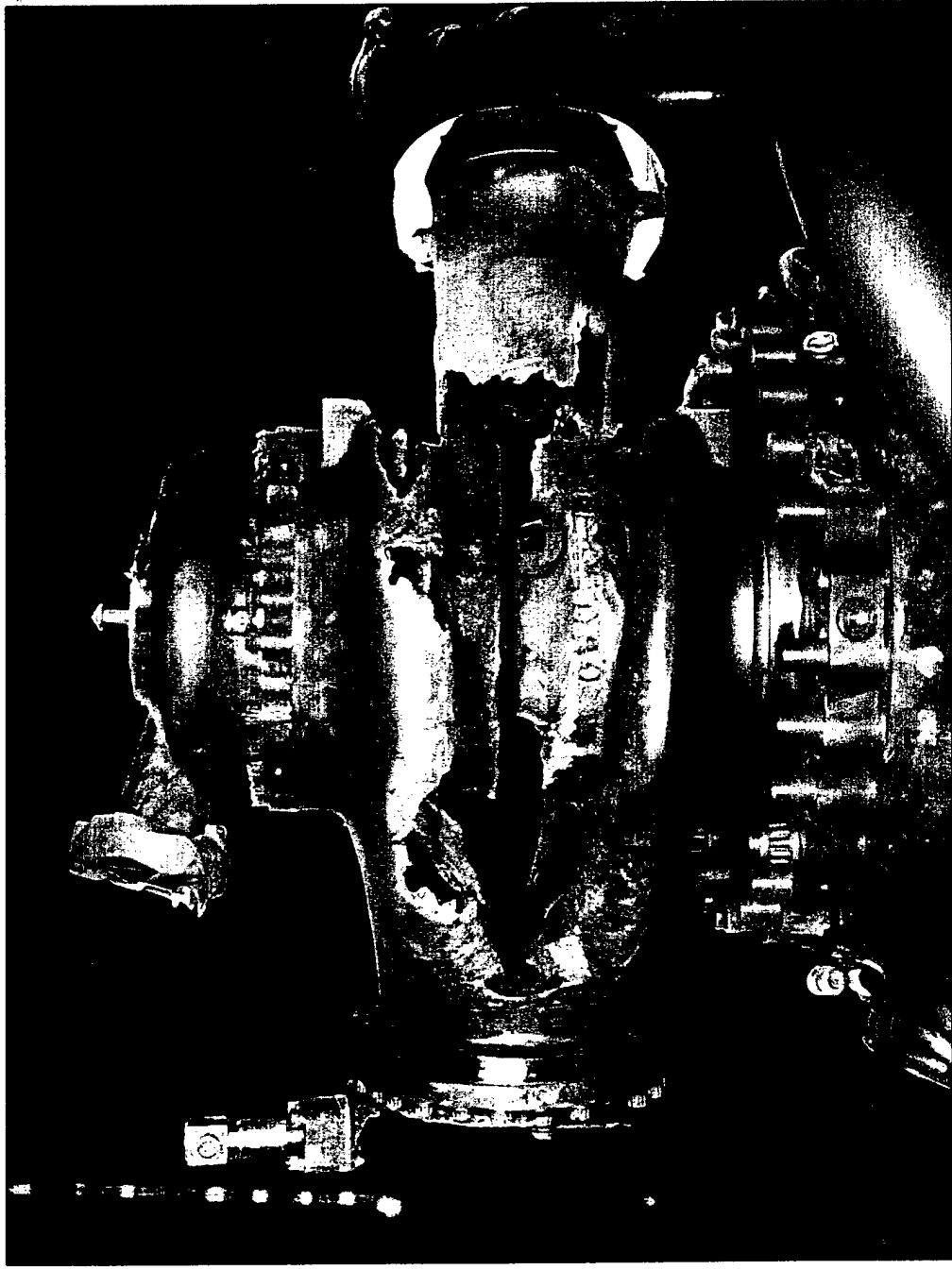
“Materials” Requirements for Full Flow Cycle



- **Oxygen Compatibility**
 - 6000 psi, 1000 deg F ox-rich steam (92 mol% O₂)
- **High strength at temperature**
 - 175 ksi at 850 deg F
- **Creep resistant**



