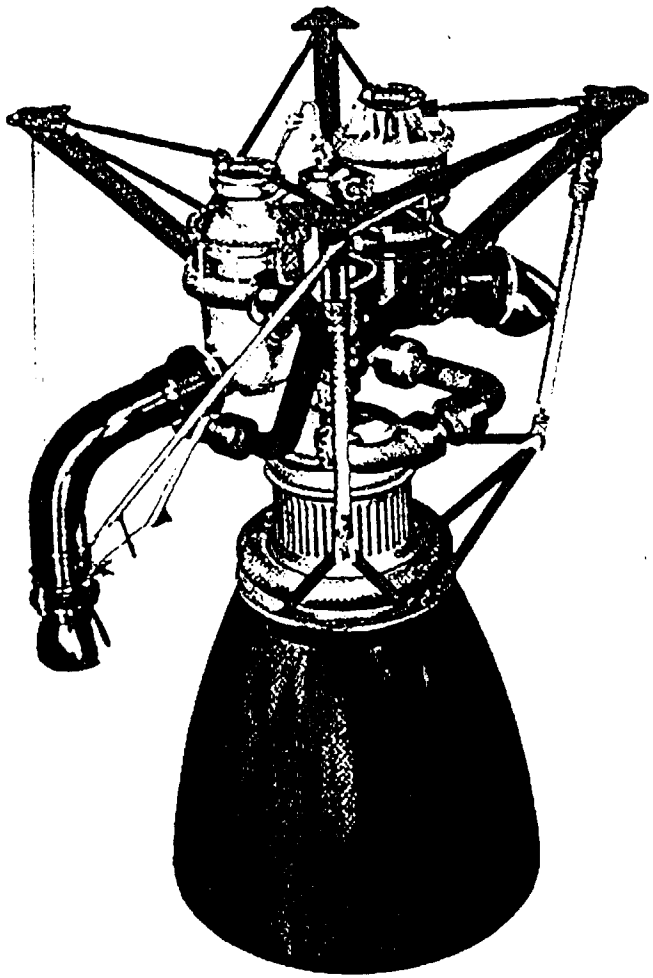
Liquid Rocket Propulsion
50th IAF Congress
Amsterdam, 11-12 October 1999

RS-68 & Linear Aerospike

Terry Murphy
Rocketdyne Propulsion & Power
The Boeing Company

RS-68 Booster Engine



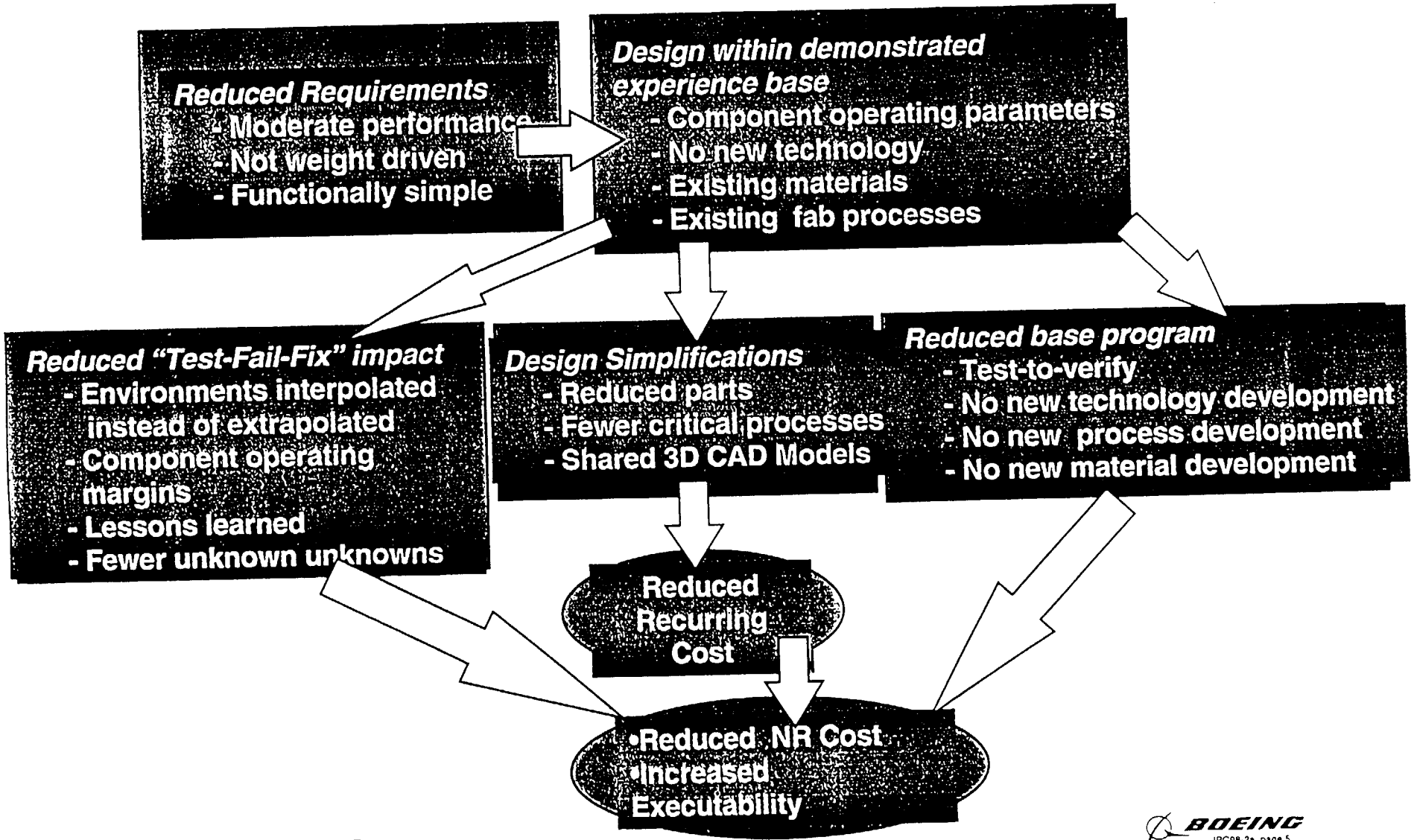
Agenda

- Mission
- Design & Development Strategies & Trades
- Design Solution
- Development Program

