N93-22102

HYBRID ROCKET PROPULSION

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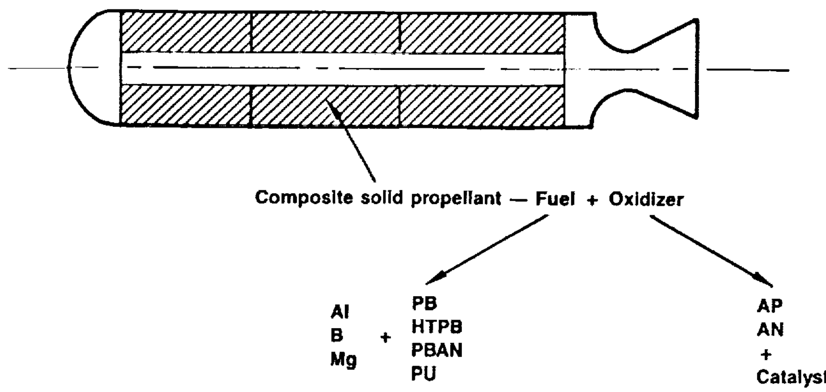
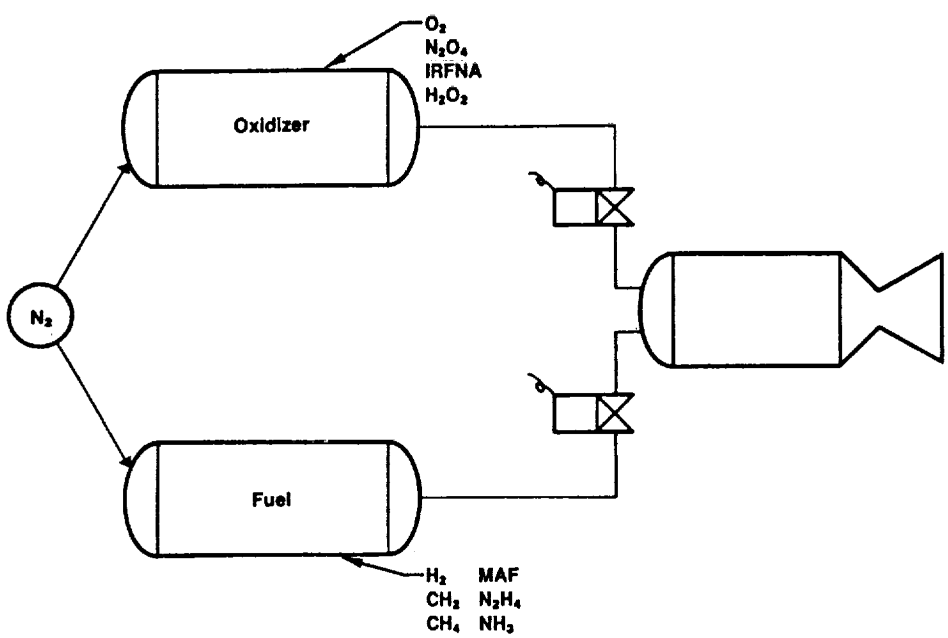
UNITED TECHNOLOGIES CHEMICAL SYSTEMS

