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MEMORANDUM FOR PRS (In-HousePublication)

FROM: PROI (TI) (STINFO) 10 September 1999

SUBJECT: Authorization for Release of Technical Information, Control Number: AFRL-PR-ED-TP-FY99-0180, Karen Olson, "Material Property Sensitivities on Cryo Upperstage Rocket Engines," **26th Annual Western Regional Conference** **(Statement A)**

Material Property Sensitivities on Cryo Upperstage Rocket Engines

Karen Olson
Applications and Assessments Branch
Propulsion Sciences & Advanced Concepts Division
AFRL/PRST

Overview

- Objective
- Baseline & Demonstrator Engine Description
- Material / Engineering Limits
- Sensitivities
- Weight Estimations
- Impact on Payload
- Conclusion
- Recommendation

Study Objective

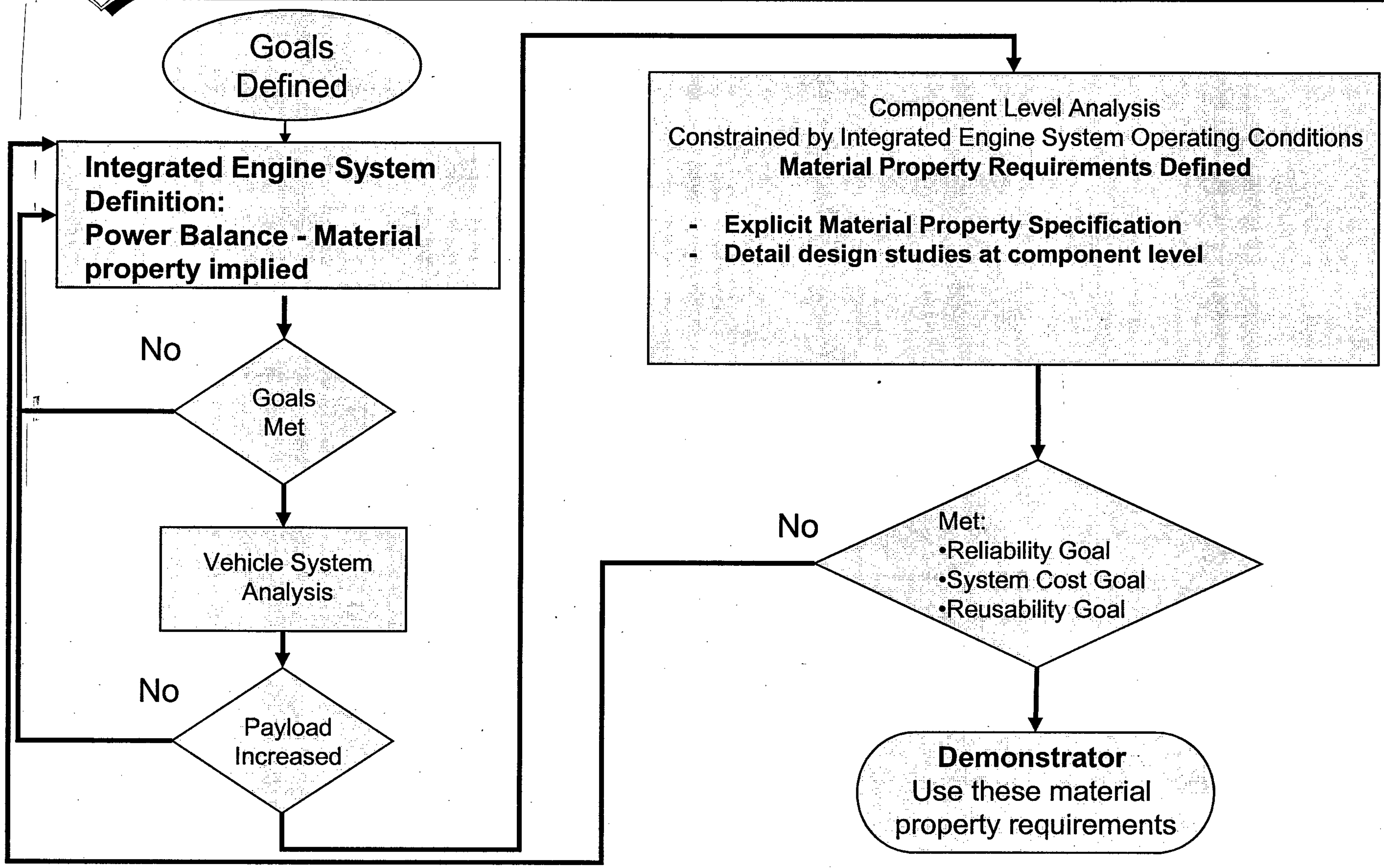
Identify the critical material properties that enable a demonstrator engine to meet **I**ntegrated **H**igh **P**ayoff **R**ocket **P**ropulsion **T**echnology (IHPRPT) performance (Isp and thrust-to-weight) goals.

IHPRPT Goals

Boost and Orbit Transfer Propulsion	2000	2005	2010
• Reduce Stage Failure Rate	25%	50%	75%
• Improve Mass Fraction (Solids)	15%	25%	35%
• Improve ISP (sec)	14	21	26
• Reduce Hardware Costs	15%	25%	35%
• Reduce Support Costs	15%	25%	35%
• Improve Thrust to Weight (Liquids)	30%	60%	100%
• Mean Time Between Removal (Mission Life-Reusable)	20	40	100
Spacecraft Propulsion			
• Improve I_{tot}/Mass $_{(wet)}$ (Electrostatic/Electromagnetic)	20%/200%	35%/500%	75%/1250%
• Improve Isp (Bipropellant/Solar Thermal)	5%/10%	10%/15%	20%/20%
• Improve Density-Isp (Monopropellant)	30%	50%	70%
• Improve Mass Fraction (Solar Thermal)	15%	25%	35%
Tactical Propulsion			
• Improve Delivered Energy	3%	7%	15%
• Improve Mass Fraction (Without TVC/Throttling)	2%	5%	10%
• Improve Mass Fraction (With TVC/Throttling)	10%	20%	30%

lower case to match second group

Liquid Rocket Engine Material Property Requirement Generation Flow Diagram



Performance Goals for Cryogenic Upperstage Rocket Engine

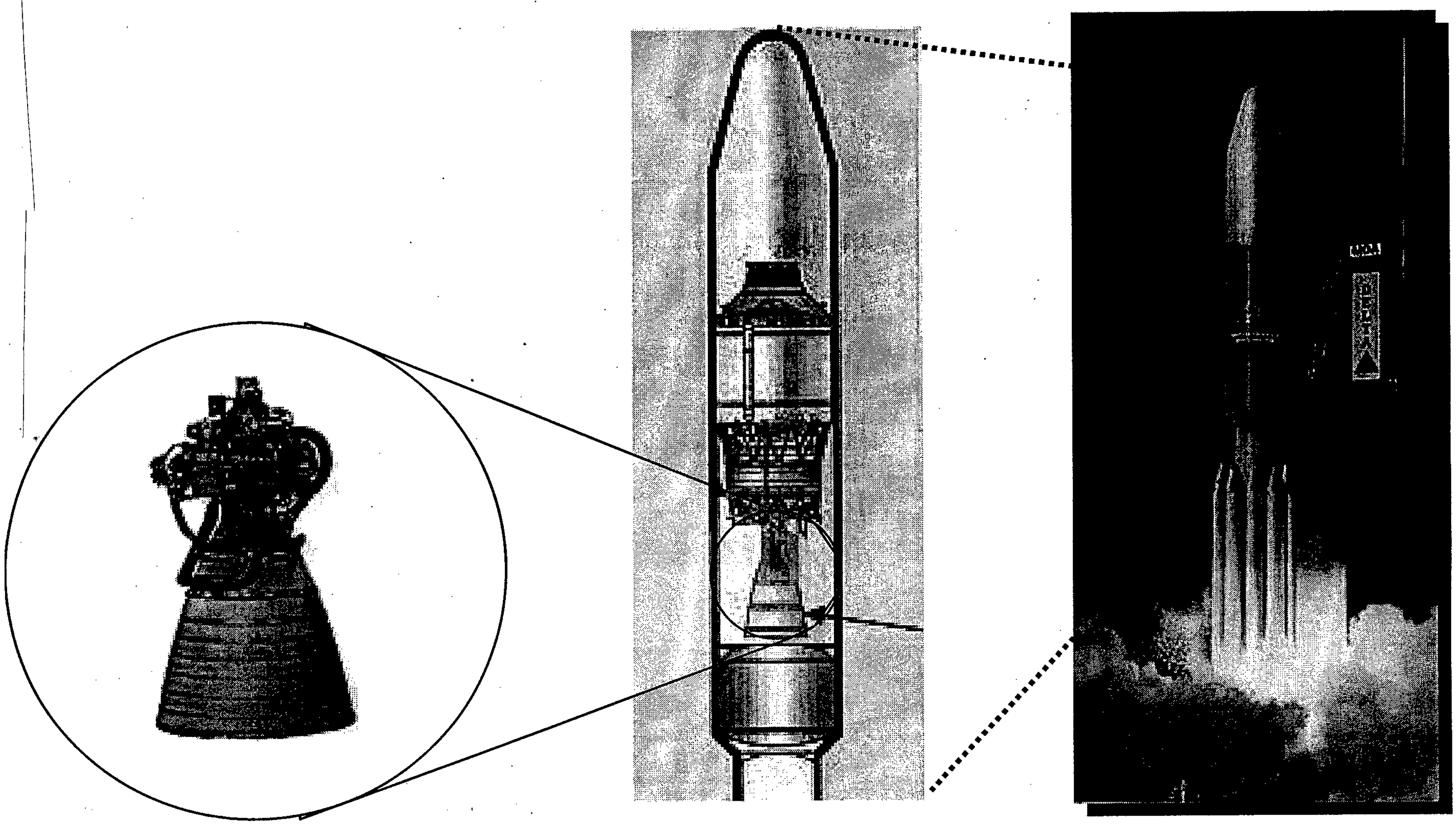
Goals:

- Isp improvement of 3% over Baseline
- Thrust-to-weight improvement of 100% better than Baseline

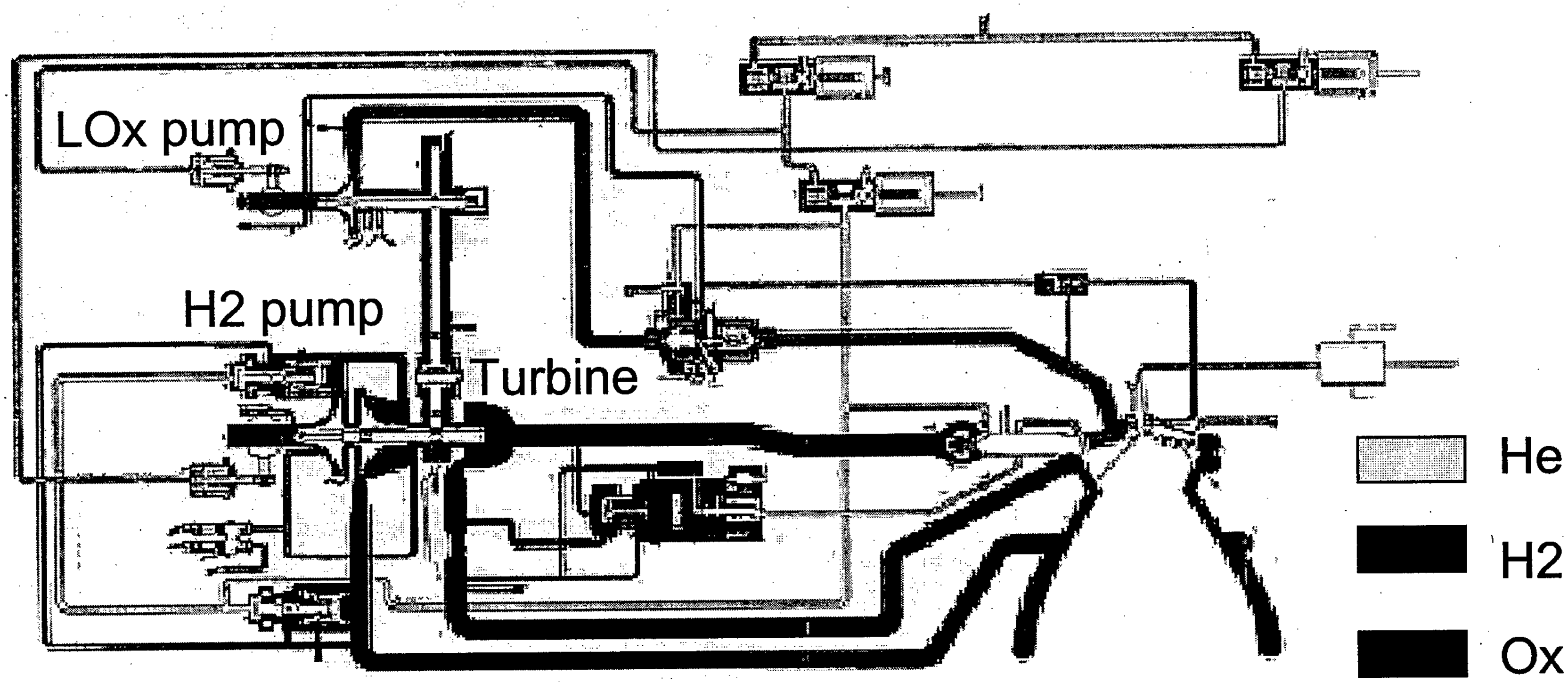
Baseline & Demonstrator Engine Comparison

	Baseline Engine	Demonstrator - Space
Thrust	16,500 lbs	50,000lbs
Mixture Ratio	5.0	5.0
Chamber Pressure	500 psia	2000 psia
Nozzle Area Ratio	60:1	170:1
Turbopump Description	2-stage Fuel	3-stage Fuel