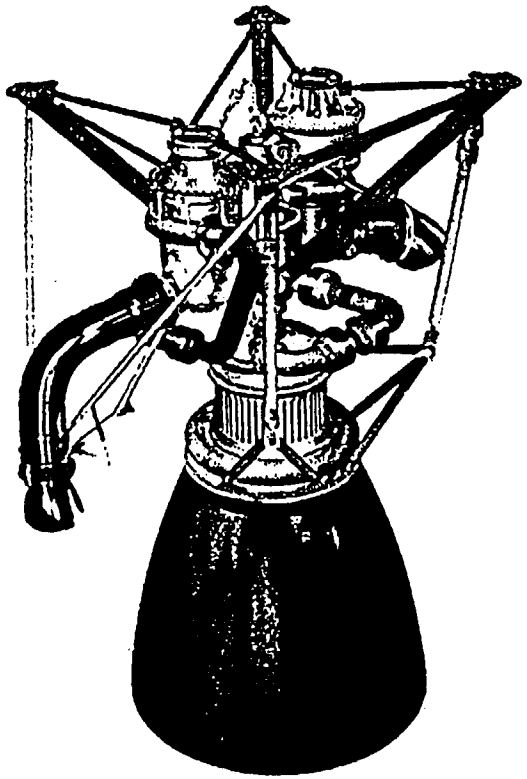
The Mission

Booster propulsion for the Boeing Delta IV family of launch vehicles

Design & Development Strategies

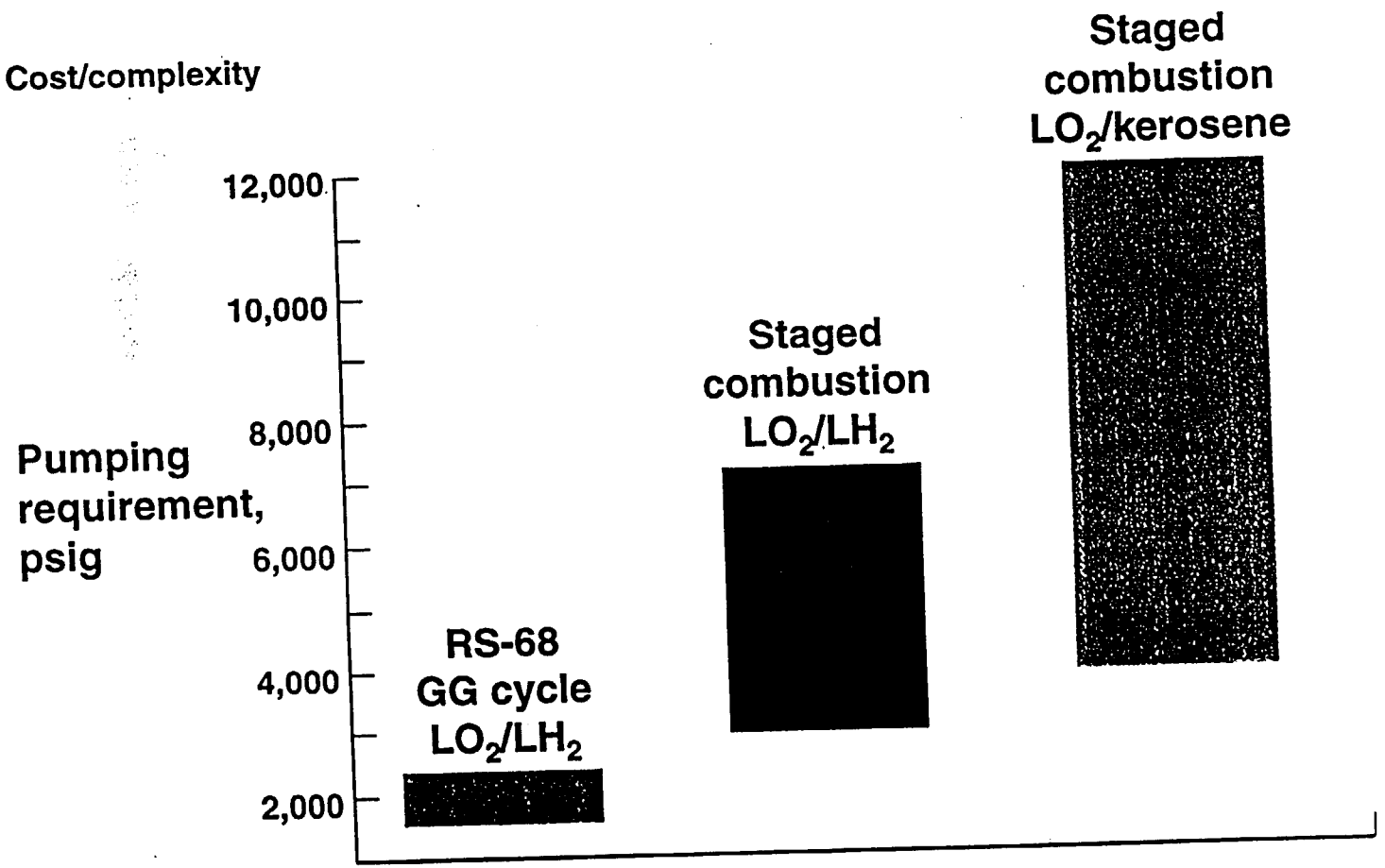


Cost Driven Design Trades

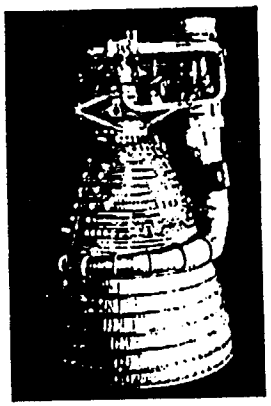


- Gas Generator Cycle
  - Simplicity, experience, environment
  - Vehicle roll control
- Parallel Flow Turbines
  - Simplified turbopump design & test
  - Simplified engine control & sequence
- Coaxial Injectors
  - Performance margins
  - Stability
- Channel Wall Combustion Chamber
  - Simplicity, structural margins
- Ablative Nozzle
  - Simplicity/Cost

Moderate Pressure Requirements Enable Reduced Complexity



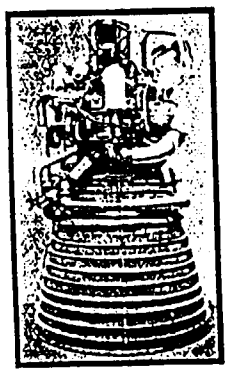
Experience Based Design



LOX/RP Engines
- GG Cycle
- Comb Stability
- Scaling
- Development
- Integration
- TP Tech
- Flex Ducts

RS-68

STME
- Perf for Cost Trade
- Design-to-Cost
- Casting Devel.
- Low Torque Vlvs
- Concurrent Engrg

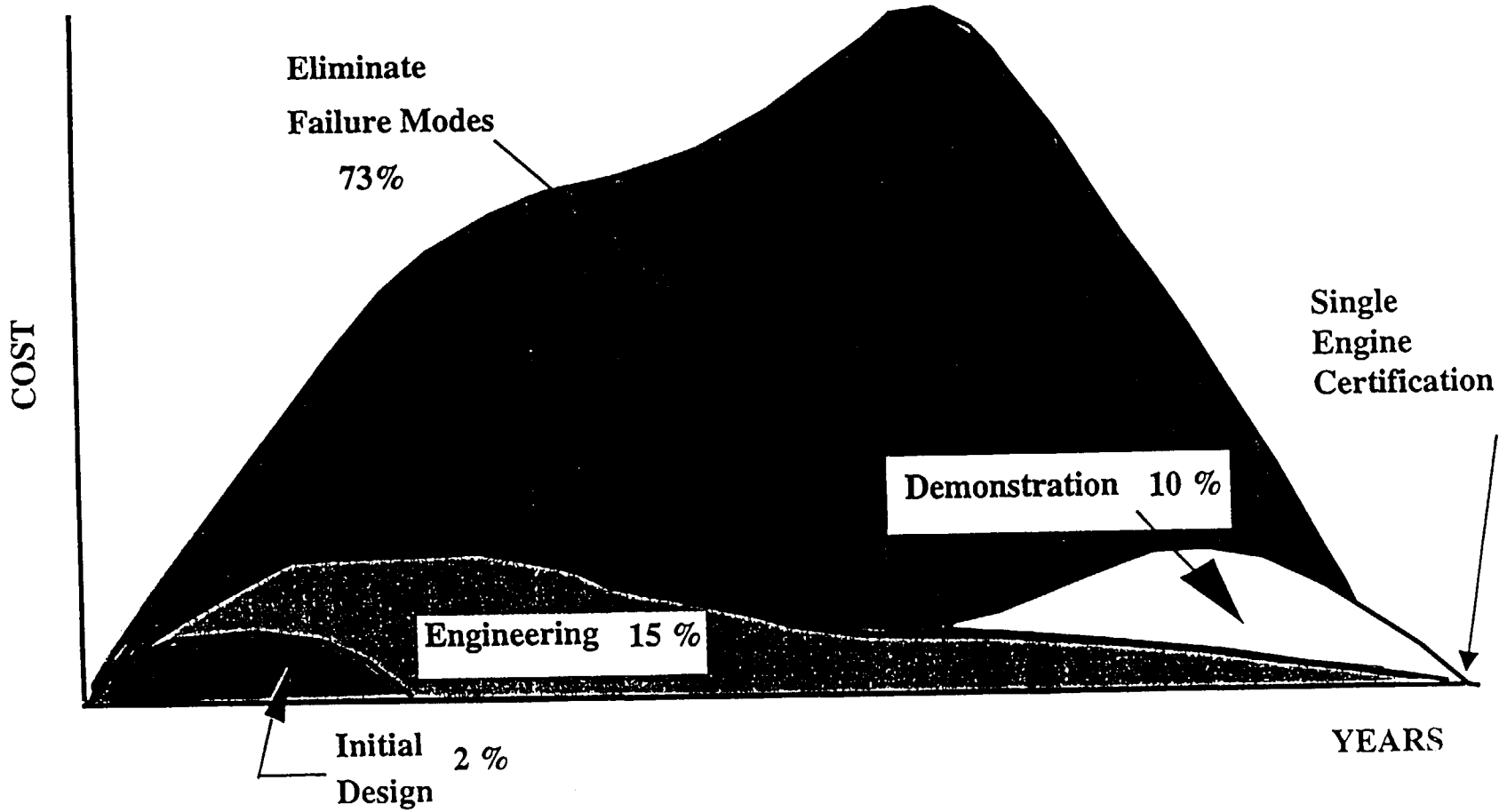


J-2/J-2S Engines
- Hydrogen tech
- HEE Materials
- High Density Coax
- TP Design Tech
- GG Cycle
- Regen Cooling

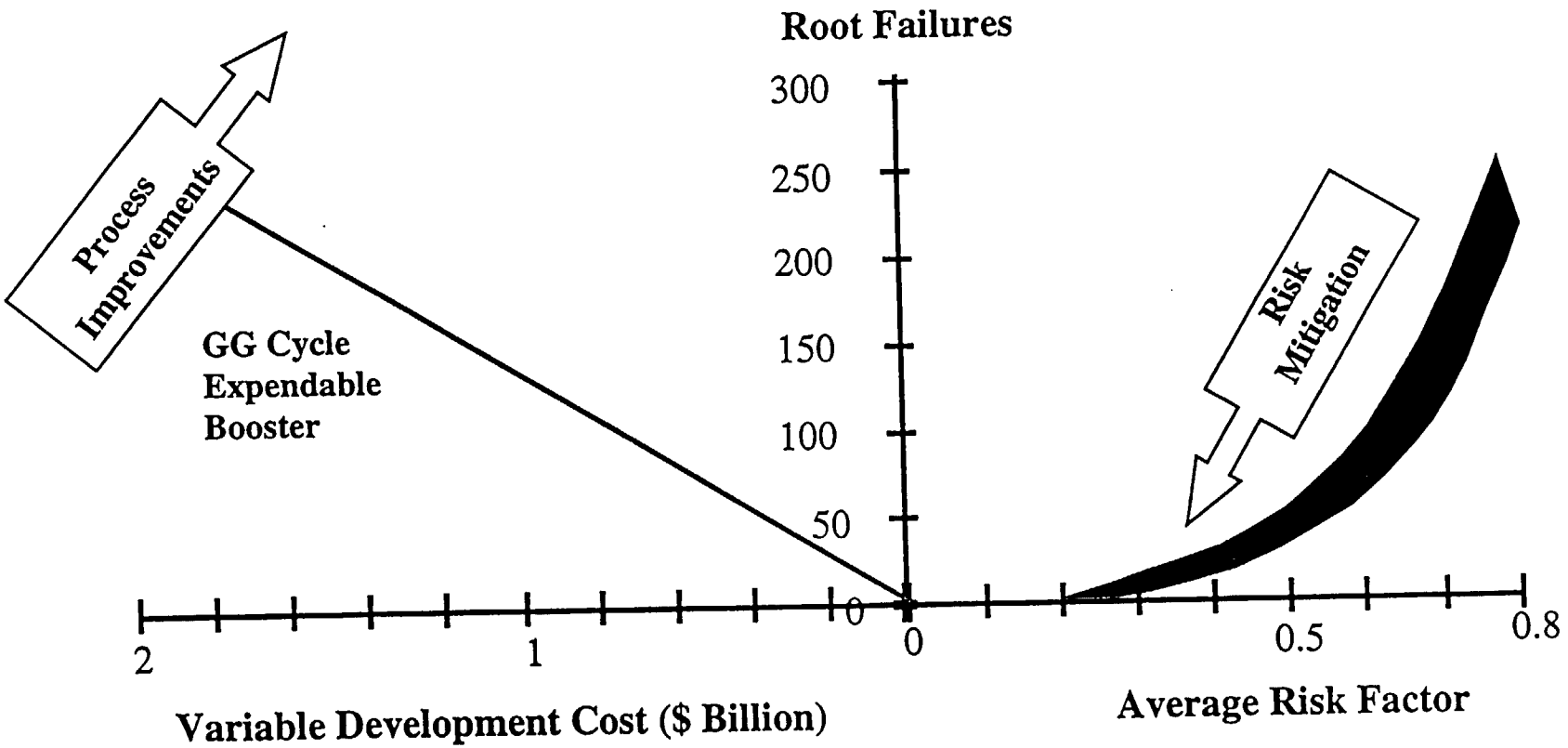
- Low Cost/Risk Driven
- DTC/IPPD/Variability Red.
- GG Cycle, Mod. Pc
- Low Density Coax Injector
- Simple Regen MCC
- Ablative Nozzle
- Simple, Low HP Pumps
- Flex Ducts
- Investment/Spin Castings
- Fewer Parts/Processes