Most High Strength Alloys Burn in High Pressure GOX



From Cliff Bampton, Boeing - Rocketdyne



Full Flow Projects



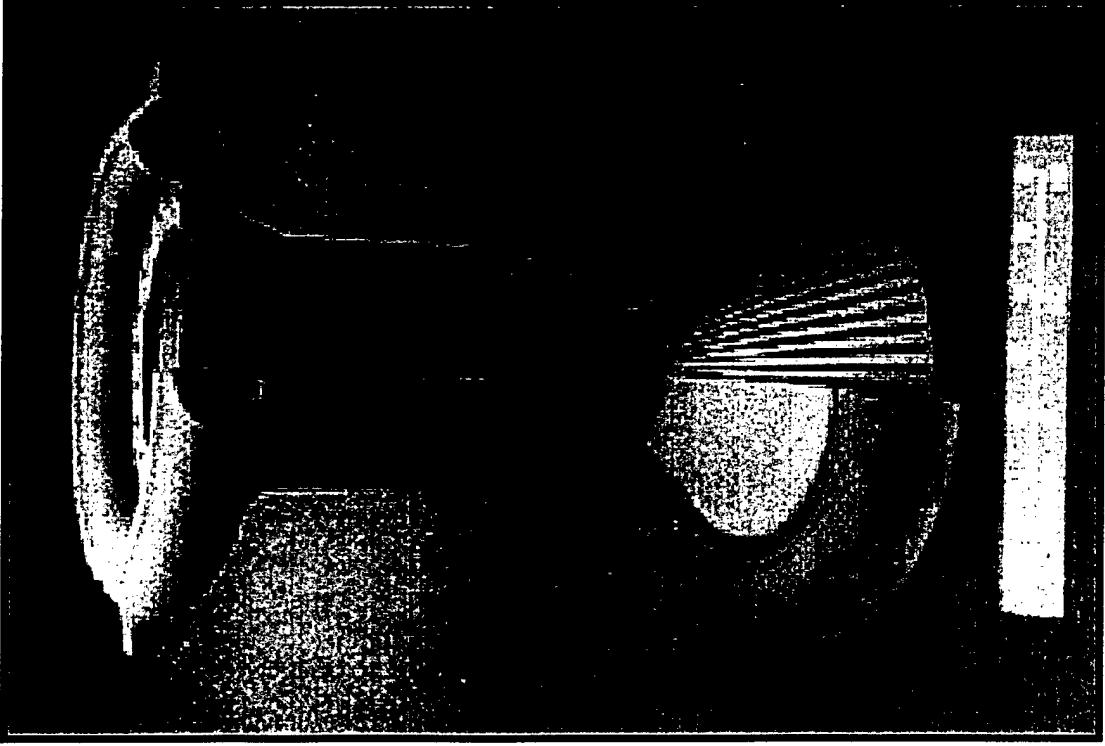
- Nickel superalloy development

- composition control for good oxygen compatibility
and good structural performance
 - PM and casting process development
- Handwritten notes:*
2 →
RSC
N: Superalloy
Effort

- Future potential projects
 - environmental barrier coatings development
 - nickel MMC



Typical Combustion Chamber



- Injector attaches at top
- Flow is from top to bottom
- Hot gas wall is copper alloy
- Structural Jacket and manifolds are high strength steel or nickel alloy
- Coolant channels contain high pressure (7000 psi) fuel (LH2)



Increased Combustion Pressures



- Greater need for cooling (heat flux greater than 100 btu/in²sec)
 - transpiration cooling
 - extreme temperature gradients (6000 °F combustion temperatures, cryo coolant)



“Materials” Requirements for Transpiration Cooling



- Defined heat transfer rate
 - reliable structural performance at temperature with temperature gradient
- Controlled porosity
 - size of pores
 - density, density gradient
- Fabricatable into “hour-glass” shape (double curvature)



Current Transpiration Cooling Projects



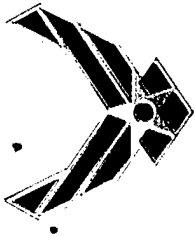
- Design optimization
 - analytical modeling and simulation effort
- Process and Fabrication efforts
 - “cool wall” copper liner
 - MRL = 4, PRL = 4, TRL = 2
 - “hot wall” concept
 - MRL = 1, PRL = 1, TRL = 1
- Future Efforts
 - small article demonstration testing