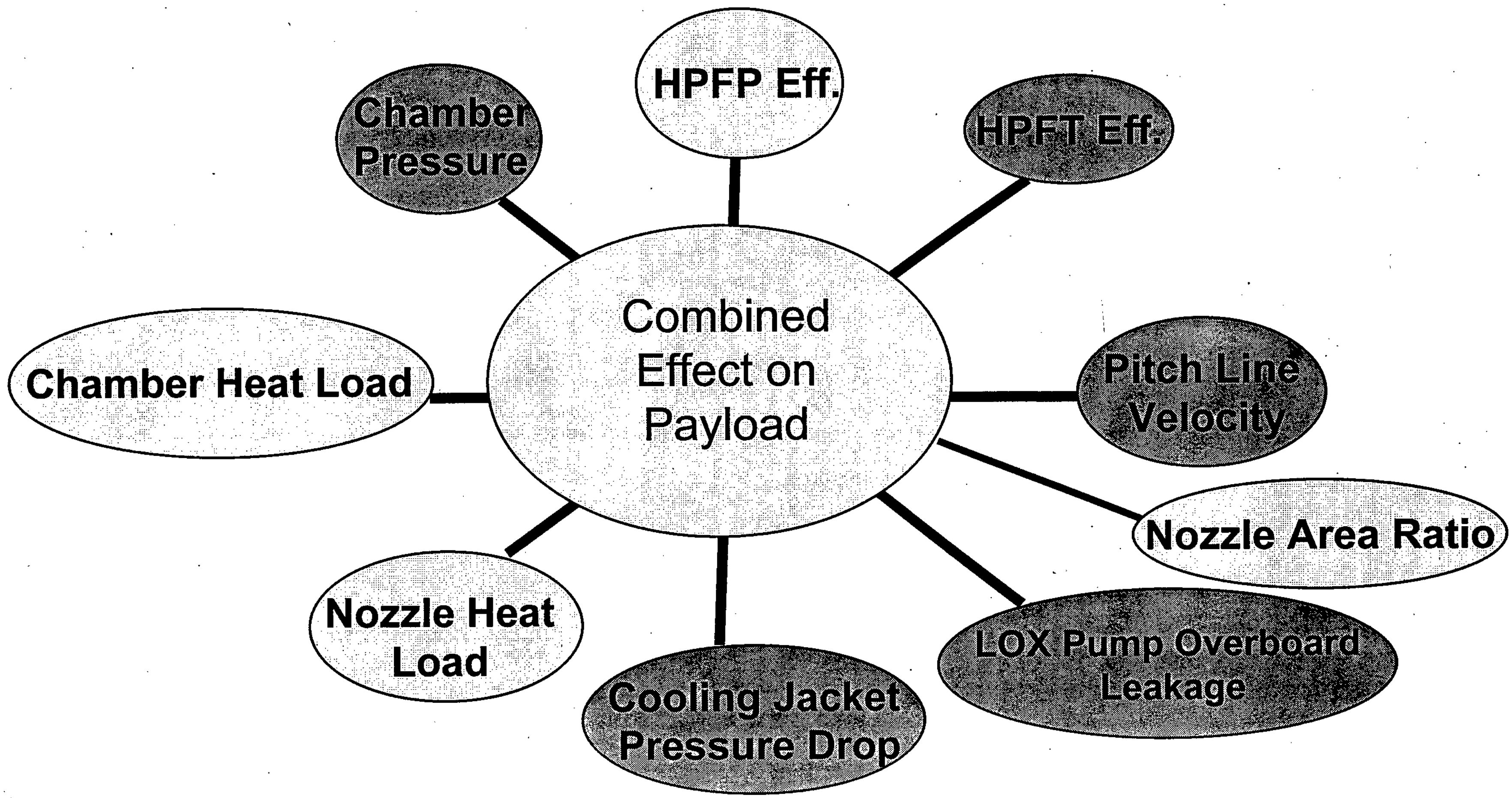
Delta III Configuration



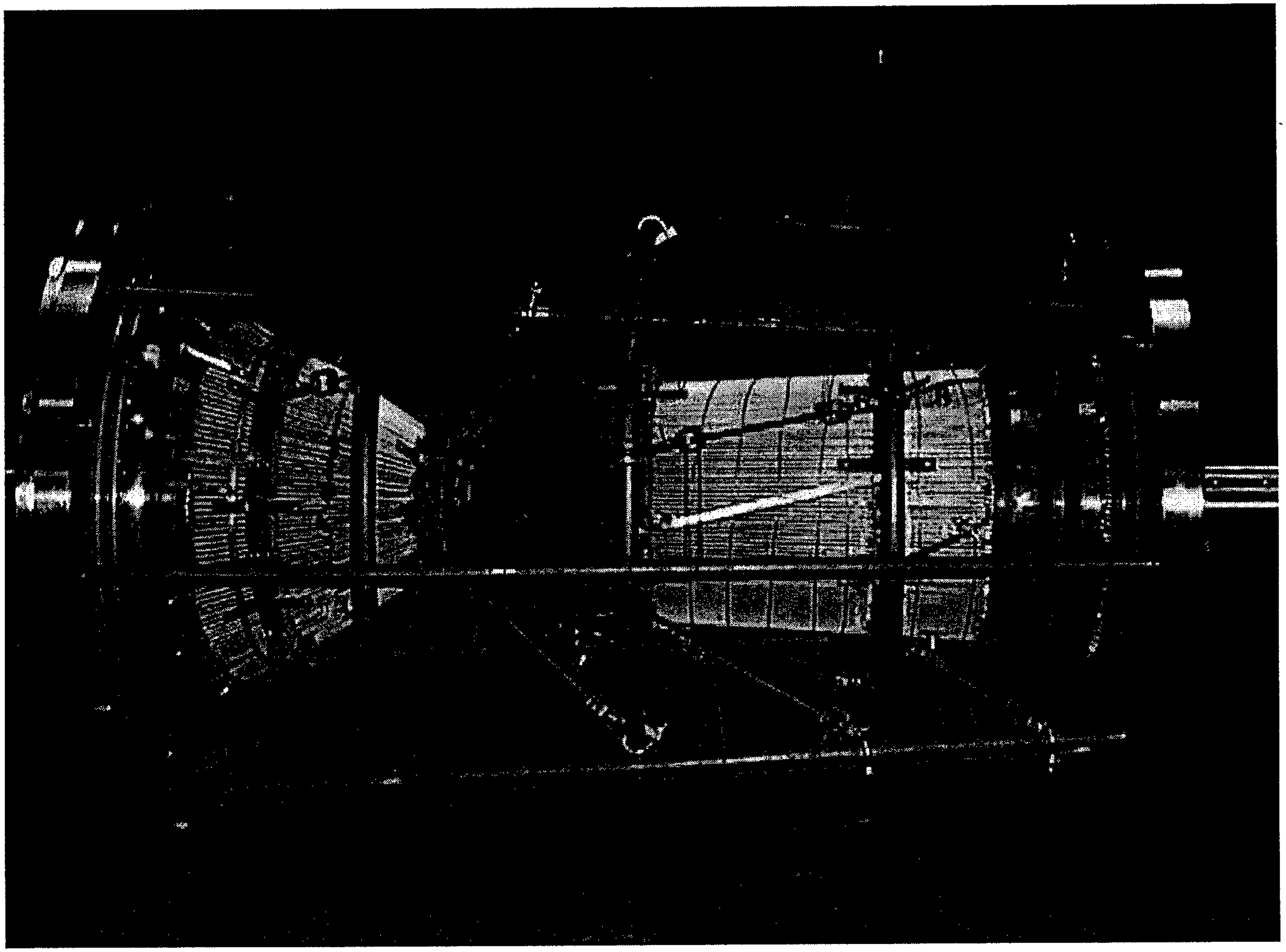
Baseline Flow Schematic



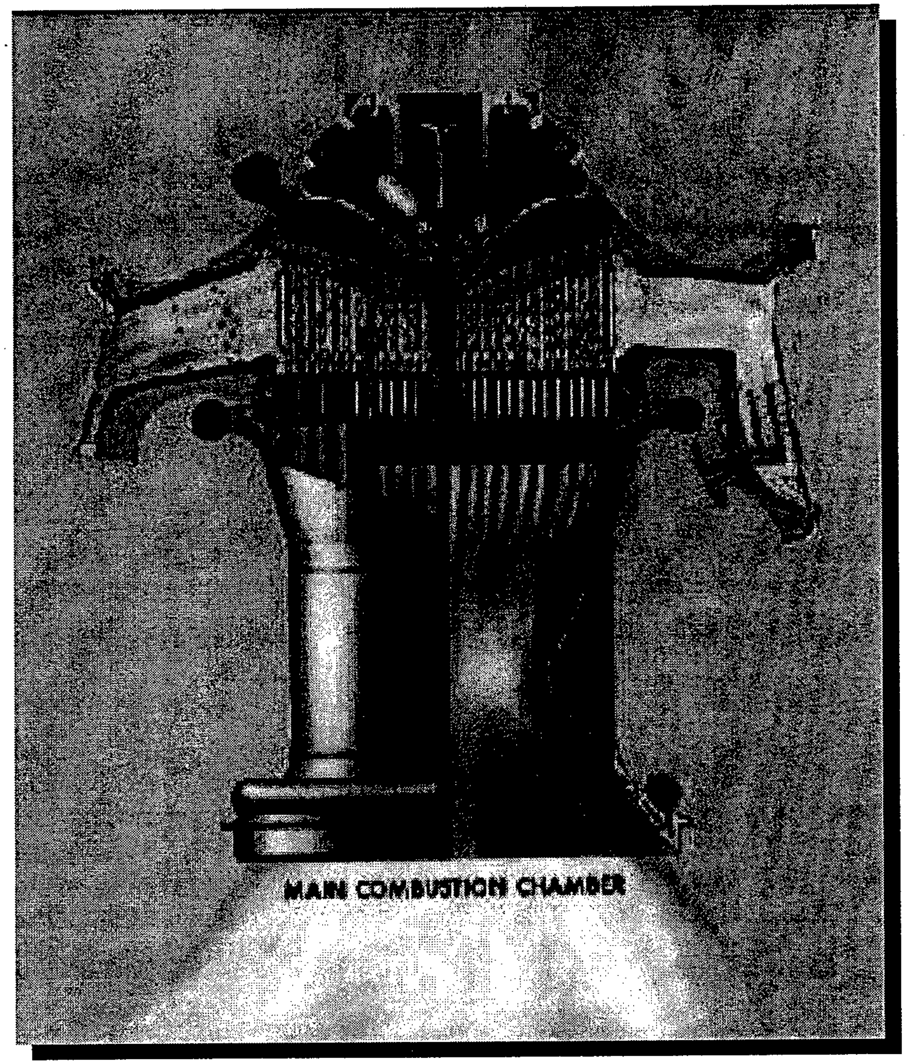
Engine Modifications



Advanced Expander Combustor



Powerhead–Showing Chamber Detail

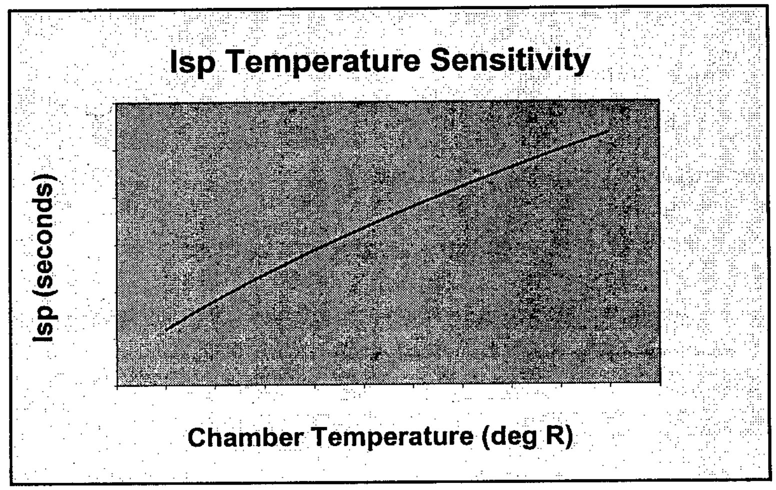


Material Limits Impacting Performance
Combustion Chamber

Main combustion chamber wall temperature limit about 1100° F with Ox/H2 propellants

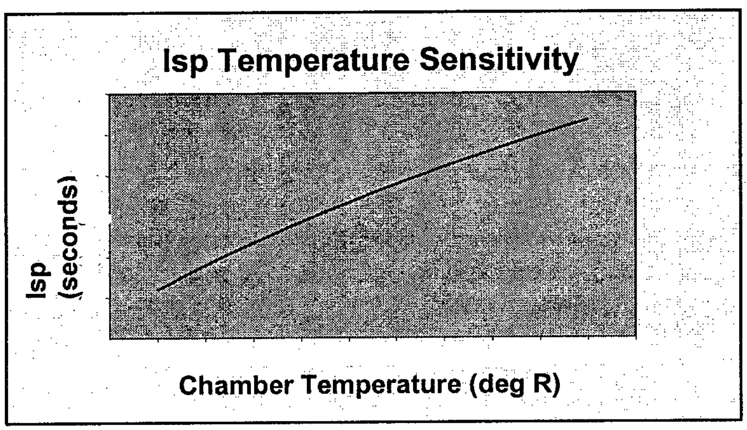
- Performance penalties :
  - Film cooling requirement for low grain growth temperature - Isp loss from unreacted propellant
  - Lowered heat load transferred to coolant due to high resistance in material (thermal conductivity, low yield strength) and design - Turbopump reliability loss from increased pressure requirement