SSME
- High Perf Cycle and Component Designs
- High Density Coax Inj
- Stability Aid Design
- Regen MCC
- TP Hydro Design and Mechanical elements
- Fabrication Methods

Development Costs Dominated by Cost of Eliminating Failure Modes

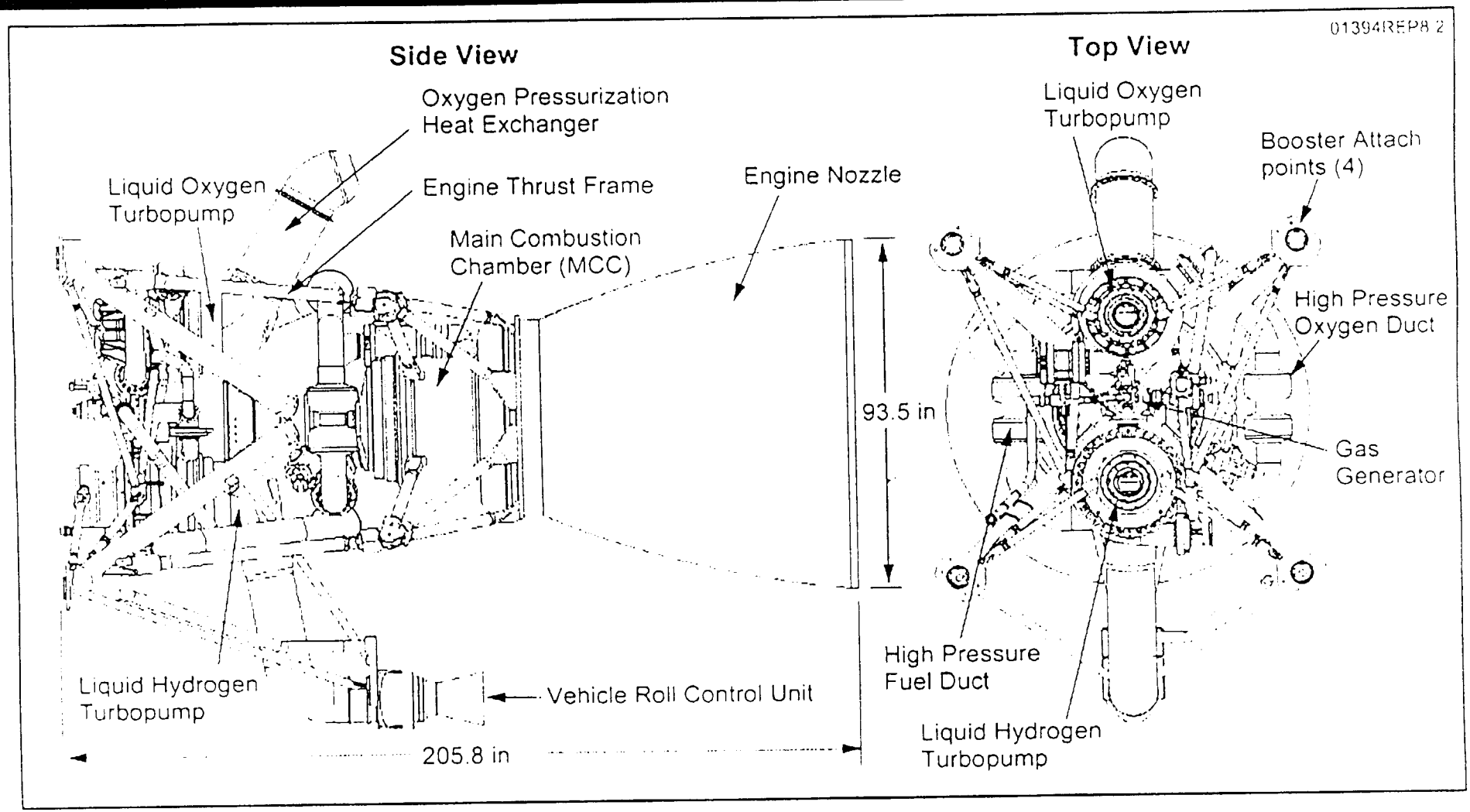


Reducing Development Costs

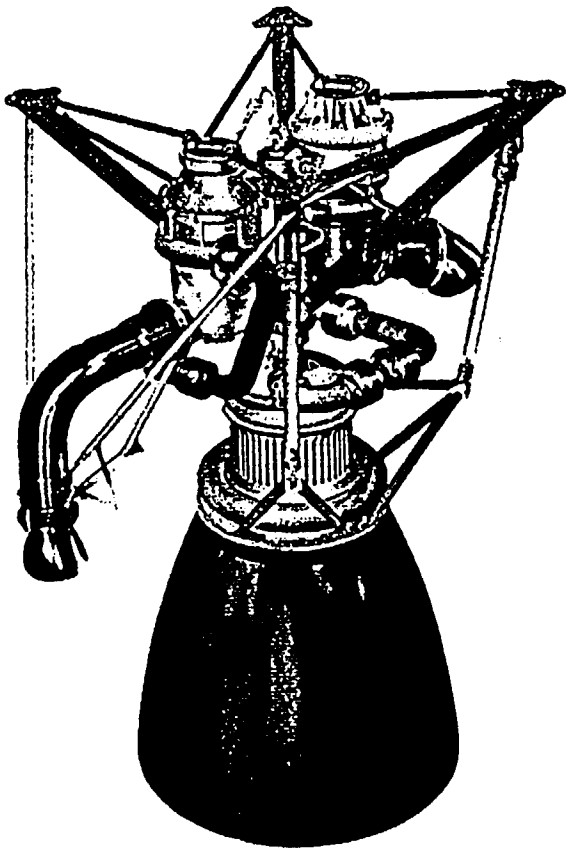


TC

RS-68 Engine

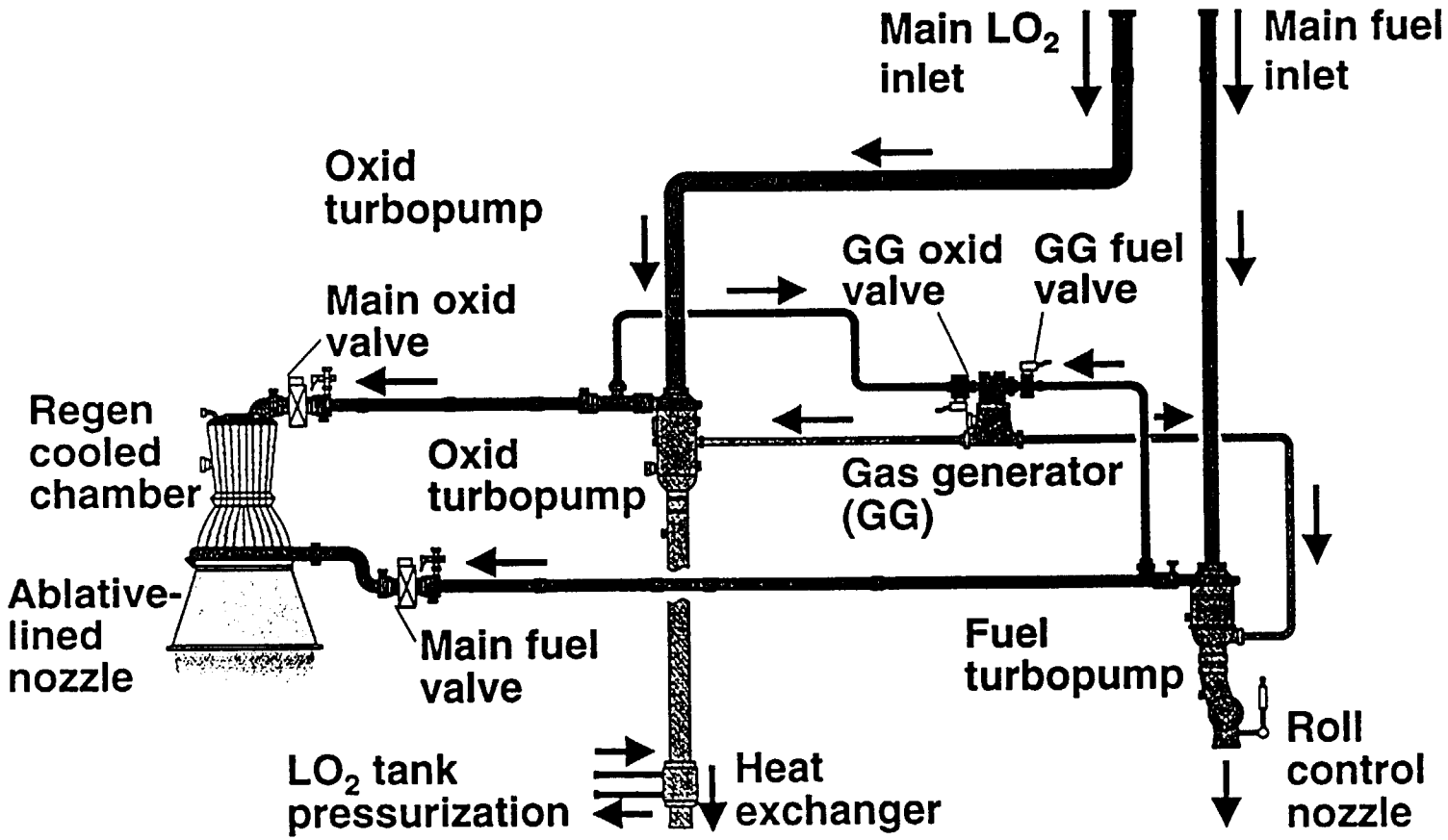


RS-68 Engine Performance Baseline



	Rated	Throttled
Thrust, vac, klbf	745	440
Thrust, s/l, klbf	650	N/A
Chamber pressure, psia	1410	836
Engine mixture ratio	6.0	
I_{sp}, vacuum, sec	410 Avg	
Expansion ratio	21.5	
Weight, lb	< 15,000	
Reliability, %	99.73	