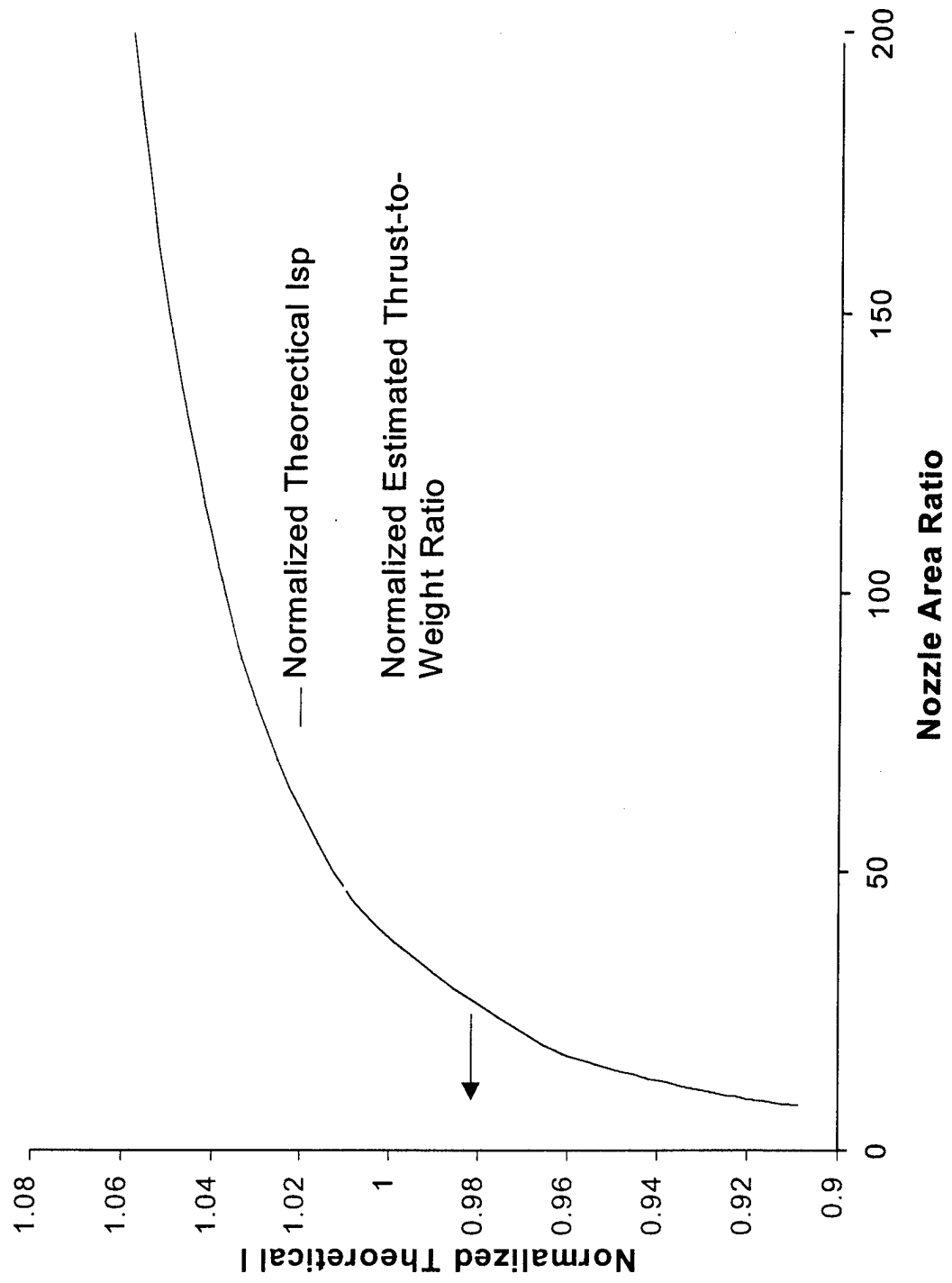
Higher Area Ratio Nozzles



- Ratio of throat area to exit plane area has a large influence on engine performance
- Influences engine weight with a practical size limit based on vehicle diameter
- Other Design Trades
 - amount of regenerative cooling
 - structural performance for side loads and gimbalng