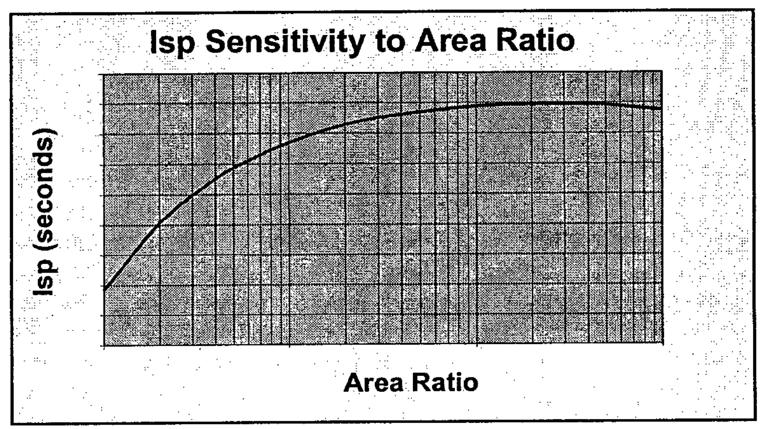
	Stainless Steel	Narloy-Z
Thermal Conductivity (W/M-K)	22	350
Yield Strength (inches)	72,413	13,000



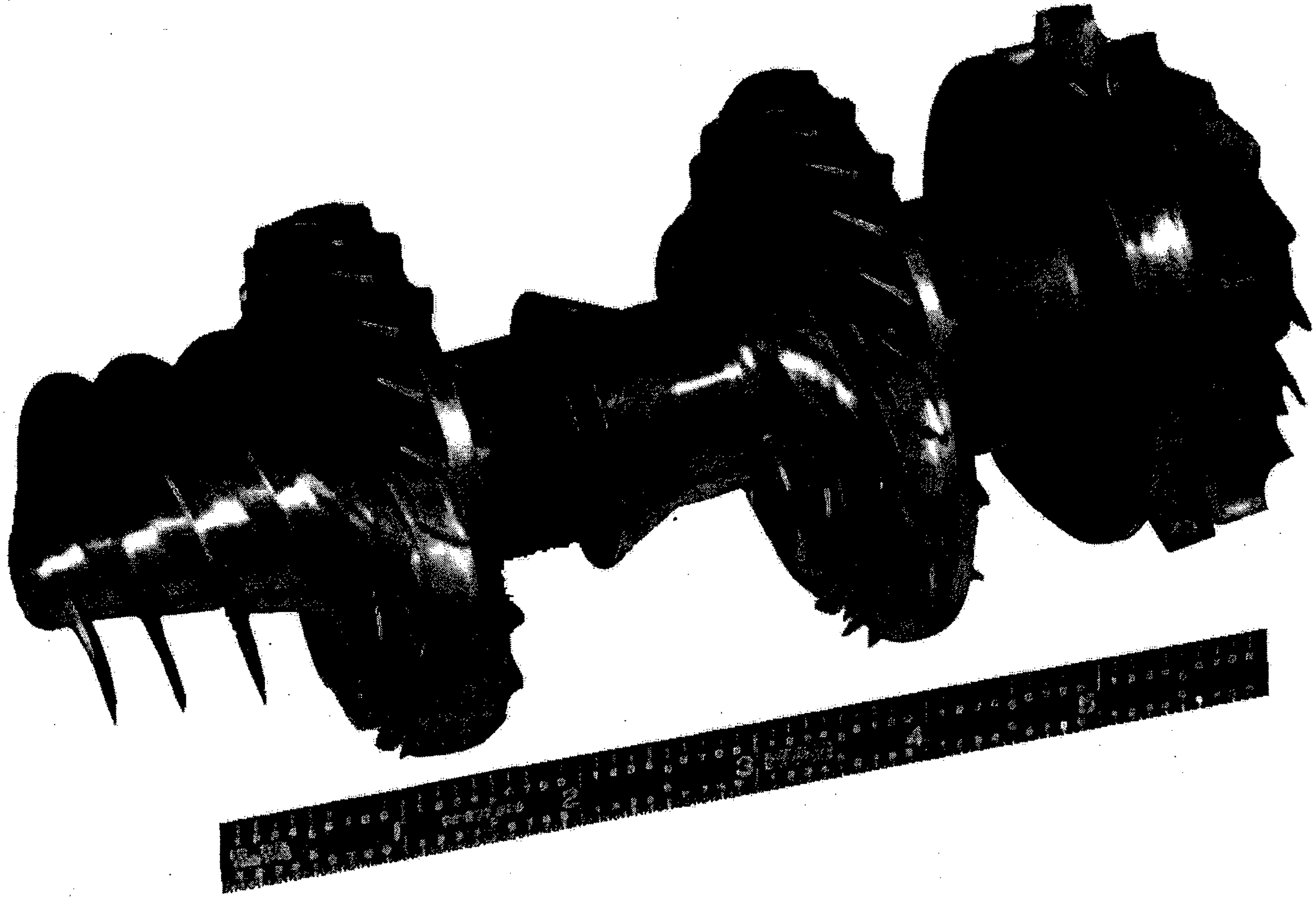
Material Limits Impacting Performance Nozzle

- Weight gain
  - Requires reduction in nozzle area ratio
  - Lead to decreased Isp and thrust
- Temperature limitation
  - Reduces power available to the turbine
  - Leads to decreased thrust and/or reliability (depending on how the pressure loss is divided)
- Current material: 347 Stainless Steel
  - Specific Strength (Yield Strength / Density) = 93,103 in

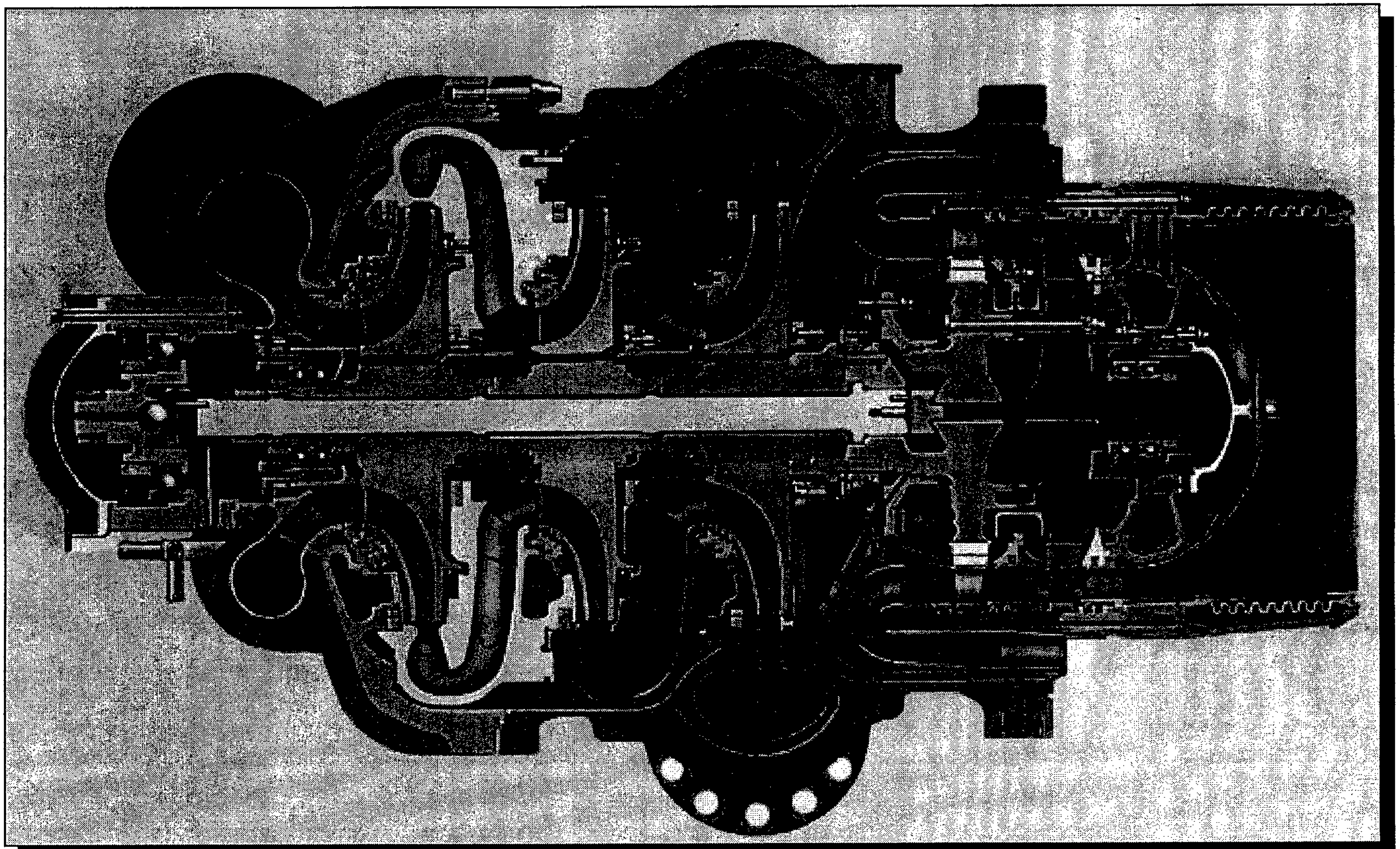




Advanced Liquid Hydrogen Turbopump



Turbopump

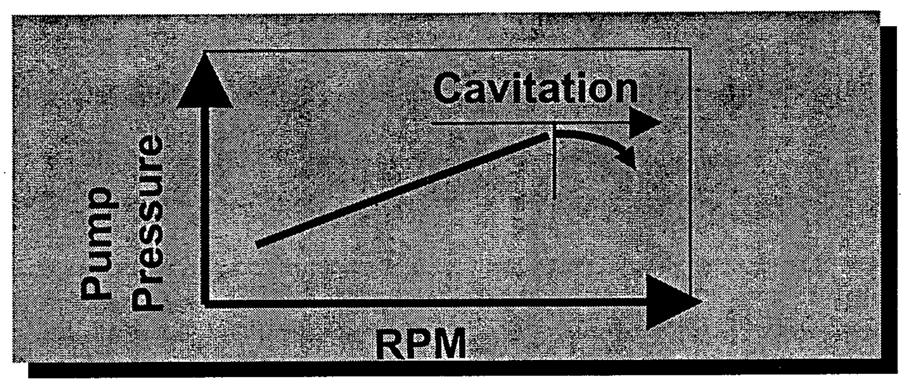


Material Limits Impacting Performance
Turbopump

Turbopump shaft speed limits:

- Turbine AN^2 - tensile strength and creep at high temp
- Bearing DN - modulus of elasticity & rigidity
- Pump impeller tip speeds - same as turbine
- why bold? → **Pump labyrinth seal clearance** - heat distortion temp

Lower shaft speed = Less available pressure to produce thrust



Existing Labyrinth Seal material: Kel - F
Heat Distortion Temp: 259 deg F

Material and Engineering Limits Exploited

to what do the asterisks refer?

Table II Engineering (Material) Limits Varied for Sensitivity

	Representative Material Property	Normal Limit	Increased Limit
Turbopump			
Pump Eff.	**Heat Distortion Temp & Internal Friction of the Seal Material**	**10% Drop in Efficiency 259 °F***	**0% Drop in Efficiency Property Requires Research**
Impeller Tip Speed	Modulus-Elasticity/Rigidity	1900 ft/sec	Not Challenged, No Change Required
Turbine Eff.	Blade Melting Temp	Turbine Temperature Limit to Efficiency = 6% Loss	Turb Temp 1.5x Limit to Eff = 5% Loss Not Needed
Bearing DN	Design	20×10^6 mm x RPM	Not Challenged, No Change Required
Turbine AN2	Modulus-Elasticity/Rigidity	8 in x RPM^2	Not Challenged, No Change Required
Heat Load	**Thermal Properties of the Combustion Chamber & Nozzle**	**25,000 BTU/sec k=202.3 BTU/ft-hr-°F Melt. Temp: 2500 - 2600 °F**	**39,000 BTU/sec New Property**
Nozzle Area Ratio	**Specific Strength of Nozzle**	**175:1** Spec. Str. 74K in***	**300:1**

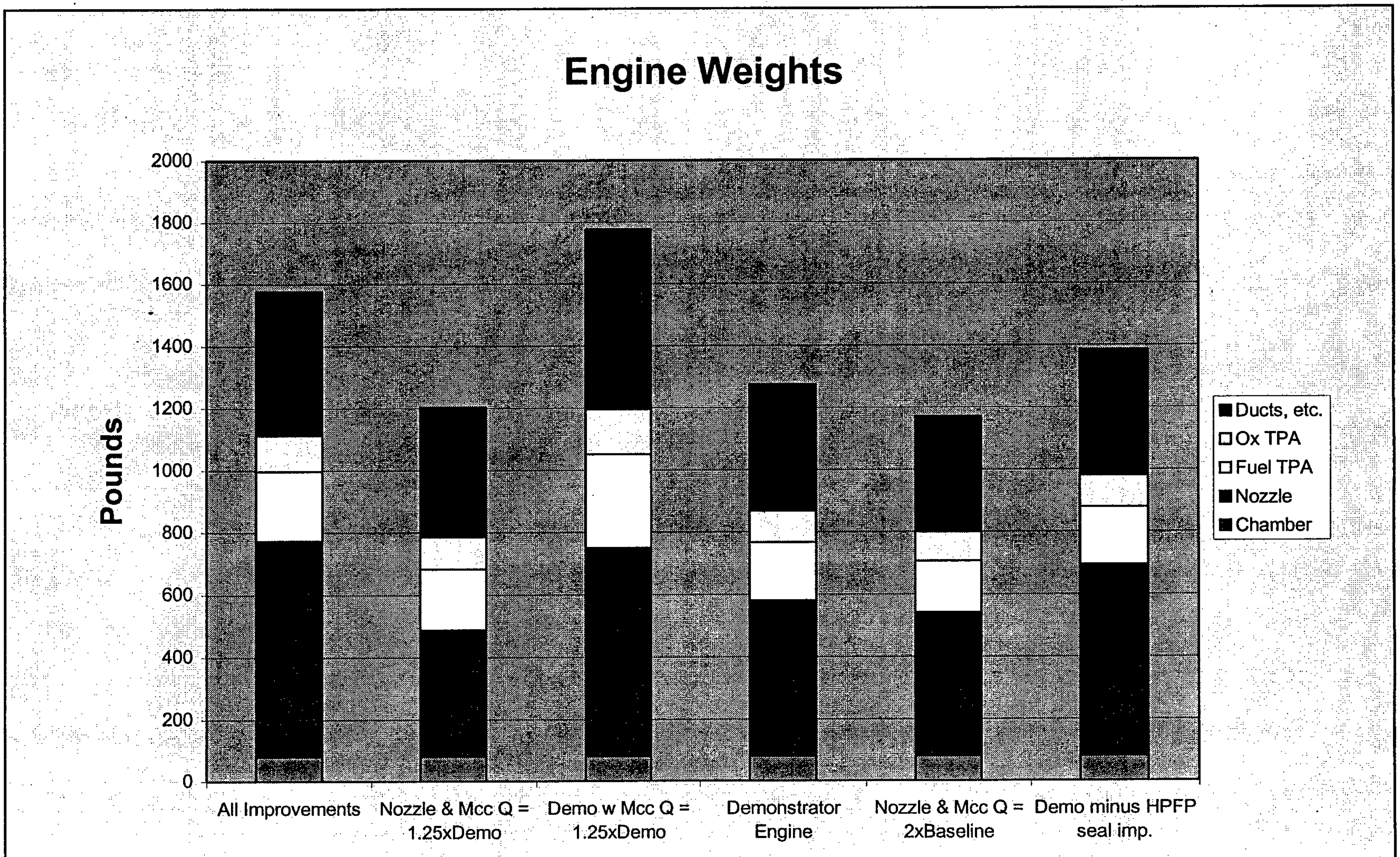
Weight Estimation Methodology (All Weights Assumed Stainless Steel)

By IMWG Direction:

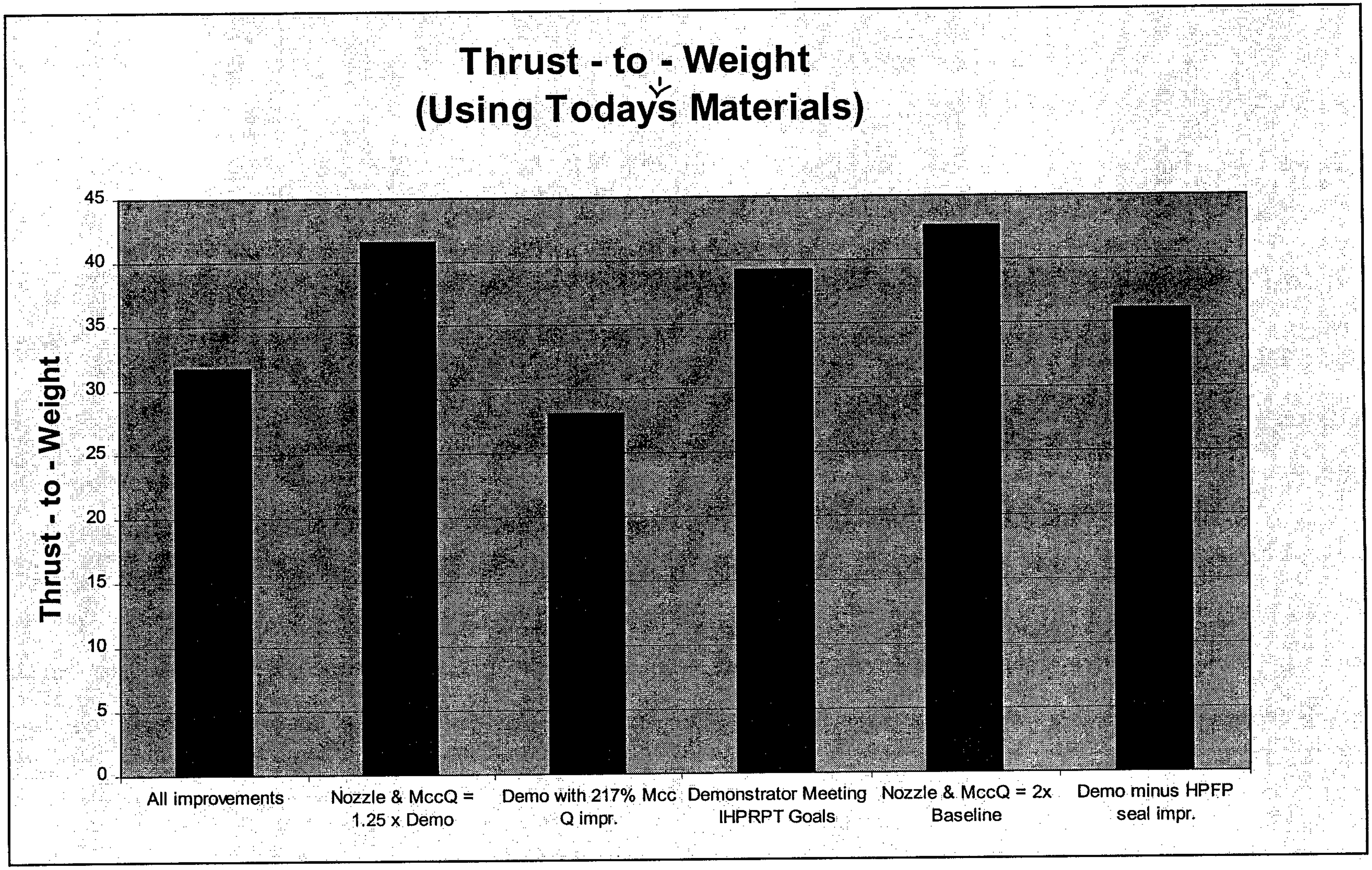
Material Property Advances are Assumed; Particular Advanced Materials are to be Selected Later