Simple Gas Generator Cycle



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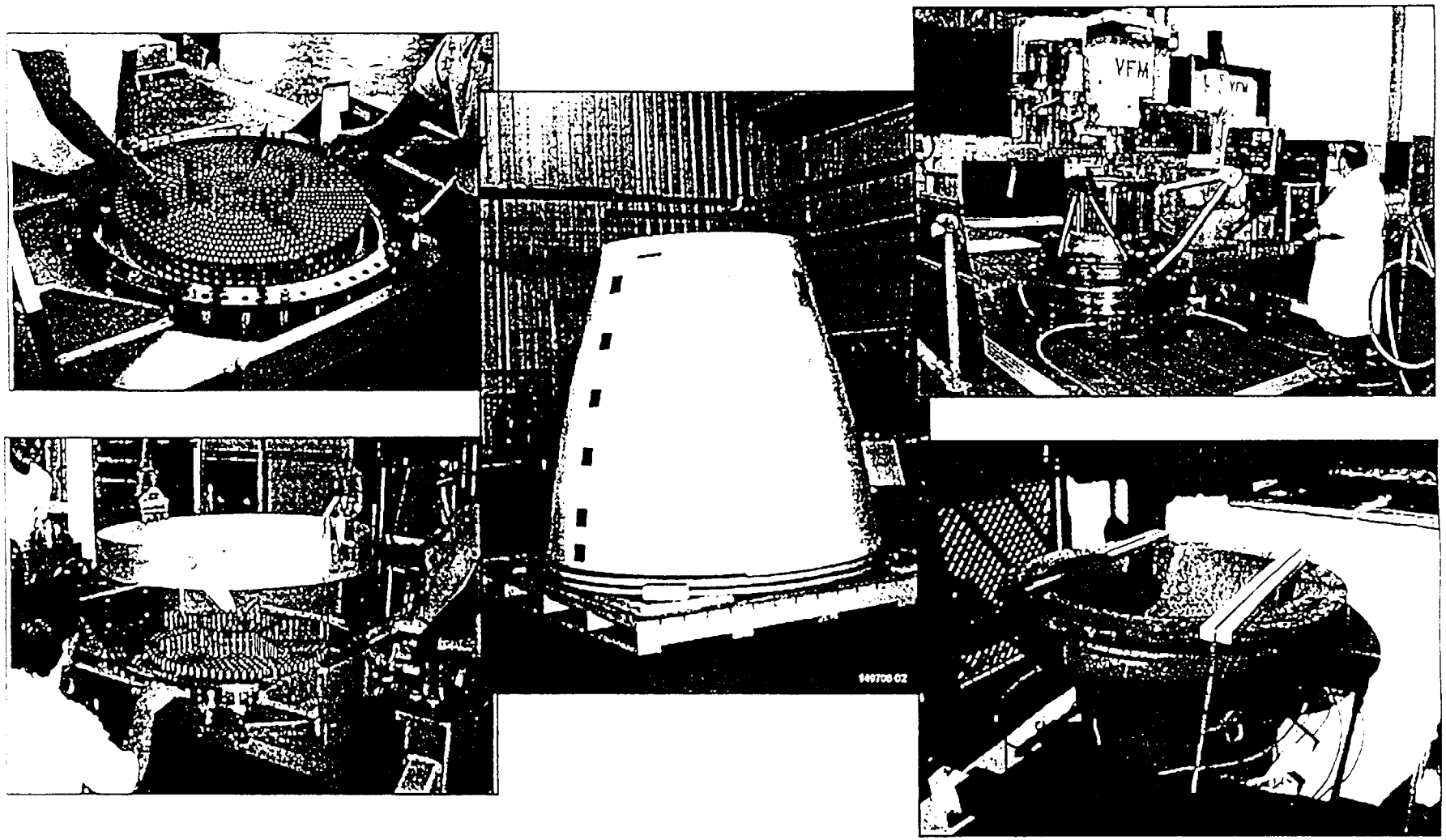
Main Combustion Elements Hardware