Theoretical Engine Performance





“Materials” Requirements for Nozzles



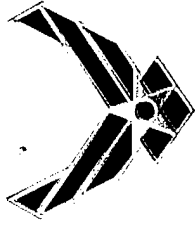
- **Resistance to chemical and thermal environment**
 - **actively or passively cooled**
- **“Reusability”**
 - **uncooled re-entry**
 - **replacement / repair**
- **Impermeability to exhaust gases**
- **Low density**



Current Projects for Nozzles



- **Exploratory effort for erosion-resistant high-temperature materials**
- **Future Efforts**
 - **engineering design trade studies**
 - **environmental protective coatings**
 - **potential expendable exit cone development**
 - **materials for high-stiffness nozzle concepts**



Summary



- **“Materials” development efforts are essential to achieving IHPRT Phase II and III goals**
 - **engine system goals for performance, reliability, and cost**
- **Affordability is based on low production rate, high reliability, specialized components**
- **Ongoing and planned “materials” efforts**
 - **near net shape processes**
 - **composite engineering**
 - **design trade studies**



Bibliography



- C. J. Meisl “Rocket Engine vs Jet Engine Comparison”, AIAA 92-3686, 28th Joint Propulsion Conference, July 6-8 1992, Nashville, TN (1992).
- J. C. Williams “Materials Requirements for High-Temperature Structures in the 21st Century”, Phil Trans Royal Soc London, 351 (1995) pp435-449.

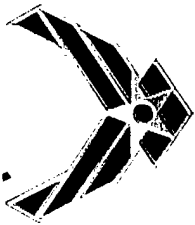


Back up
Slides



IRLs and PRLs

- **Creates a framework for judging material readiness for a particular application**
 - application (component) specific
 - time frame specific
- **Establishes uniform demonstration goals for material development and insertion**
 - no specific route of progression implied
 - no assessment of degree of difficulty of progression



Aerospace Corp MRL and PRL



DEFINITIONS

Materials Readiness Level (MRL)

Material routinely available and used in similar components

Material applied to shapes of the size and type of objective component with verified properties

Material applied to objective shape with verified properties

Material data properties verified

Material within family identified

Material family/families identified

Process Readiness Level (PRL)

Process applied to object has produced defect free components; process parameter ranges identified

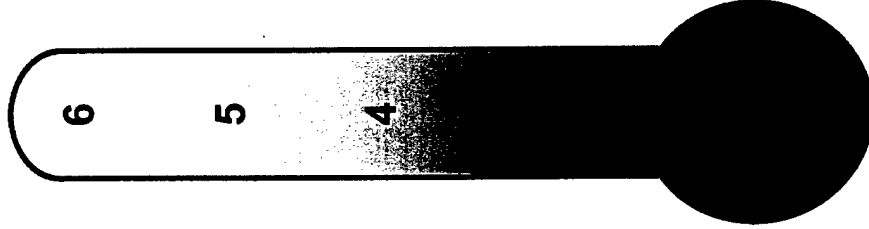
Process has been applied to shapes of the size and type of the objective component.