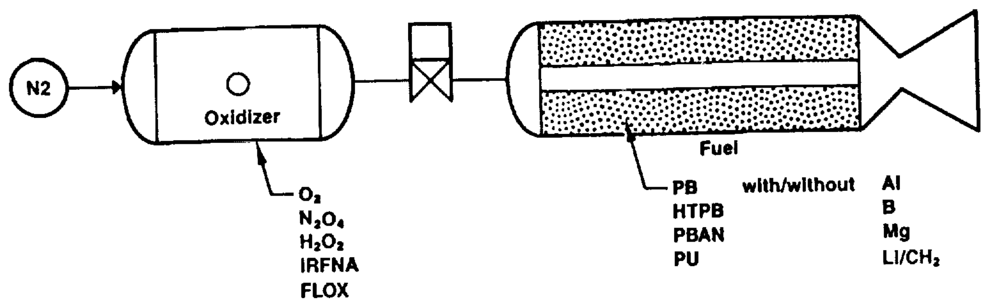
SOLIDS



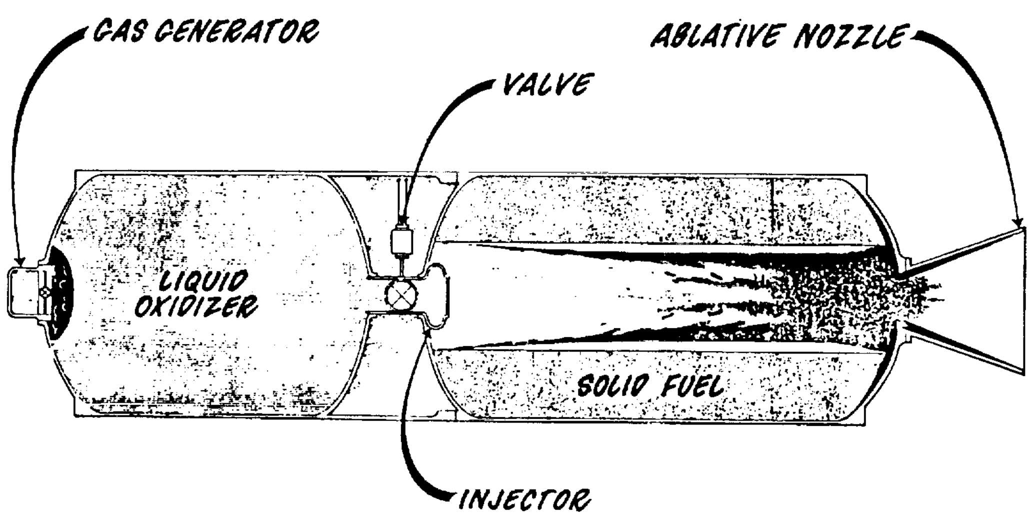
LIQUIDS



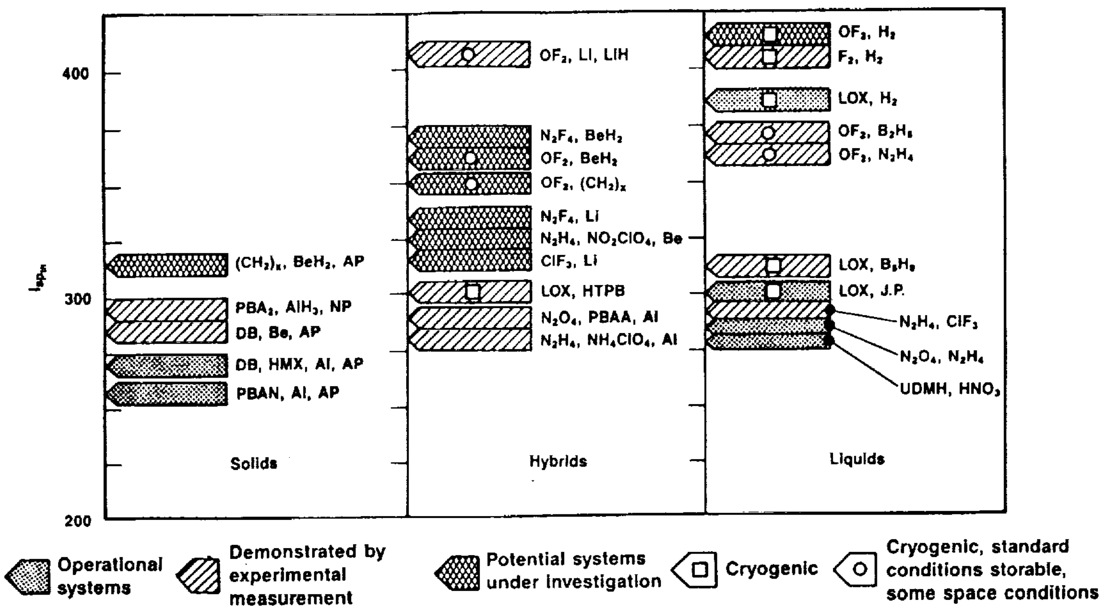
HYBRIDS



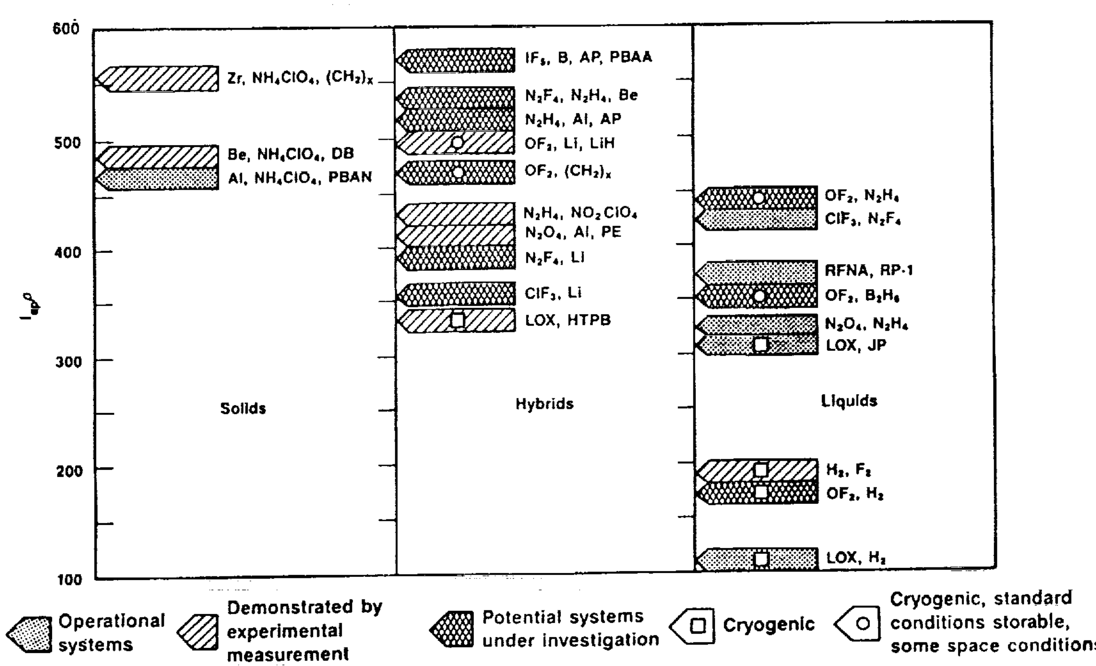
HYBRID ENGINE OPERATION



COMPARISON OF THE THEORETICAL SPECIFIC IMPULSES
ATTAINABLE WITH SOLID, LIQUID AND HYBRID PROPELLANT SYSTEMS



COMPARISON OF THE DENSITY-SPECIFIC IMPULSES
ATTAINABLE WITH SOLID, LIQUID AND HYBRID PROPELLANT SYSTEMS



HISTORY

o 1930's	California Rocket Society - static tests
o 1940's - 50's	Pacific Rocket Society - LOX/Douglas fir fuel flight tested to 30,000 ft.