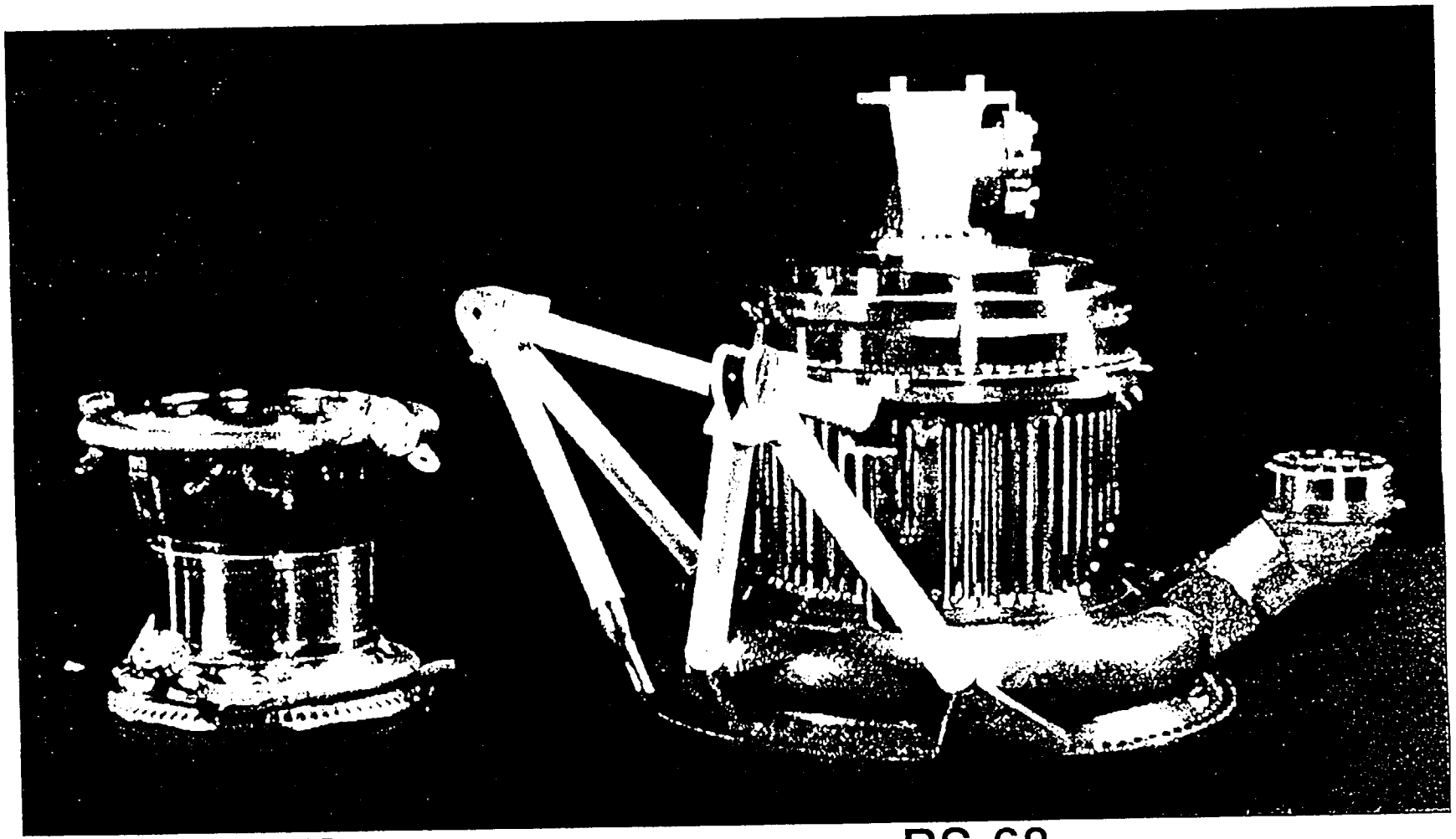


Rocketdyne
Propulsion & Power

BOEING

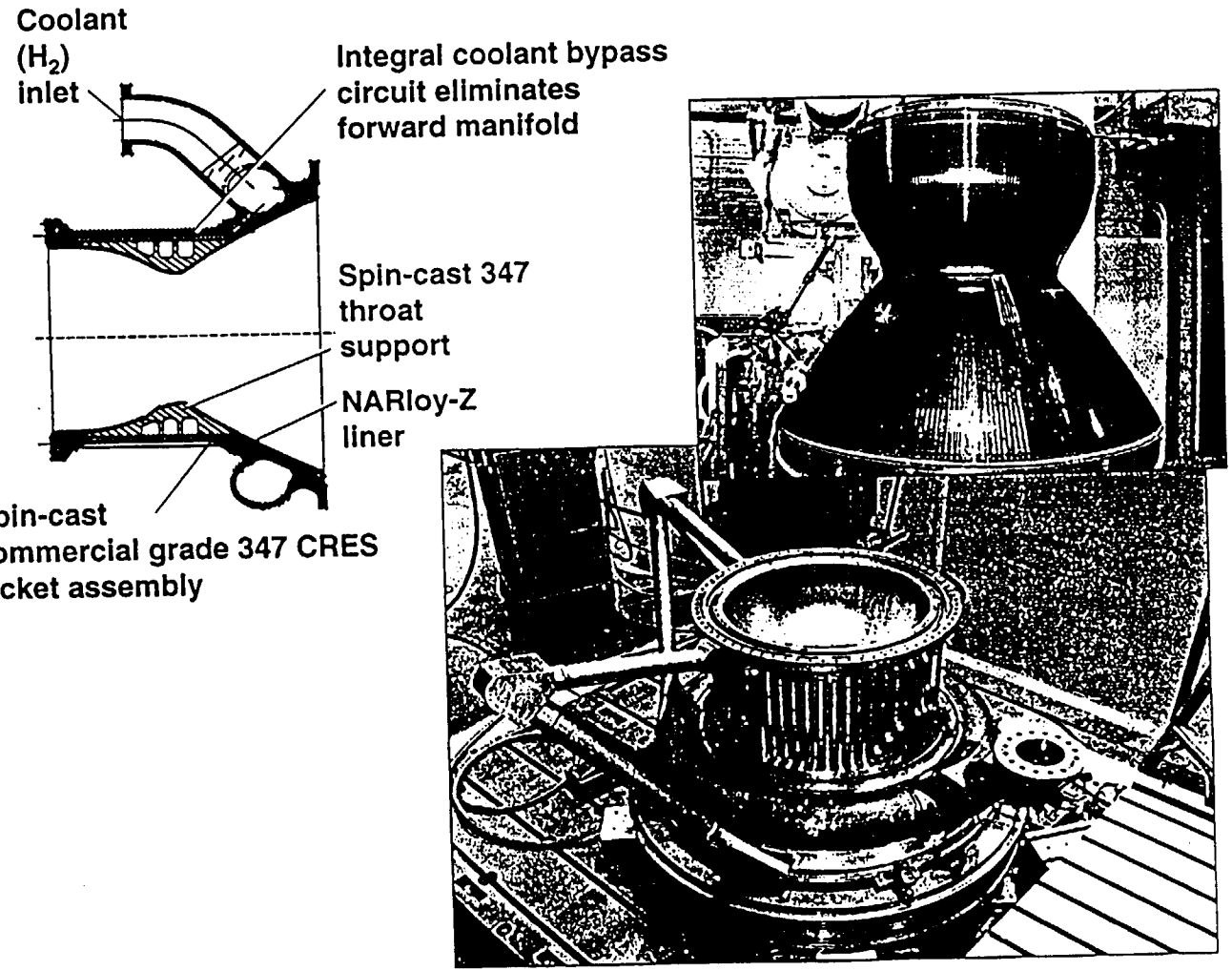
TC

Big Brother

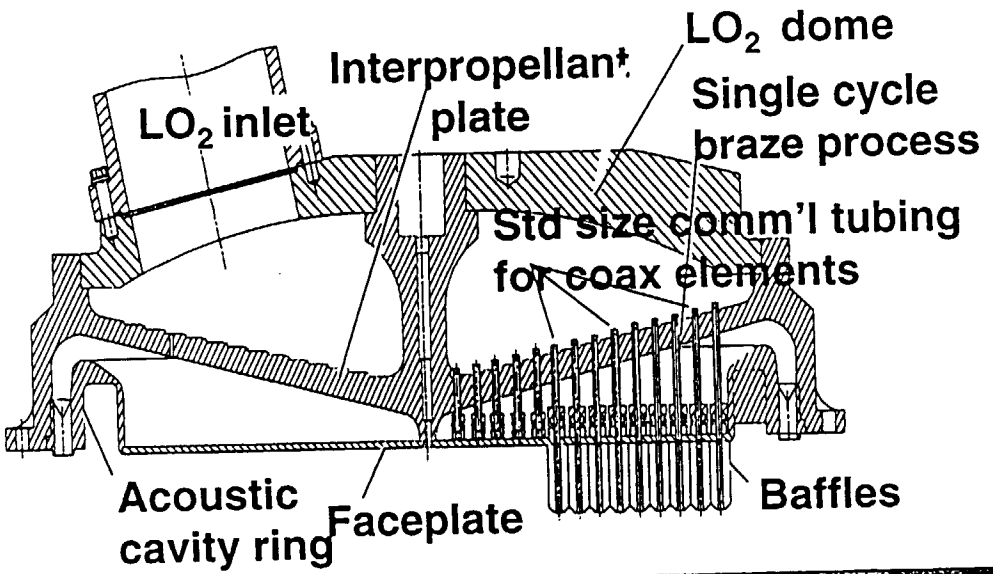


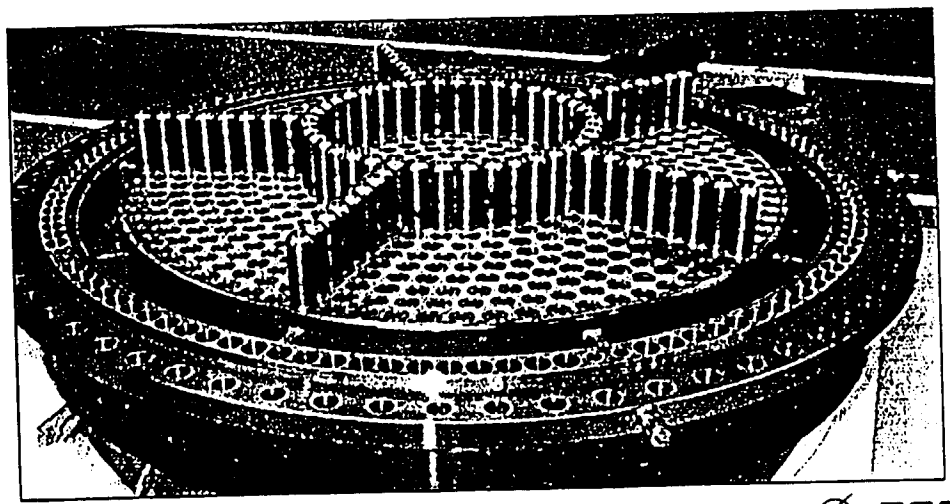
SSME RS-68

Combustion Chamber

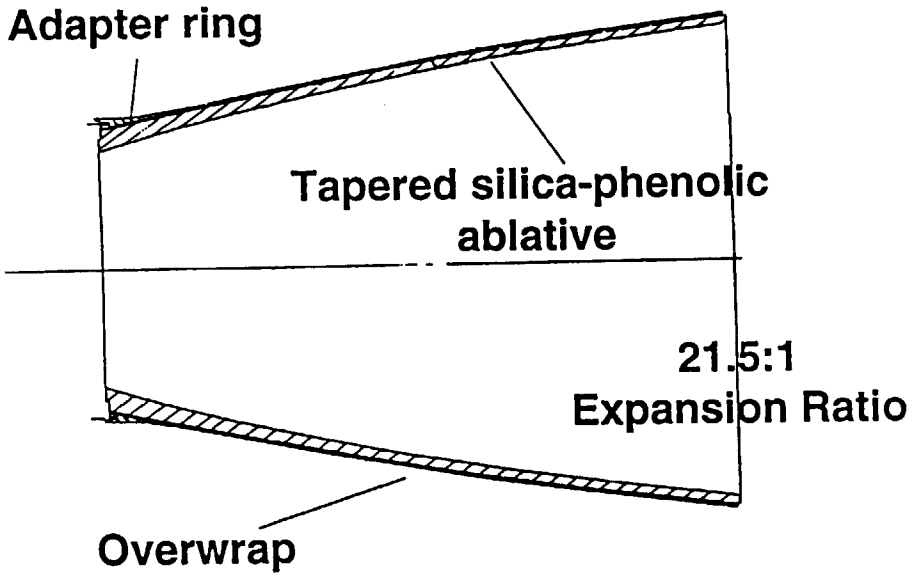


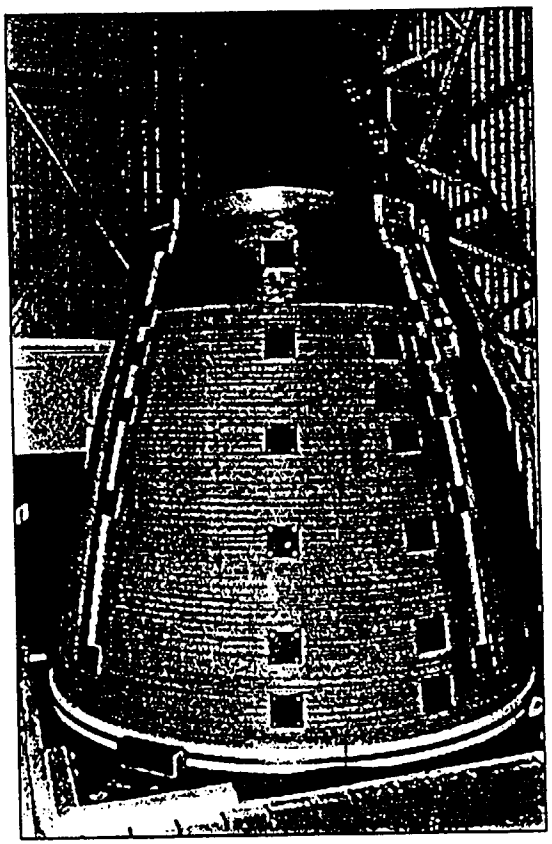