- Turbopumps & Combustion Chamber:
  - Hoop Stress Calculation - High Pressure Devices
- Nozzle
  - Method of Characteristics - For Shape and Area
    - High Pressure Across Nozzle Wall for thickness
- Remaining Hardware
  - Scaled to Turbopump and Nozzle

Engine Weight Comparison



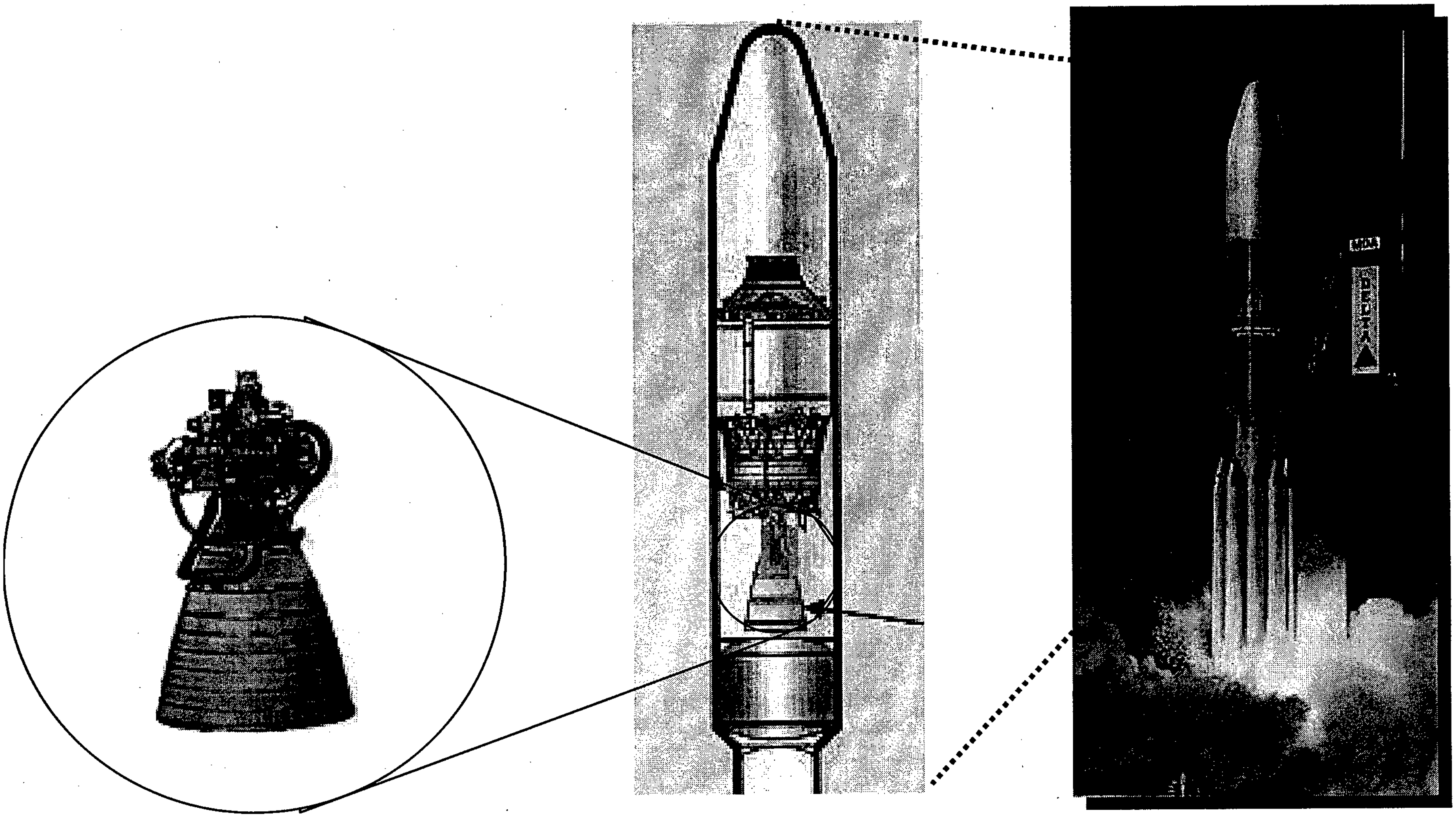
Thrust-to-Weight Comparison



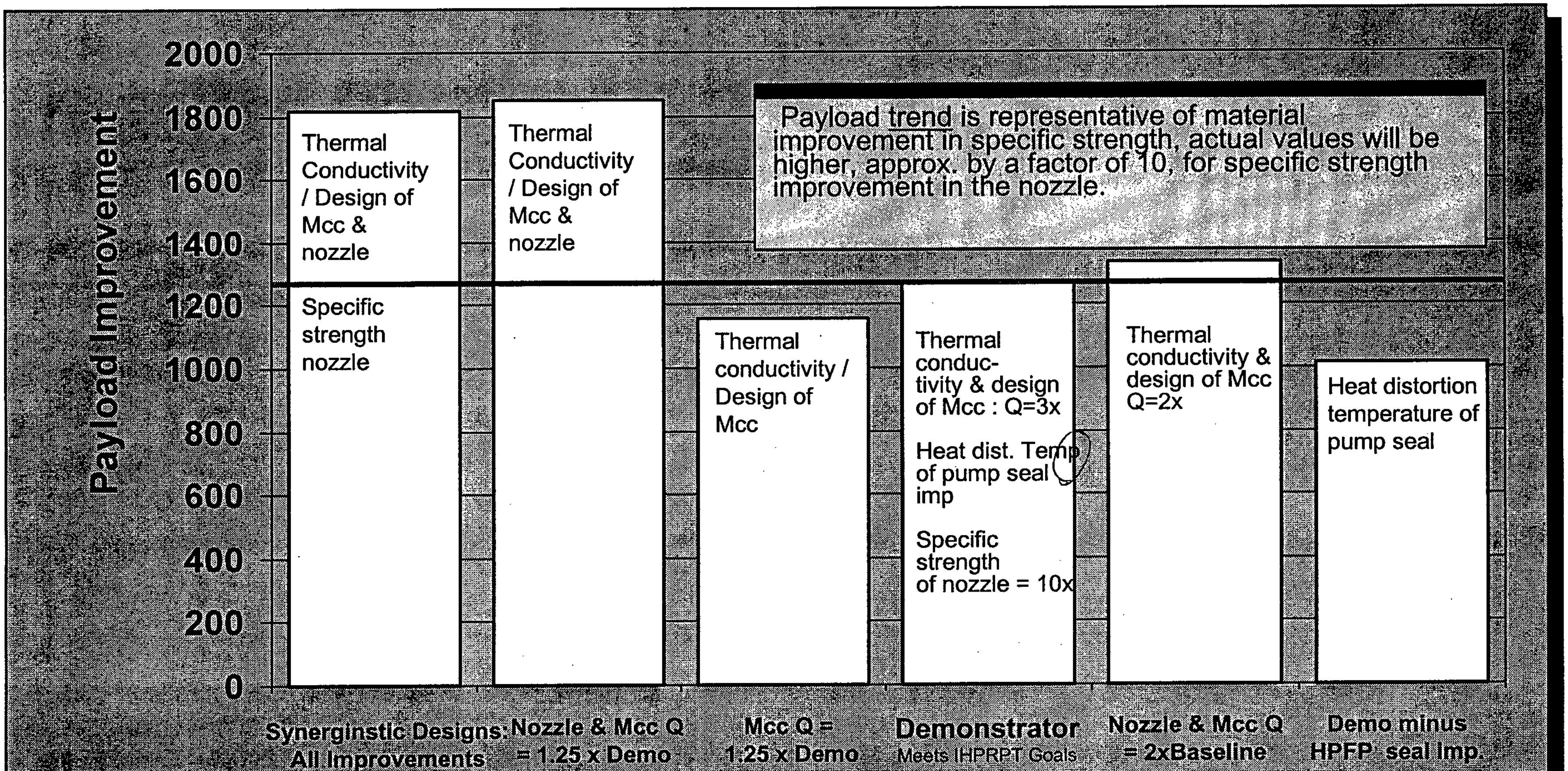
Weight Effects on Vehicle Performance

- Payload gains from the higher ISP Engines are offset by weight penalties.
- Single heaviest engine component: Nozzle - about 40% of Engine total weight
- 10x Specific Strength improvement of nozzle will result in more reasonable weight reduction in remaining components