	GE - evaluated H_2O_2/PE engine
o 1950's - 60's	APL - reverse hybrid NH_4NO_3/JP
o 1960's - 70's	CSD - fundamental regression/combustion studies - supersonic target drones, flight tests (Sandpiper/HAST/Firebolt) - High energy FLOX/Li/LiH/HTPB tests 380-sec I_{sp} @ 40/1 expansion ratio - 50K-lb thrust N_2O_4/Al/PBAN
	ONERA/SNECMA/SEP - HNO_3/amine fuel, sounding rockets, flight tests
o 1980's	AMROC - 50K-lb thrust LOX/PB
o 1990's	AMROC - 75K-lb thrust LOX/PB

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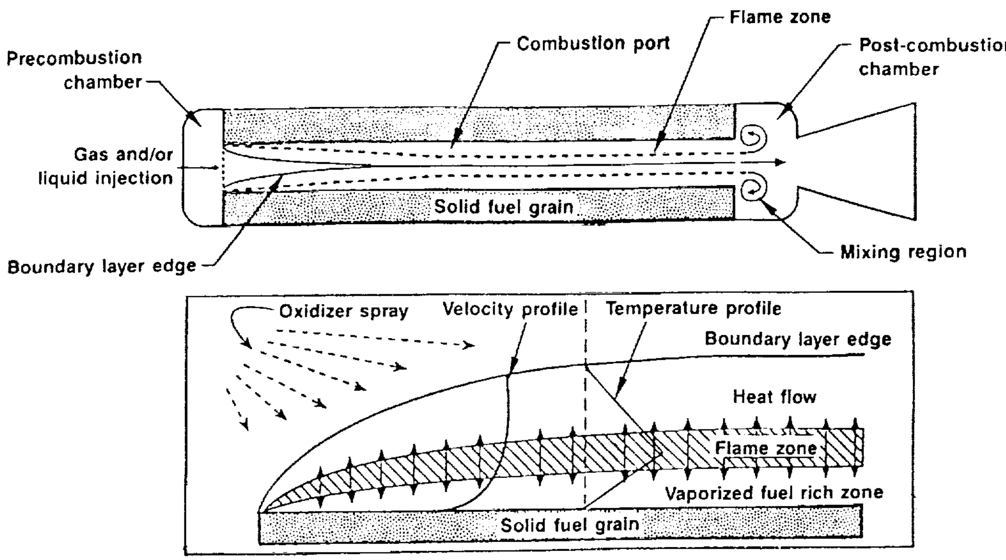
GENERAL PROPULSION SYSTEM FEATURES COMPARISON