Main Injector

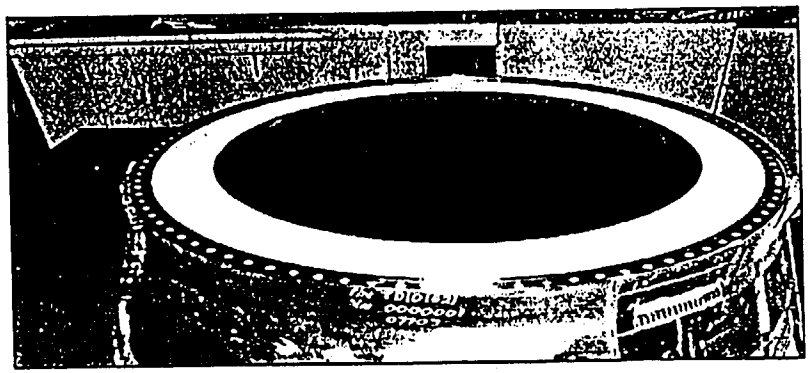




Ablative Nozzle Assembly

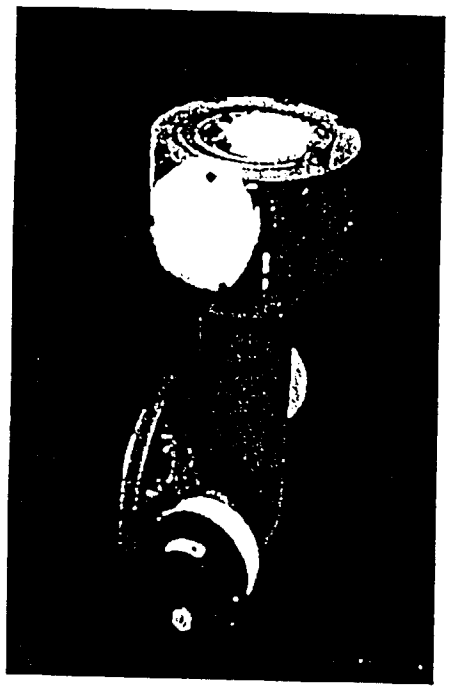




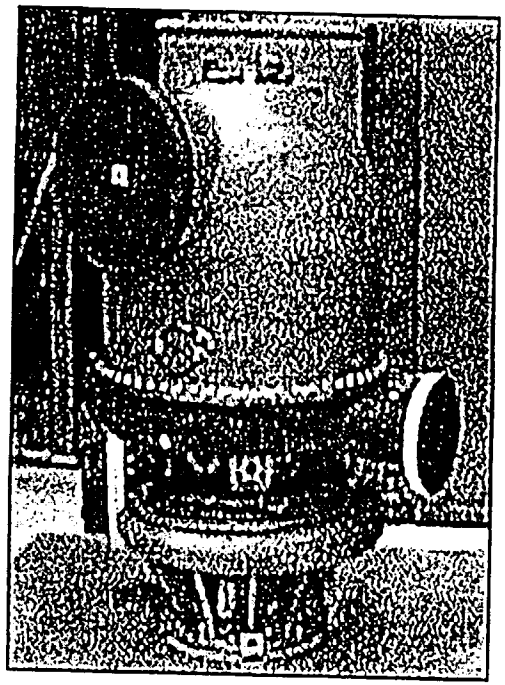


TC

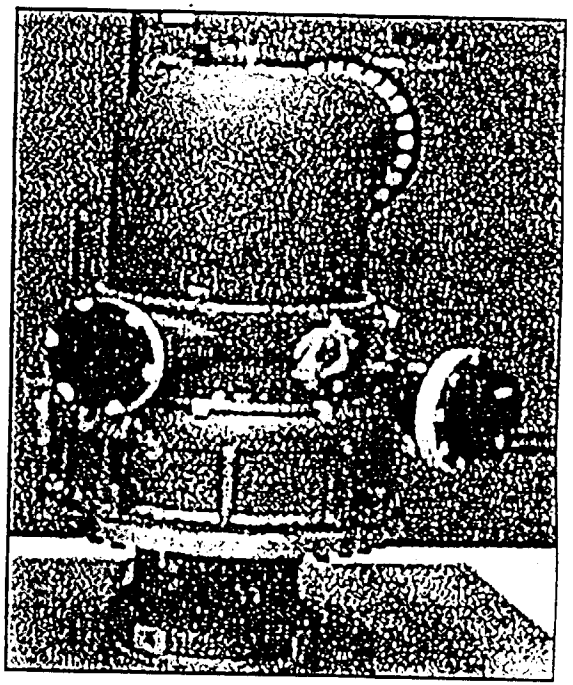
Powerpack



Gas Generator

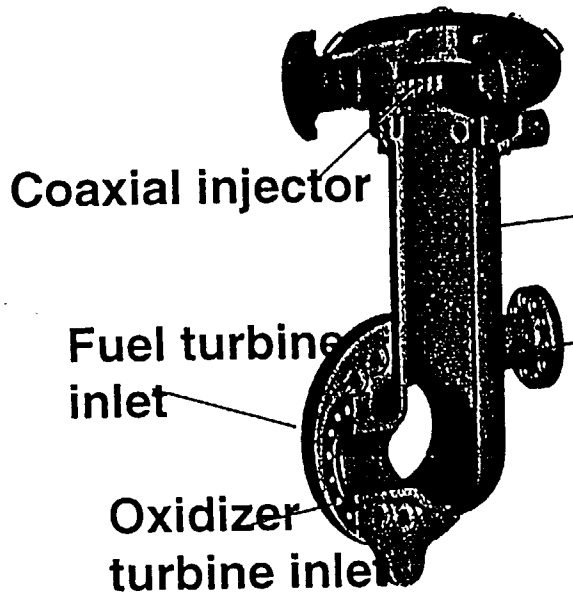


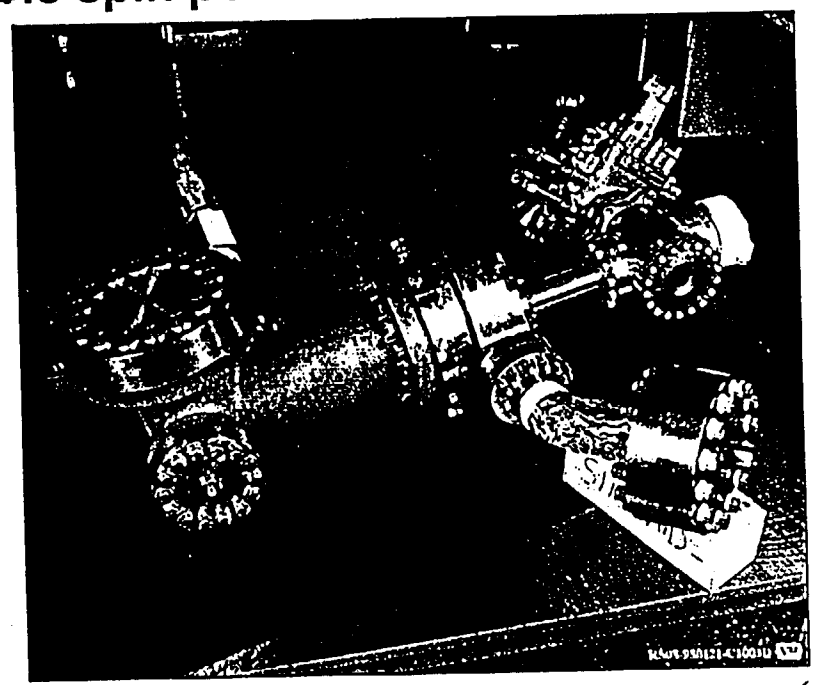