Process has been modified to apply to objective shape

Process produces desired physical and mechanical properties

Process has been applied to simple test coupons

General classes of possible processes identified

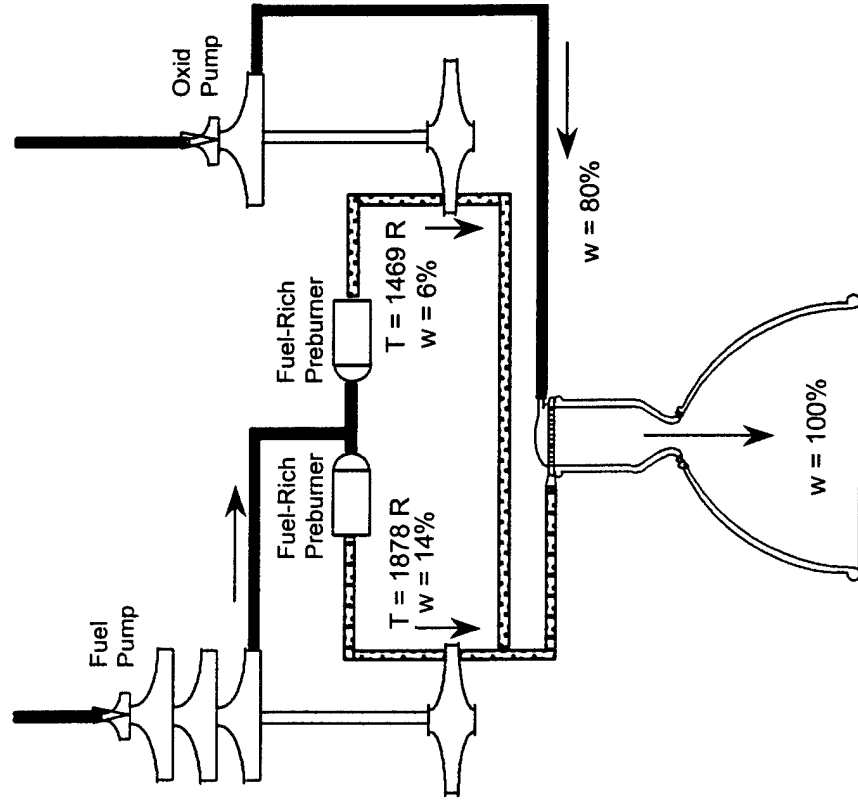




Full Flow Cycle

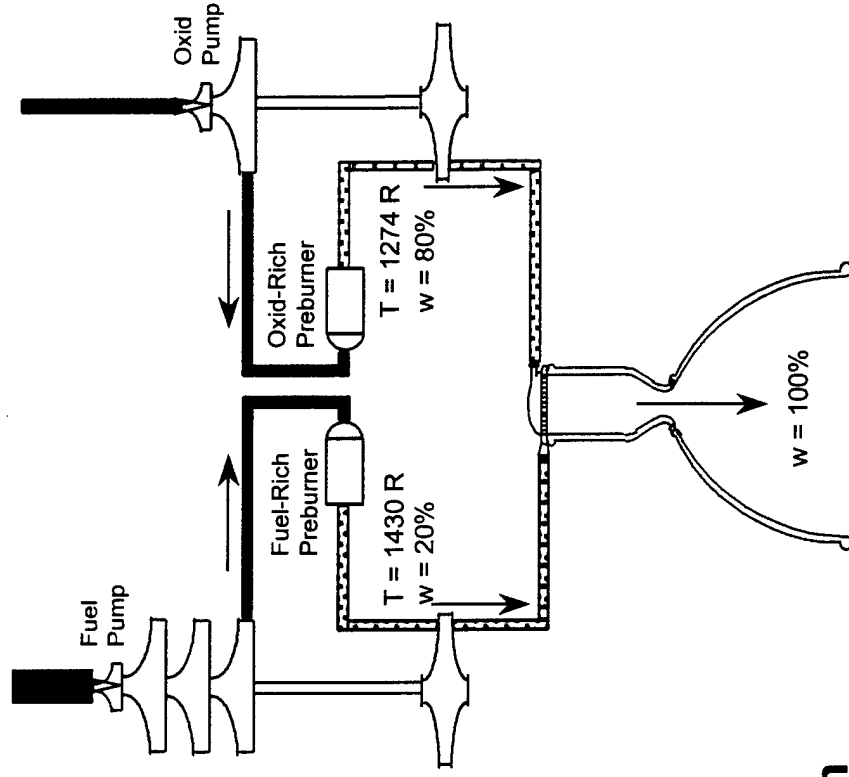


Staged Combustion Cycle (SSME)