Feature	Solid	Liquid LOX-JP	Classical Hybrid
DOT classification	Class B	Inert when-MT	Inert
Explosive classification	1.3	60% TNT equiv. when full	NA
Sensitivity to grain cracks/voids	Yes	NA	No
Launch abort capability (propulsion termination)	No	Yes	Yes
Handling costs	Highest	Medium	Lowest
I_{sp}	Low	High	High
ρI_{sp}	High	Low	Medium
Exhaust HCl	20%	0	0
Exhaust particulate	High	Low	Either

HYBRID COMBUSTION BOUNDARY LAYER



BASIC HYBRID BURNING RATE LAWS

Elementary pipe flow

$\dot{Q}_w = \dot{m}_f h_v = (h/c_p)\,\Delta h_c$

$\therefore \dot{r} = \dfrac{1}{\rho_f}\,(h/c_p)\,(\Delta h_c/h_v)$

with $h \propto \dfrac{c_p\,G^{0.8}}{D^{0.2}}$ (turbulent pipe flow)

Refined relation

$$\dot{r} = \left(\frac{0.036\mu^{0.2}}{\rho_f\ x^{\,0.2}}\right)\left(\frac{C_H}{C_{H_o}}\right)\left(\frac{U_e}{U_b}\right)\left(\frac{\Delta h_c}{h_v}\right)G^{0.8} + \frac{Q_R}{\rho_f h_v}$$

Good working equation

$\dot{r} = a\,G_o^{\,n}$

Q_W = heat flux to wall (fuel)
m_F = fuel flow rate
h_v = effective heat of vaporization
Δh_c = heat of combustion of fuel
G = mass flux in port
U = gas velocity

WHY AREN'T HYBRIDS OPERATIONAL?

- Operational success of liquid F-1 engines and SRM boosters for the shuttle and Titan III caused interest in hybrids to wane.
- Early emphasis was only for high density impulse systems. Cost, safety, environmental and reliability issues were of second order.
- All the 1960s and 70s work in hybrids was done by primarily liquid and solid propulsion companies. In any selection process for upcoming systems, hybrids were always perceived second best.
- Customer liquid and solid propulsion communities (incumbents) are not interested in sharing funding.
- It is difficult to generate funding for an order of magnitude scale increase to 750K and larger thrust engines.
- "Political factors interfere with technical factors."

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HYBRID SYSTEMS

BOOSTER APPLICATIONS

ATLAS BOOSTER DEVELOPMENT AND QUALIFICATION

	Year 1	2	3	4	5	6
1. Fuel formulation studies	X——X					
2. Sub-scale port tests	X——	—X				
3. Injector development	X——	——	——X			
4. Analytical modelling	X——	——	——	——X		
5. Trade studies	X——	——	——X			
6. Full-scale motor tests			X——	—X		
7. Nozzle development				X——X		
8. Throttling tests				X–X		
9. Process develop & verif.		X—	——	—X		
10. Full scale qualification testing				X—	——X	

HYBRID SYSTEM ADVANTAGES

BOOSTER APPLICATIONS

	Hybrids	Solids	Liquids
Explosive hazard	none	high	high
HCl in exhaust	none	high	none
Specific impulse	high	low	highest
Density impulse	high	highest	lowest
Throttleability	yes	no	yes
On pad costs	low	high	high
System cost	low/medium	medium	high
Abort capability	yes	no	yes
Understanding of basic analytical regression/ combustion model	yes	no	no

COMPARISON OF THROAT BETAS

	O/F	T_c °R	Beta --	I_{spvac} sec	c^* ft/sec	m.f Al_2O_3 @ throat
Solid propellant ASRM TP-H-1233	--	6411	0.096	287.	5178	0.096
LOX/Hydrogen	5.0	6110	0.626	433.	7961	--
LOX/100% HC	2.37	6698	0.269	323.	5830	--
LOX/35% aluminum/ 65% HC	1.36	7149	0.130	321.	5786	.084
LOX/45% Aluminum/ 55% HC	1.17	7377	0.083	319.	5716	.176