Oxidizer Turbopump



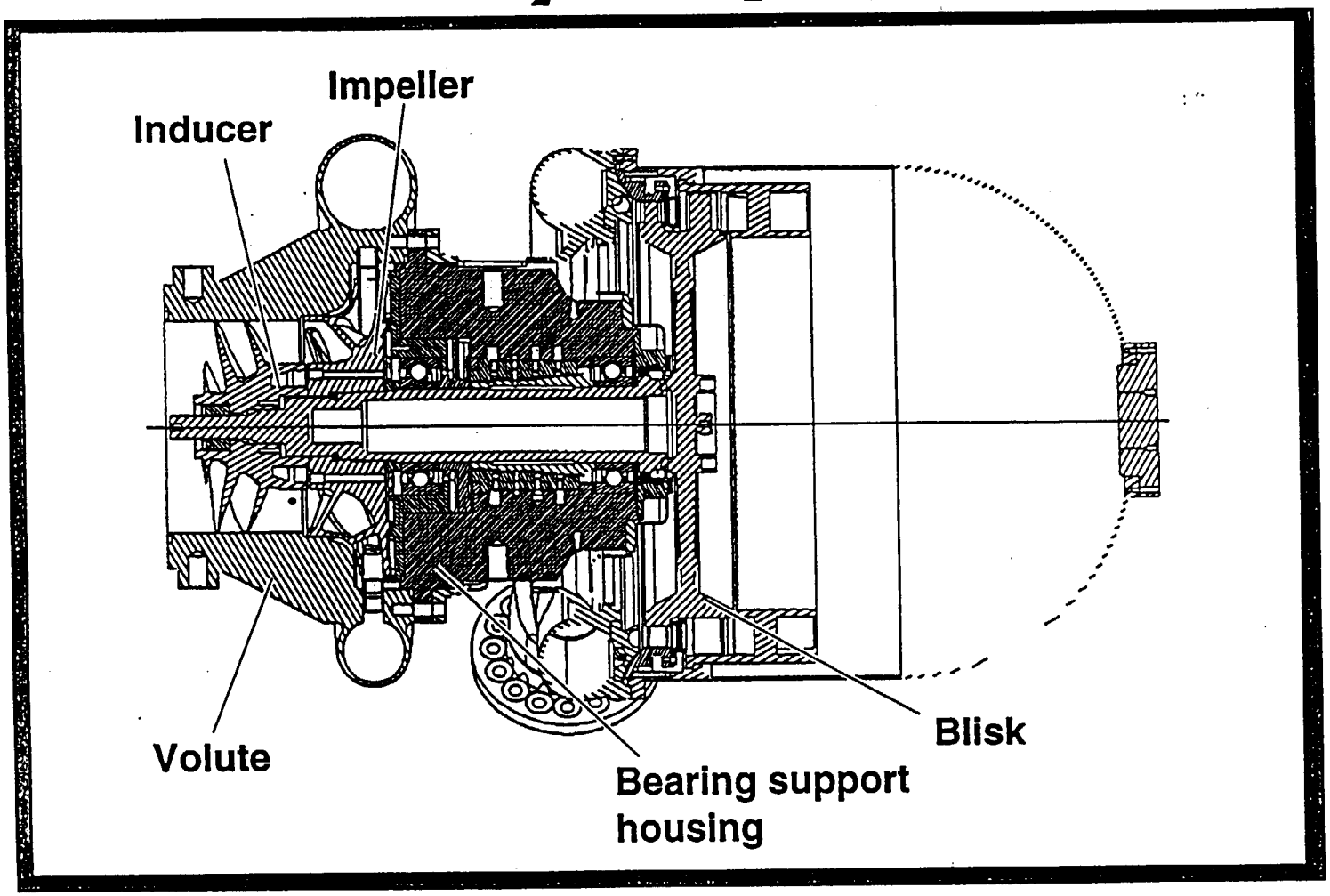
Hydrogen Turbopump

Gas Generator Assembly

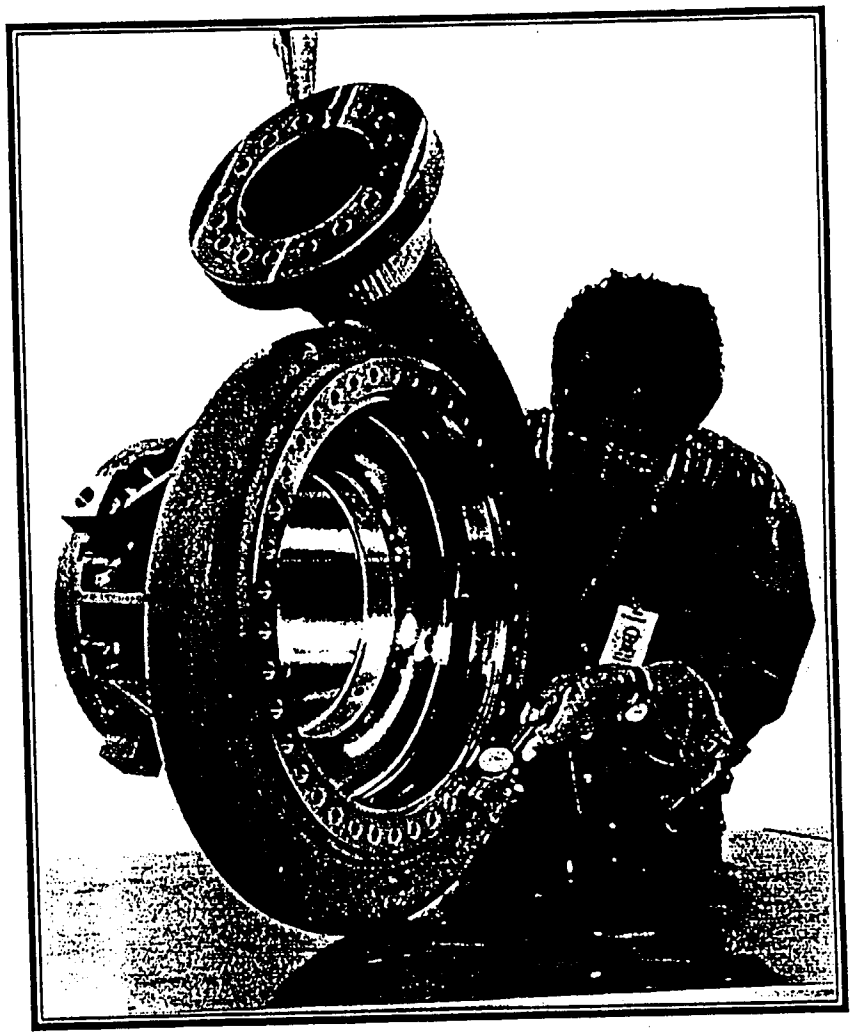




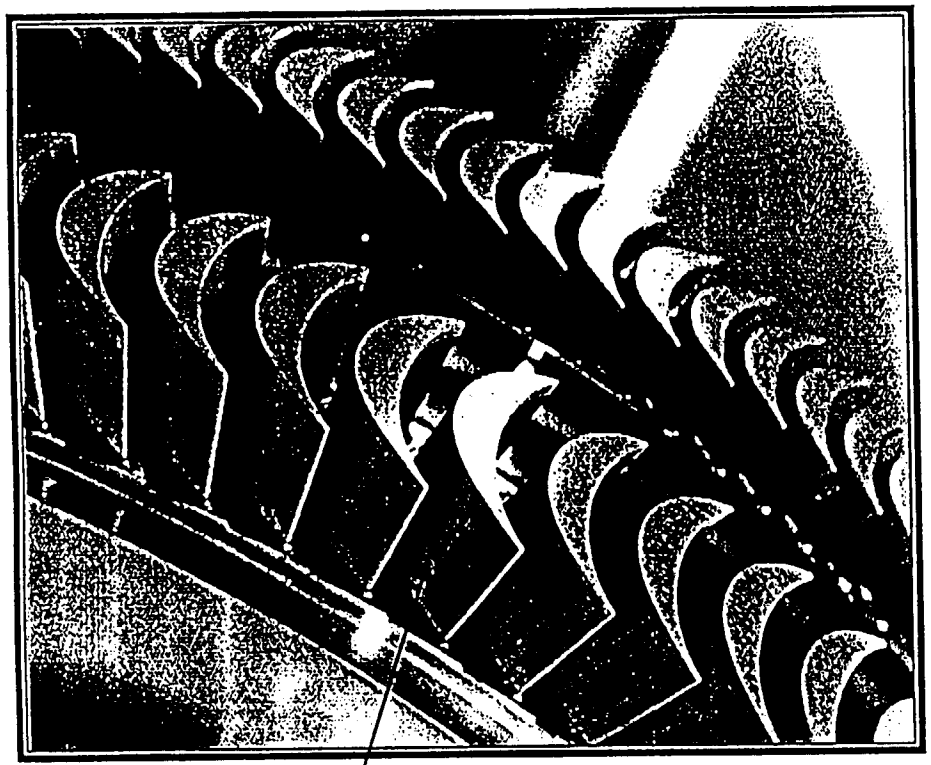
LO_2 Turbopump



LO2 Turbopump Inlet/Volute Casting

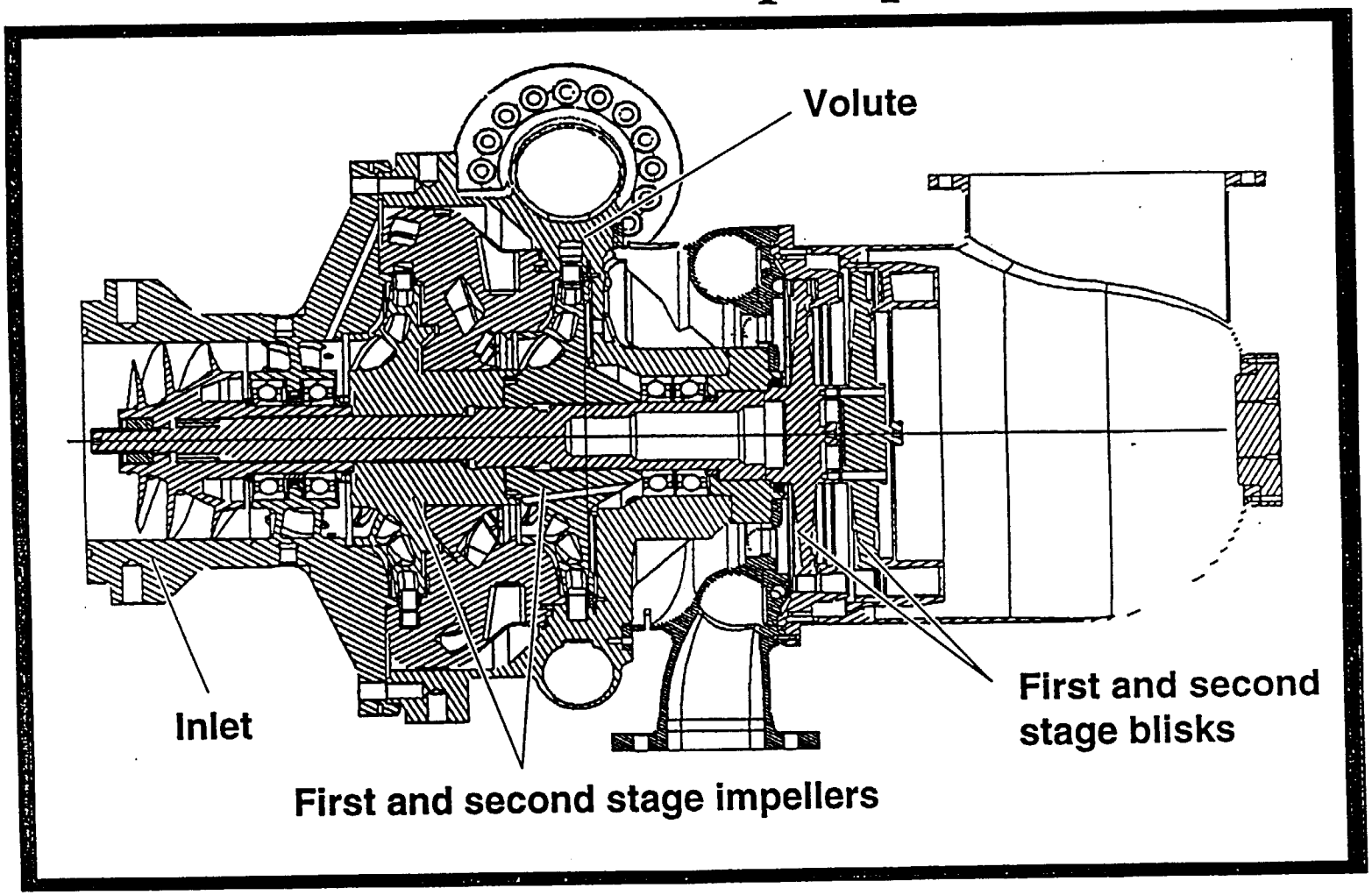


LO2 Turbopump Shaft/Blisk