— hydrogen
— oxygen

Full Flow Staged Combustion Cycle





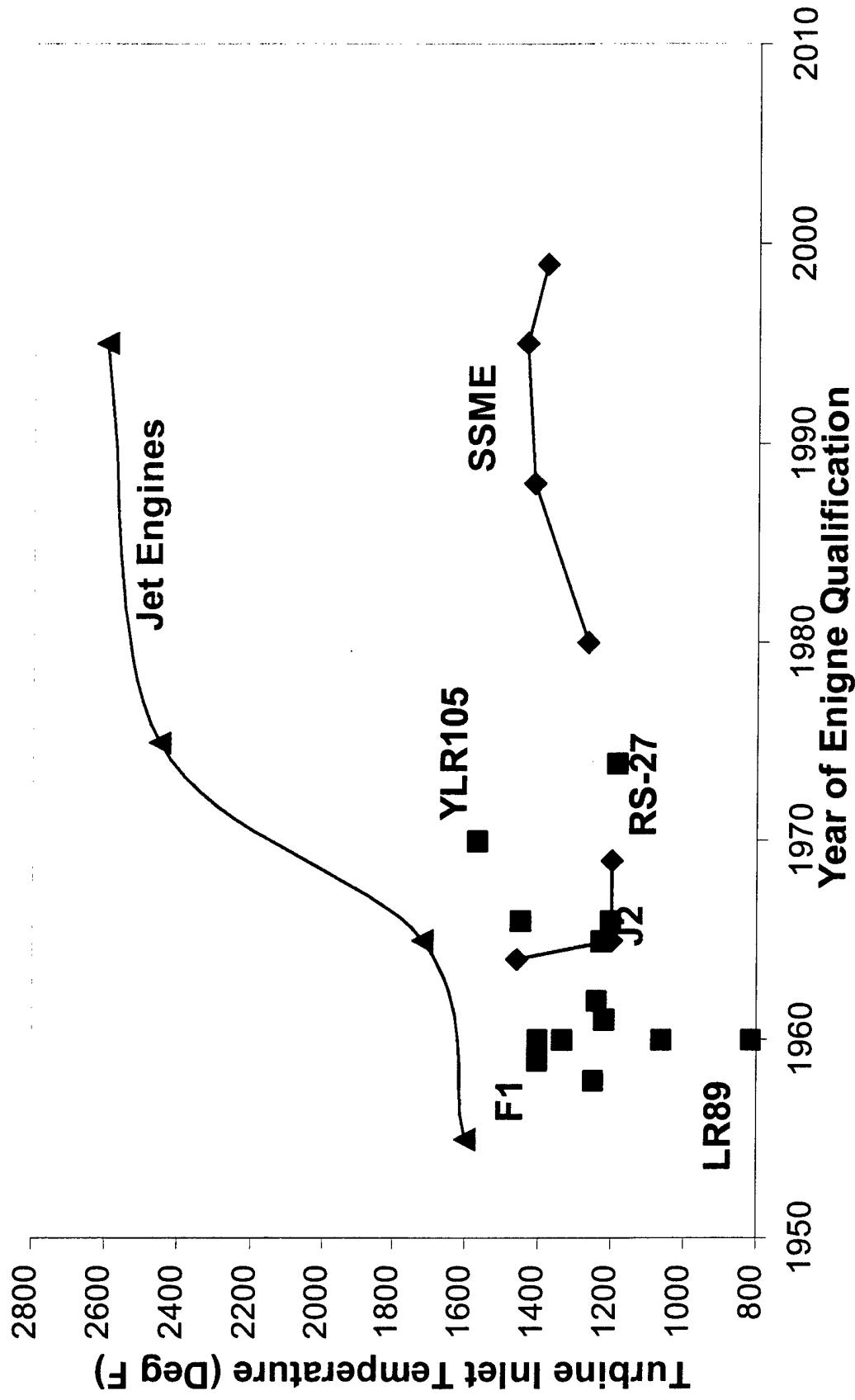
Reduced Pump Stages



- Historical engines typically have 2 or 3 stage pumps
 - SSME has 2 pumps for each fuel and oxidizer
 - relies on forged and machined Titanium
- To meet IHPRPT goals
 - reduce parts count
 - reduce complexity
 - remove a pump stage while increasing discharge pressure



Liquid Rockets Engines Face Great Materials Challenge



◆ Hydrogen Engines ■ Hydrocarbon Engines ▲ Air Breathing Jets



NASA Technical Readiness Levels