All values theoretical for P_c = 1000 psia, nozzle area ratio = 10.0

HYBRID SYSTEM DISADVANTAGES

NON-METALLIZED FLOW

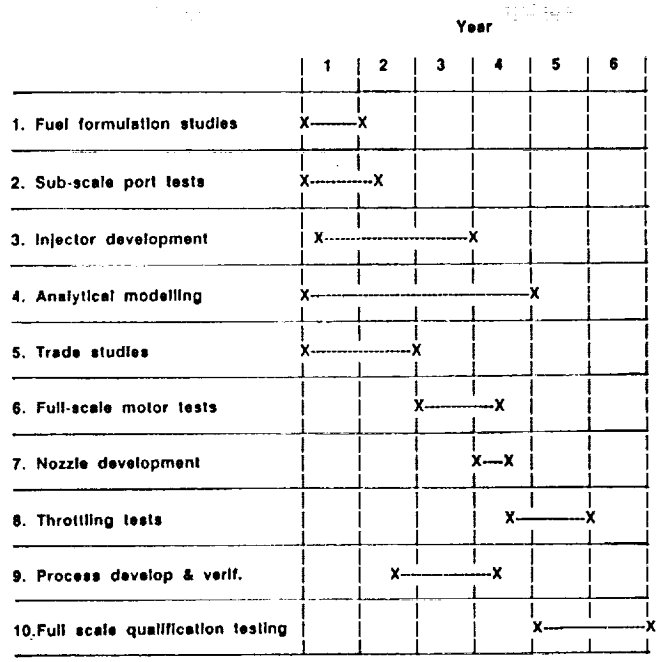
BOOSTER APPLICATIONS

	Hybrids	Solids	Liquids
Nozzle erosion	high	low	n.a.(regeneratively cooled)
Residual fuel/ox	6%/1%	<< 1%	< 1%
Accumulated data	low	high	high

HYBRID SYSTEMS

UPPER STAGE PROPULSION APPLICATIONS

UPPER STAGE HYBRID MOTOR DEVELOPMENT AND QUALIFICATION



HYBRID PROPULSION INDUSTRY ACTION GROUP

Aerojet
AMROC
Atlantic Research
Boeing Aerospace
General Dynamics
Hercules
Lockheed
Martin Marietta
Rocketdyne
Thiokol
United Technologies

HPIAG SUPPORTS HYBRID PROPULSION DEVELOPMENT AND DEMONSTRATION

HPIAG Program Planning Presentations

Presentations	Date
• NASA/MSFC (W. Littles)	12/89
• NASA HQ (Dr. Rosen, G. Reck)	1/11/90
• NASA/MSFC (J. Lee, J. McCarty)	7/24/90
• NASA HQ (A. Aldrich, G. Reck)	8/10/90
• National Space Council (I. Bekey)	8/29/90
• NASA HQ (J. R. Thompson)	8/29/90
• Space Systems & Technology Advisory Committee	9/13/90
• NASA HQ (J. R. Thompson)	9/20/90
• NASA/MSFC--Program Development*	10/25/90
• AF Space Division (Col. Colgrove)*	10/29/90
• Aerospace Safety Advisory Panel	10/31/90
• Stafford Group	11/16/90
• NASA/MSFC (J. Lee, J. McCarty)	12/5/90
• NASA/Code R (A. Aldrich)	12/18/90
• NASA HQ (J. R. Thompson)	12/19/90
• AF Space Division*	3/14/91
• NASA/MSFC--Research and Technology (J. Moses/J. Redus)*	6/20/91

*Full HPIAG not present

Augustine Report Excerpts on the Future of the U.S. Space Program

"Over the longer term, the nation must turn to new and revolutionary technologies..."

- More capable and significantly less costly means to launch manned and unmanned spacecraft
- Architecture studies now underway will define capable, low-cost launch vehicles
- Maintain vigorous advanced launch system technology program
    - Enhancement of current fleet
    - Basis for revolutionary launch systems

Hybrid Propulsion Positively Addresses OAST's Civil Space Transportation Requirements

*NASA Transportation Technology Planning Objectives**

TRANSPORTATION TECHNOLOGY

– OAST

GOAL

TECHNOLOGIES THAT SUBSTANTIALLY INCREASE OPERABILITY, IMPROVE RELIABILITY, PROVIDE NEW CAPABILITIES, WHILE REDUCING LIFE CYCLE COSTS

- IMPROVE CURRENT SPACE SHUTTLE
- PROVIDE TECHNOLOGY OPTIONS FOR NEW MANNED SYSTEMS THAT COMPLEMENT THE SHUTTLE AND ENABLE NEXT GENERATION VEHICLES WITH RAPID TURNAROUND AND LOW OPERATIONAL COSTS
- SUPPORT DEVELOPMENT OF ROBUST, LOW-COST HEAVY LIFT LAUNCH VEHICLES
- DEVELOP AND TRANSFER LOW-COST TECHNOLOGY TO SUPPORT COMMERCIAL ELV's AND UPPER STAGES
- IDENTIFY AND DEVELOP HIGH LEVERAGE TECHNOLOGIES FOR SPACE TRANSPORTATION, INCLUDING NUCLEAR PROPULSION, THAT WILL ENABLE NEW CLASSES OF SCIENCE AND EXPLORATION MISSIONS