Delta III Configuration



Resultant Delta III System Payoff to GTO



Note The highest ISP Engine is not the highest payload improvement

Conclusion

- Major Improvers:
  - Thermal Properties of combustion chamber and nozzle
  - Strength - to - Weight of nozzle
- Important Improver:
  - Heat Distortion Temp of Labyrinth Seal

Recommendations

- Develop material properties improving:
  - Thermal properties - grain growth temp for higher temp operation & thermal conductivity for high hoop stress in both the chamber and nozzle
  - Specific strength of material used in the nozzle
  - Heat distortion temperature in the fuel pump labyrinth seal
- Next Steps:
  - Start quantification of candidate material critical properties for this demonstrator.
    - Applied, Existing or New
  - Investigate other Engines and Applications.

Backup Charts

Some of these backups will not show up well if you have to use them — too busy.

Engine Weights

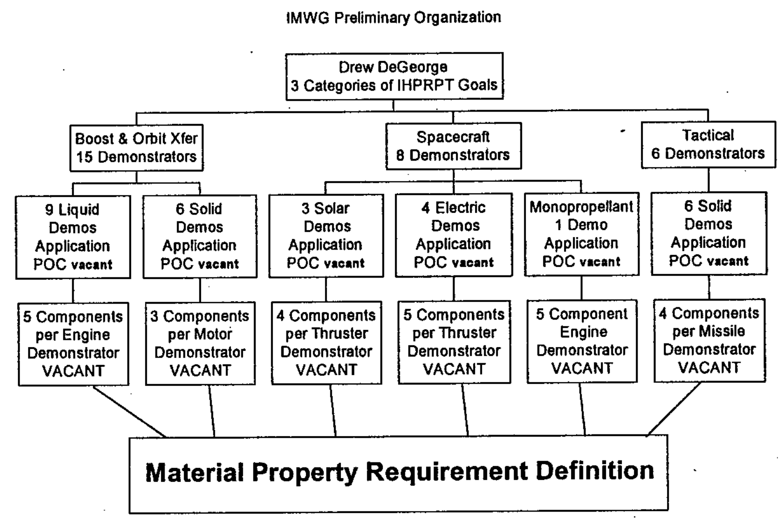
	Area Ratio	Nozzle Weight	Chamber Weight	Fuel Turbopump Weight	Lox Turbopump Weight	Ducts, Lines, & Other	Total Engine Weight
All improvements	300	692	80	224	116	464	1576
Nozzle & MccQ = 1.25 x Demo	200	407	80	194	104	418	1203
Demo with 217% Mcc Q impr.	177	669	80	301	145	582	1777
Demonstrator Meeting IHPRPT Goals	**171**	**499**	**80**	**186**	**102**	**407**	**1275**
Nozzle & MccQ = 2x RL10	170	461	80	164	93	373	1171
Demo minus HPFP seal impr.	171	612	81	185	101	406	1385

Gaps to Fill **BEFORE** Tying Material Research to IHPRPT

Step I: **Completed**
Goal definition

Step II: **Way Behind**
Rocket Design meeting goals

Step III: **Way Way Behind**
Material Property Identification



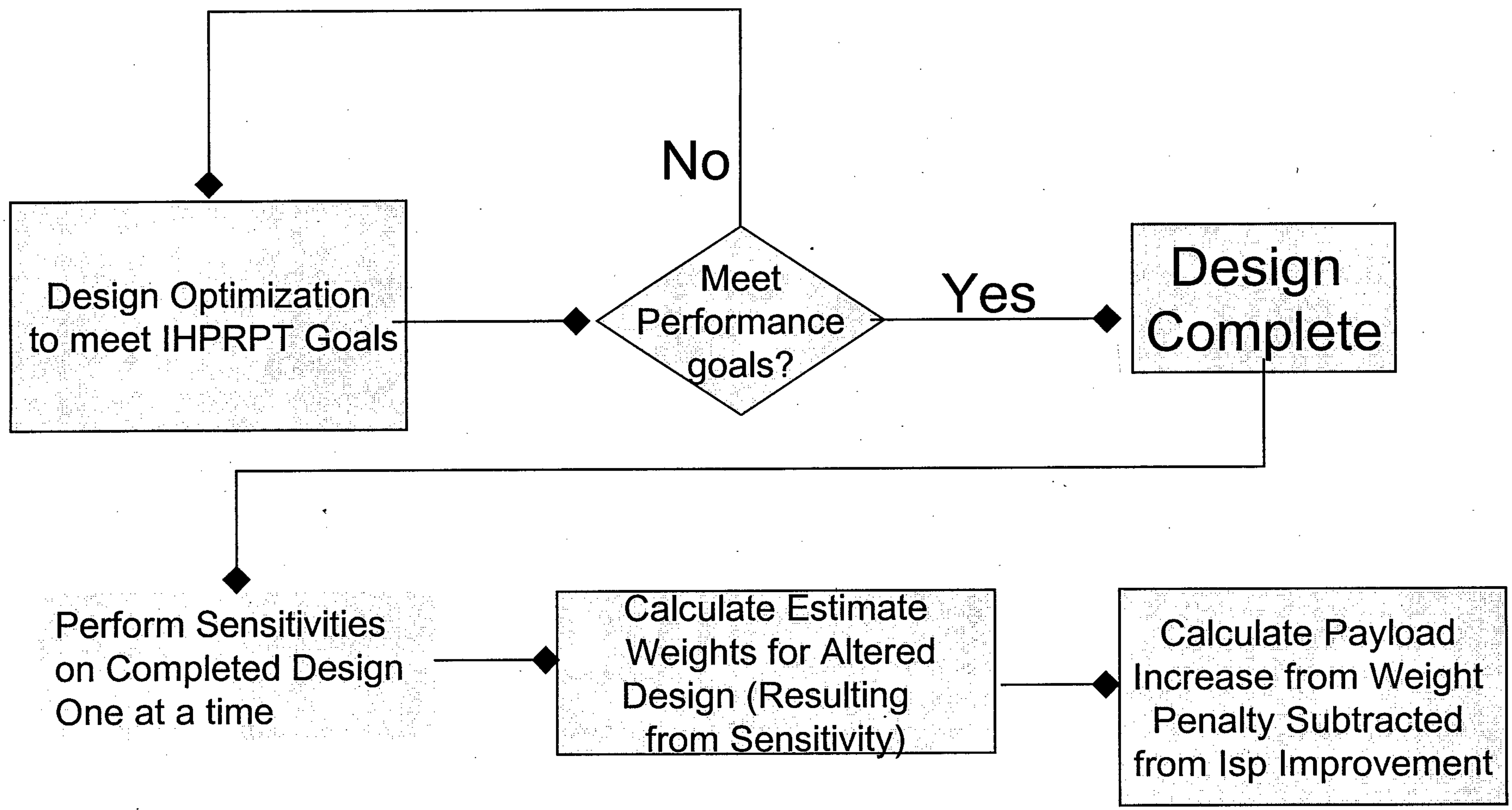
Step IV: **Completed**
Material Development Programs underway (without IHPRPT target values for their properties)

Existing Material Programs
without property values to target their results

Phase III IHPRPT Performance Goals for Cryogenic Upperstage

- Isp improvement of 3% over baseline engine
- Thrust-to-weight improvement of 100% over baseline engine