* 13 May 1991, Integrated Technology Plan Planning Review/D.R. Stone

Hybrid Propulsion Attributes

- *Expanded mission abort modes*
- *Inert VAB operations*
- *Booster operation verified prior to launch commit*

- *Reduced infrastructure costs*
- *All hybrid vehicle options*

- *High thrust minimizes number of boosters required*
- *Reduced system complexity*
- *Modular application of boosters for vehicle growth options*
- *No pad detonation concern*

- *Applications identified for Atlas and Titan*

- *Highest leverage technology identified by MM/SDV study*

An Industry Consensus on the Hybrid Potential

- Radically improves safety in all phases of manufacture, vehicle stacking/assembly, and flight, and reduces environmental concerns
- Offers a reasonable design alternative to large clusters of LO_2/LH_2 engines for heavy-lift boost propulsion
- May enable major reduction in booster life cycle costs

The United States aerospace community cannot afford to overlook the hybrid propulsion option

Review of Initial NASA Hybrid Propulsion Technology Program

- Phased technology acquisition and demonstration
  - Initial approach to technology acquisition resulting from formulation of NASA-HPT program
  - Address technology deficiencies in series of graduated subscale motor tests (Phase II)
  - Demonstrate technology at 1.5 Mlbf thrust level (Phase III)

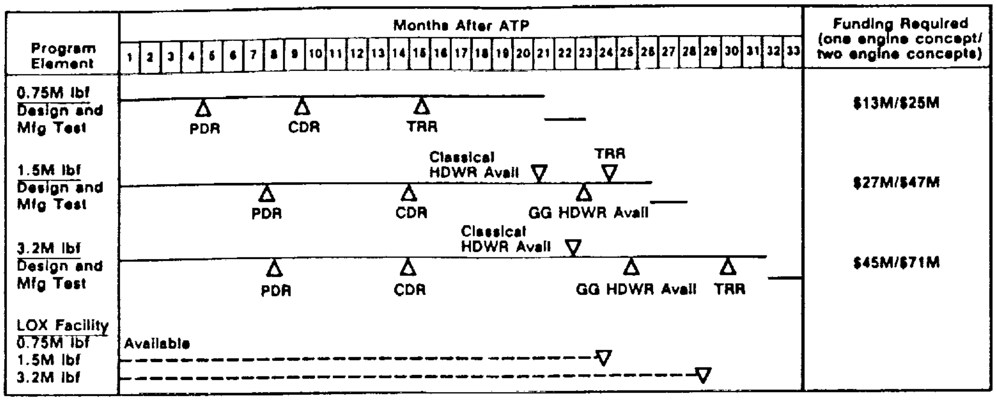
Calendar Year	88	89	90	91	92	93	94	95	96	97	$M
HPT Phase I Identify the Necessary Technology (four contracts)											2.1
HPT Phase II Acquire the Technology (two contracts)			Award Nov			Complete May					16
HPT Phase III Demonstrate the Technology in a Large Subscale System						CBD May				Complete Jan	25

Total Funding Commitment Required Is $41M

- Problems
  - Technology development does not demonstrate large-scale feasibility in time frame required for heavy-lift (SEI) applications
  - Does not utilize national aerospace assets (HPIAG)

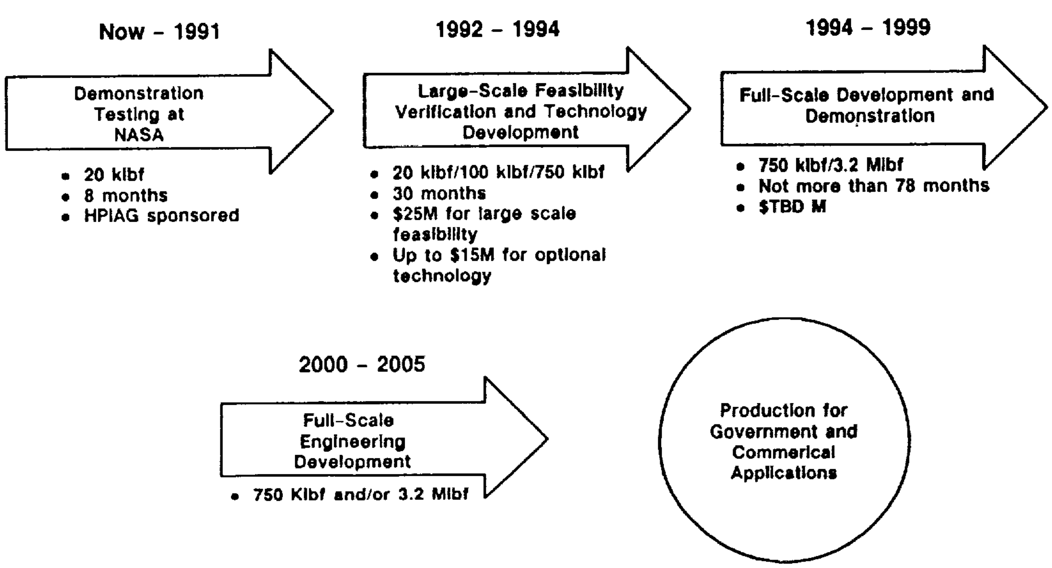
An Alternative Development Approach Provides A Fast Track Large-Scale Hybrid Demonstration

- Focused technology acquisition and demonstration
  - Approach suggested by J. R. Thompson based on successes of F-1 engine and large solid rocket motor development
  - Define specific technical issues for large booster development via early testing of Shuttle SRM-scale hybrid



- Problems
  - Effort includes a large-scale feasibility demonstration only—subsequent mix of subscale and full-scale demonstrations to address point design problems requires definition

Final HPT Development Approach Recommended to J. R. Thompson in December 1991



Recommended HPT Program Was Included In Budget Request From MSFC and LeRC for GFY 93 Start—Subsequently Pushed to GFY 95

Thrust: TRANSPORTATION-*AUGMENTATION NEW START* **Date:** 2/21/91

Key Technology Objective: 3.0 Provide Technologies to Support the Development of a Robust, Cost Effective Heavy-Lift Capability

Specific Objective: 3.7 Develop Technologies for Achieving Low Cost Booster Options and Demonstrate at an Appropriate Scale

Target Milestone:

TASK TITLE: TRANSPORTATION-HYBRID

Centers	WBS	Year	Milestone
MSFC	590-21-XX	1993	Authority to release NASA Research Announcement for Hybrid Booster Technology Program
		1993	Award contracts to begin development and testing of both Gas Generator and "Classical" Hybrid test motors
		1994	Complete 100 klbf testing
		1994	Initiate development of 750 klbf test motors for both "Classical" and Gas Generator concepts
		1996	Test both Hybrid Booster concepts at 750 klbf testing
		1996	Complete analysis of performance data and validation of analytical models
		1996	Complete documentation
LeRC	590-21-XX	1993	Begin development of analytical models and materials data base
		1995	Validate models at 100 klbf level
		1996	Validate models at 750 klbf level and extrapolation of Hybrid unique scaling data

Near-Term HPIAG Initiative Provides Program Bridge to GFY 95 HPT New Start

Program concept: Combine industry discretionary resources with NASA R&T funds to begin near-term HPT development

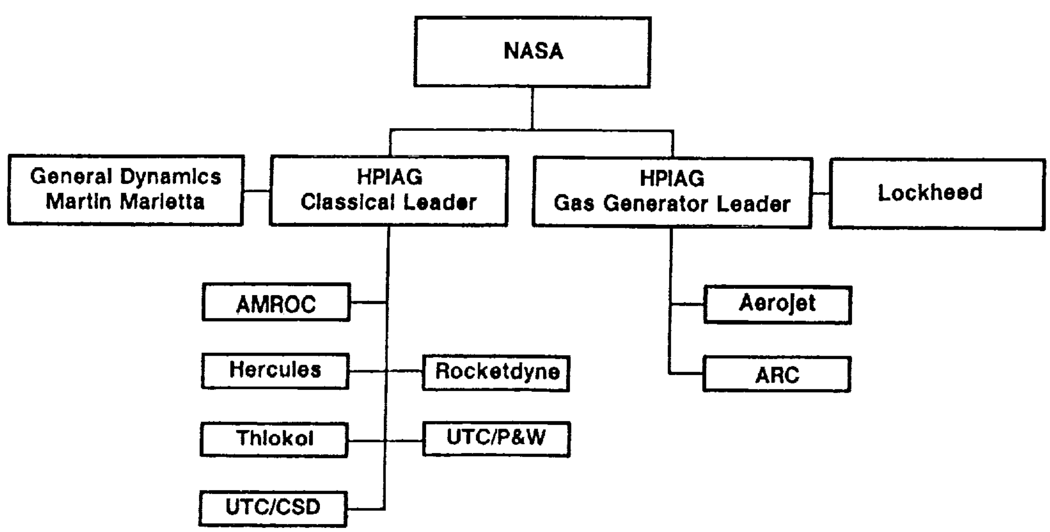
- Initiate basic technology studies at JPL
- Explore technical feasibility of hybrid propulsion for space launch applications via subscale and small-scale hybrid motor tests:
  - Both classical and aft injection cycles
  - 500-lbf, 15-klbf, 150-klbf motors (typical thrust levels)
- Begin limited hybrid propulsion launch vehicle infrastructure studies:
  - Operability issues
  - Reliability evaluation
  - Cost
- Develop program bridge to $40M CSTI effort