Progression from Demonstrator Optimization to Sensitivity

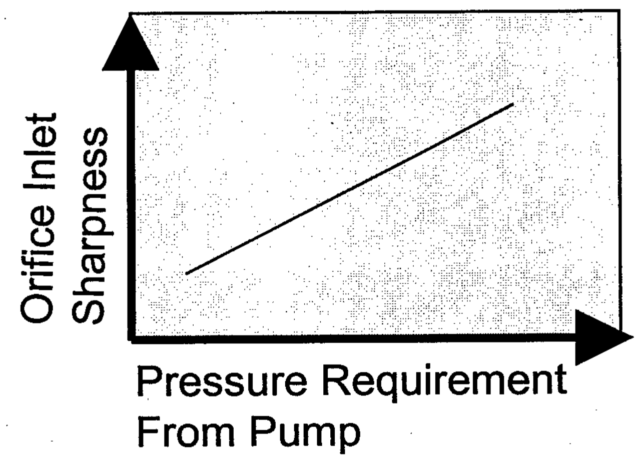


Material and Engineering Limits Exploited

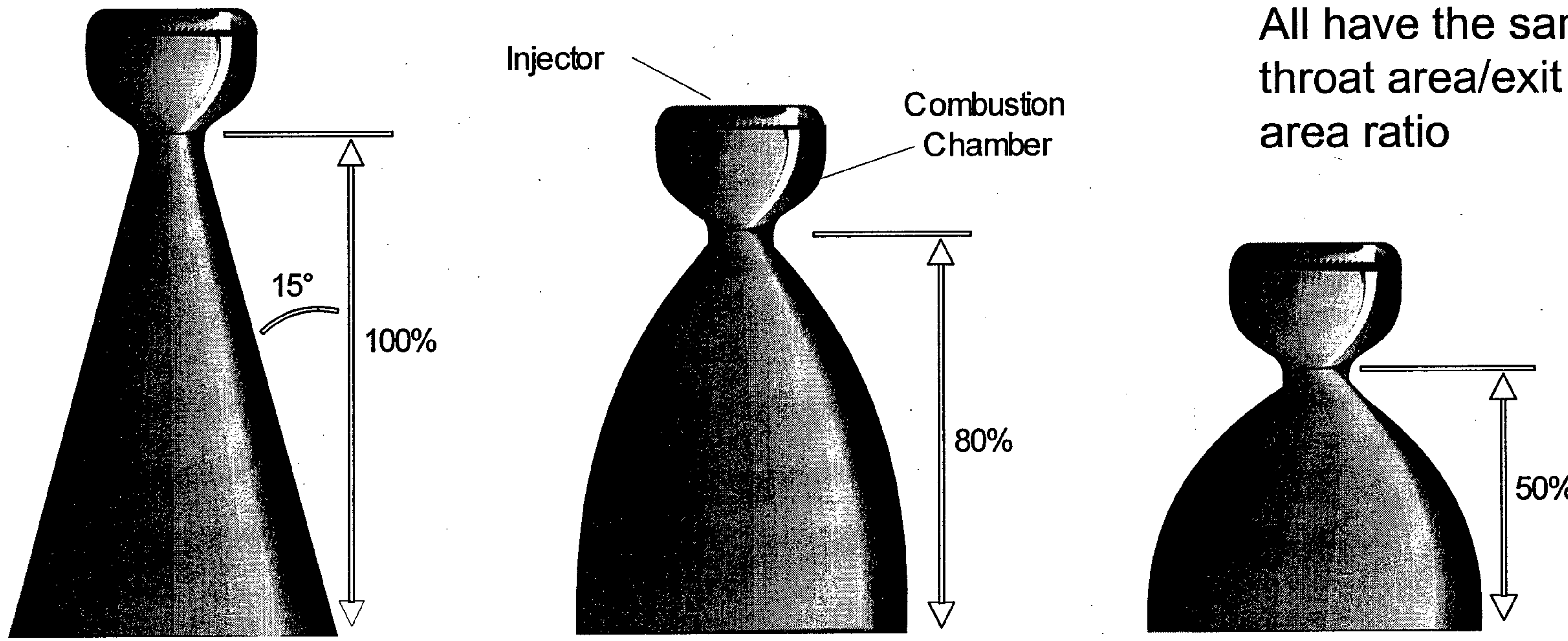
	Representative Material Property	Normal Limit	Increased Limit
Turbopump			
Pump Eff.	Heat Distortion Temp & internal friction	10% drop in Eff. 259 deg F	0% drop in Eff. Property Requires Research
Impeller Tip Speed	Modulus-Elasticity/Rigidity	1900 ft/sec	Not Challenged, no change required
Cavitation	Fluid Vapor Pressure	Function of RPM, GPM, g, & NPSH	Not Changed
Turbine Eff.	Blade Melting Temp	6% nominal eff loss	10% incr in eff.
Bearing DN	Design	20x10^6	Not Challenged, no change required
Turbine AN2	Modulus-Elasticity/Rigidity	8" RPM^2	Not Challenged, no change required

Material Limits Impacting Performance
Injector

- Material finish and orifice inlet design promote high pressure drop = lowered reliability due to increased pressure demand from pump
- Variability in material machining tolerances induce mixture ratio nonuniformity= lowered reliability and lowered thrust, this is a primary factor of combustion efficiency and stability.



Nozzle Definition



Cone

15° Half Angle

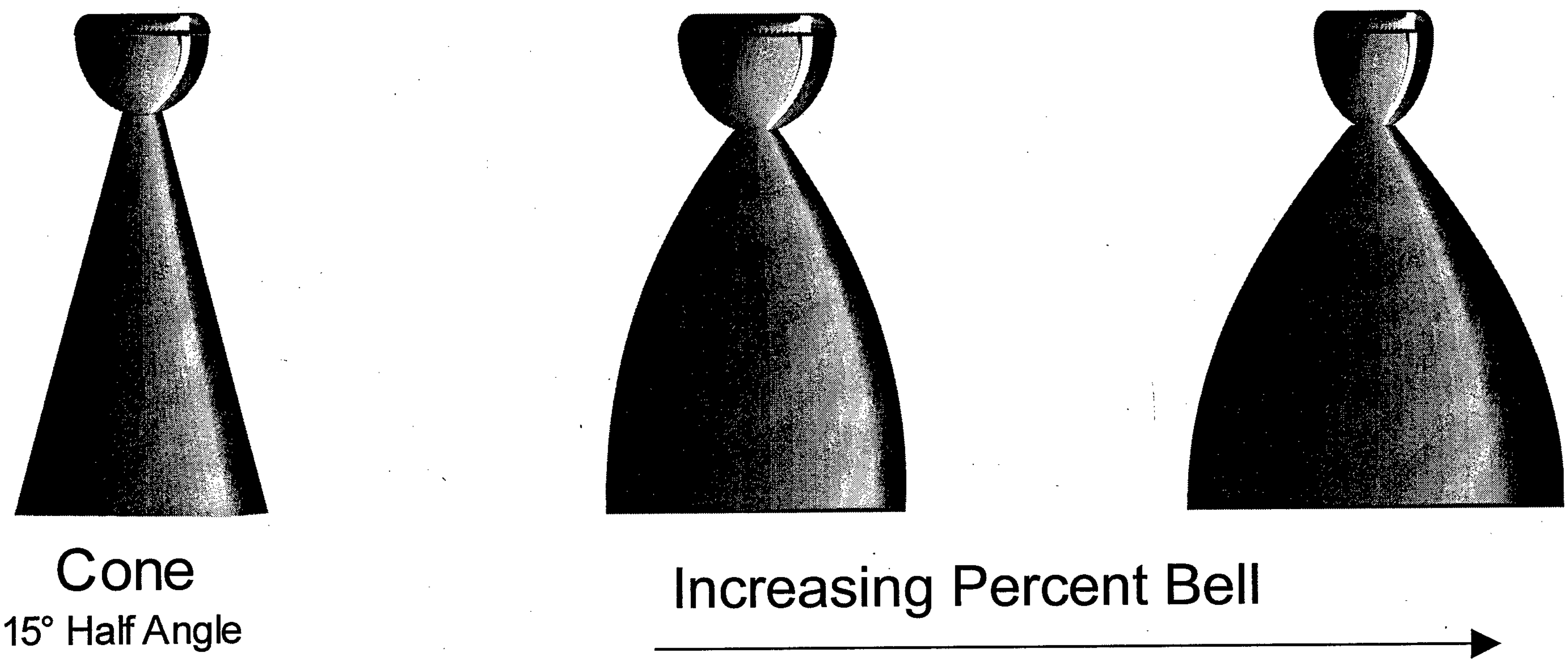
80% Bell

50% Bell

All have the same throat area/exit area ratio

Percentage is based on nozzle length compared to the length for a 15° nozzle to get to the same exit area

Variation of Length Constrained Nozzles

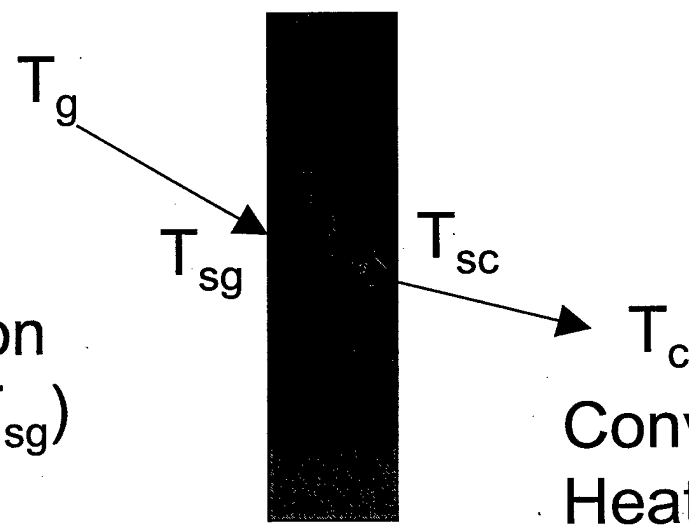


Nozzle shapes resulting from fixed length and varying area ratios

Material Limits Impacting Performance
Combustion Chamber

- Heat Load to the coolant:

Conductive
Heat Load: Q_k
$kA(T_{sg} - T_{sc})$



Combustion Gas
Heat Load: Q_{c+r}

Radiation and Convection
$h_r A(T_g - T_{sg}) + h_c A(T_g - T_{sg})$

Convective
Heat Load: Q_c
$h_c A(T_{sc} - T_c)$