Multiple Motor Scales Provide Initial Feasibility Evaluation and Hardware Basis for NRA Follow-on Work

Motor Thrust Level	Classical Objectives	Aft Injection Objectives
500 lbf	• Fuel regression rate characteristics	• GG propellant ballistic characteristics
	• Effects of defects	• Effects of defects
	• Throttle response characteristics	• Initial concept throttling characteristics
15 klbf	• Fuel regression scale-up characteristics	• GG propellant scale-up characteristics
	• Multiple-port grain retention and fuel utilization	• LO_2 injector feasibility verification
	• Combustion stability and efficiency	• Combustion stability and efficiency
150 klbf	Initial HPT demonstrations at thrust level of significance for potential launch vehicle application	

Recommended NASA/HPIAG Organization to Accomplish Goal

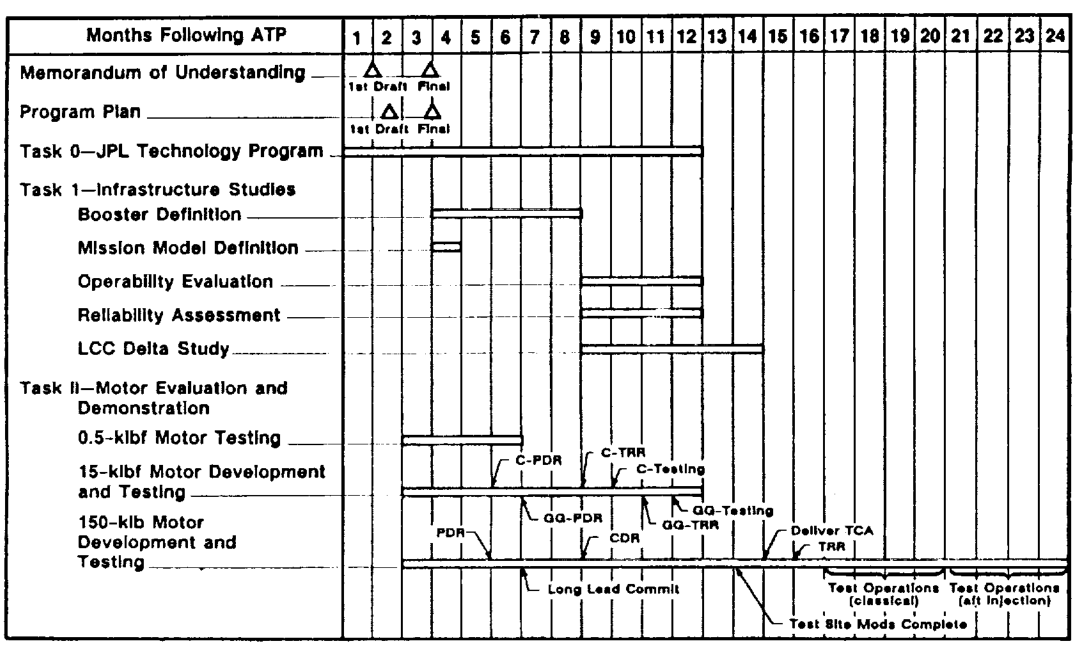
- Create two consortiums to pursue development of both classical and gas generator engine cycles
- Companies and NASA initially linked by MOU



Bridge Program Elements

- Program duration 24 months
- Program total cost $5.6M
  - $1.1M industry discretionary
  - $4.5M NASA R&T funds
- Three basic program tasks include both classical and aft injection cycles
  - Task 0--JPL Fundamental Studies (Hybrid Rocket Technology Program)
  - Task 1--Launch Vehicle Infrastructure Studies
  - Task 2--Motor Evaluation and Demonstration

Program Master Schedule



9.4.2 Reliability of Solid Rocket Motor Cases and Nozzles
by J.G. Crose