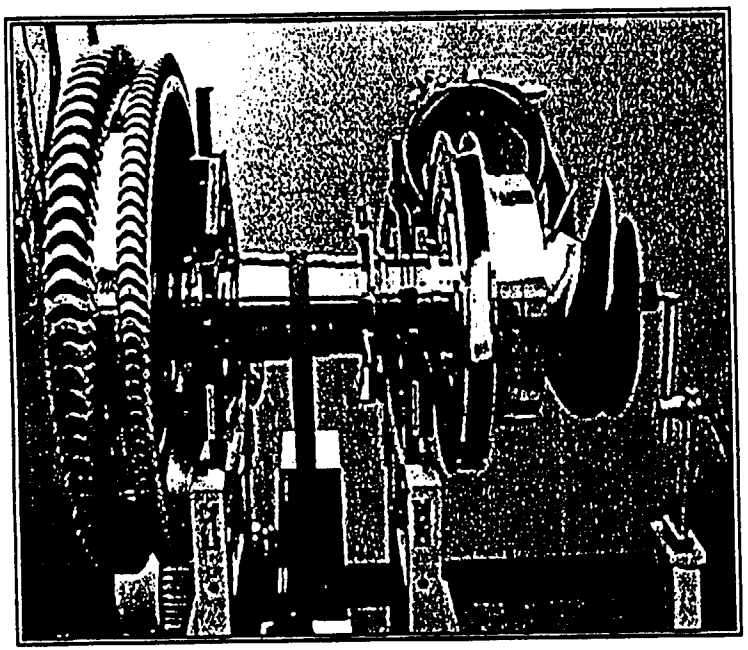


Integral turbine blades/disk

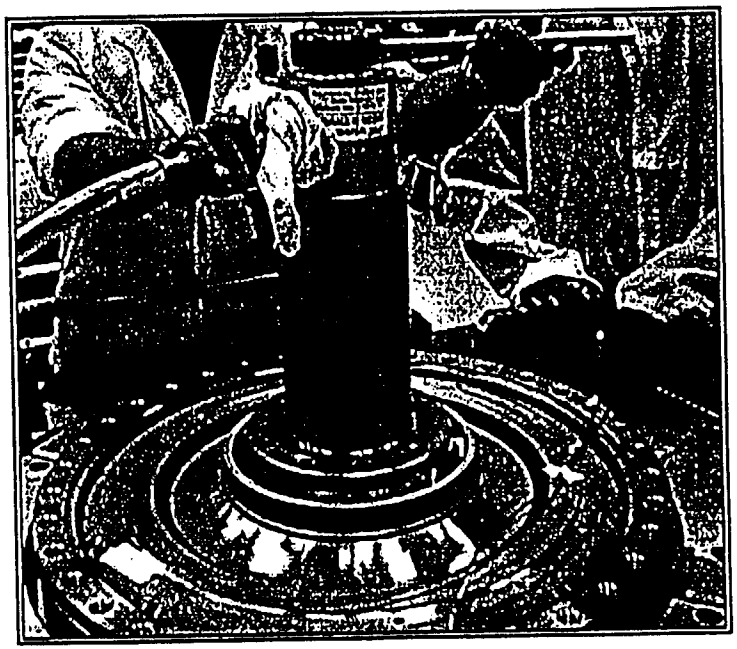
Fuel Turbopump



Turbopump Assembly

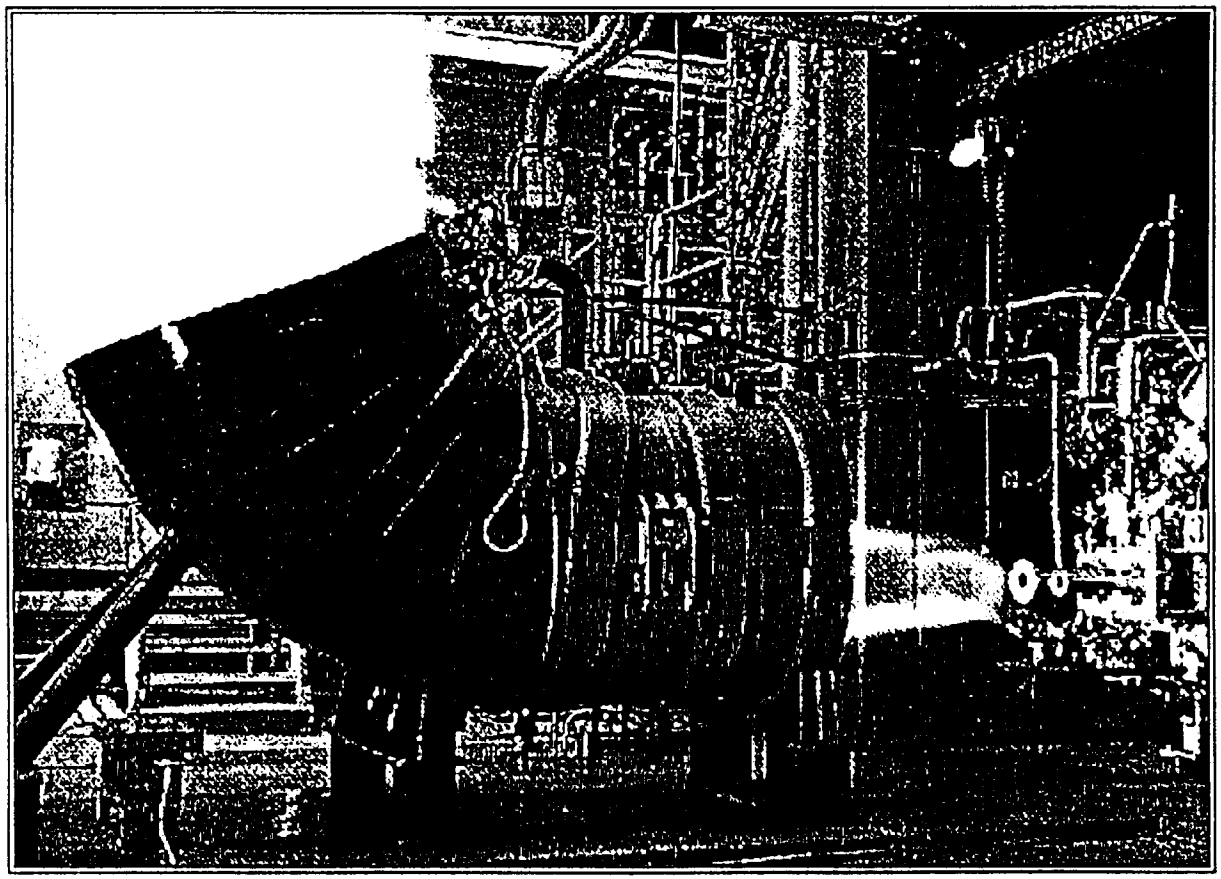


LOX Pump Shaft Balance



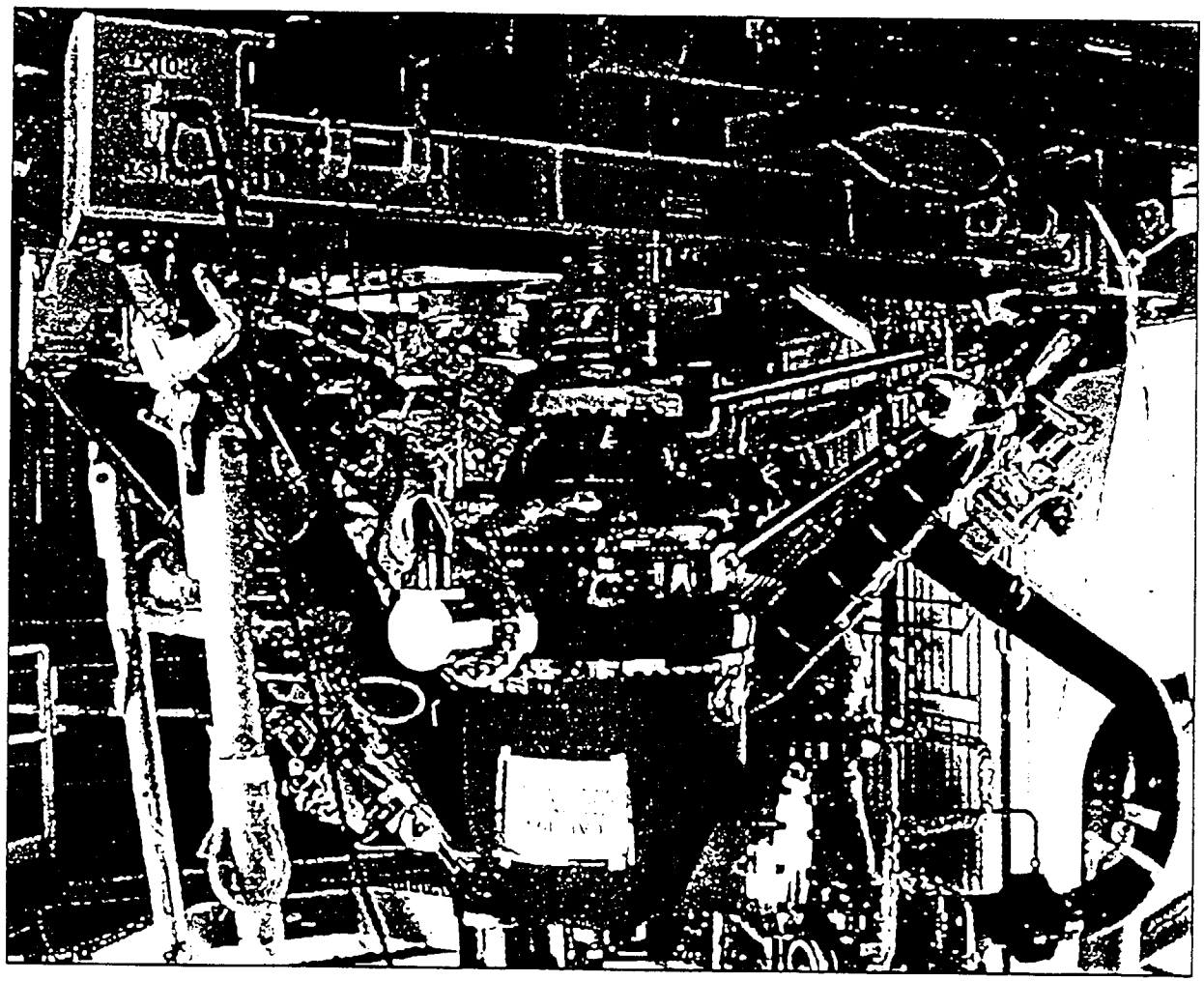
Fuel Pump Shaft Installation

Gas Generator Testing Validates Design



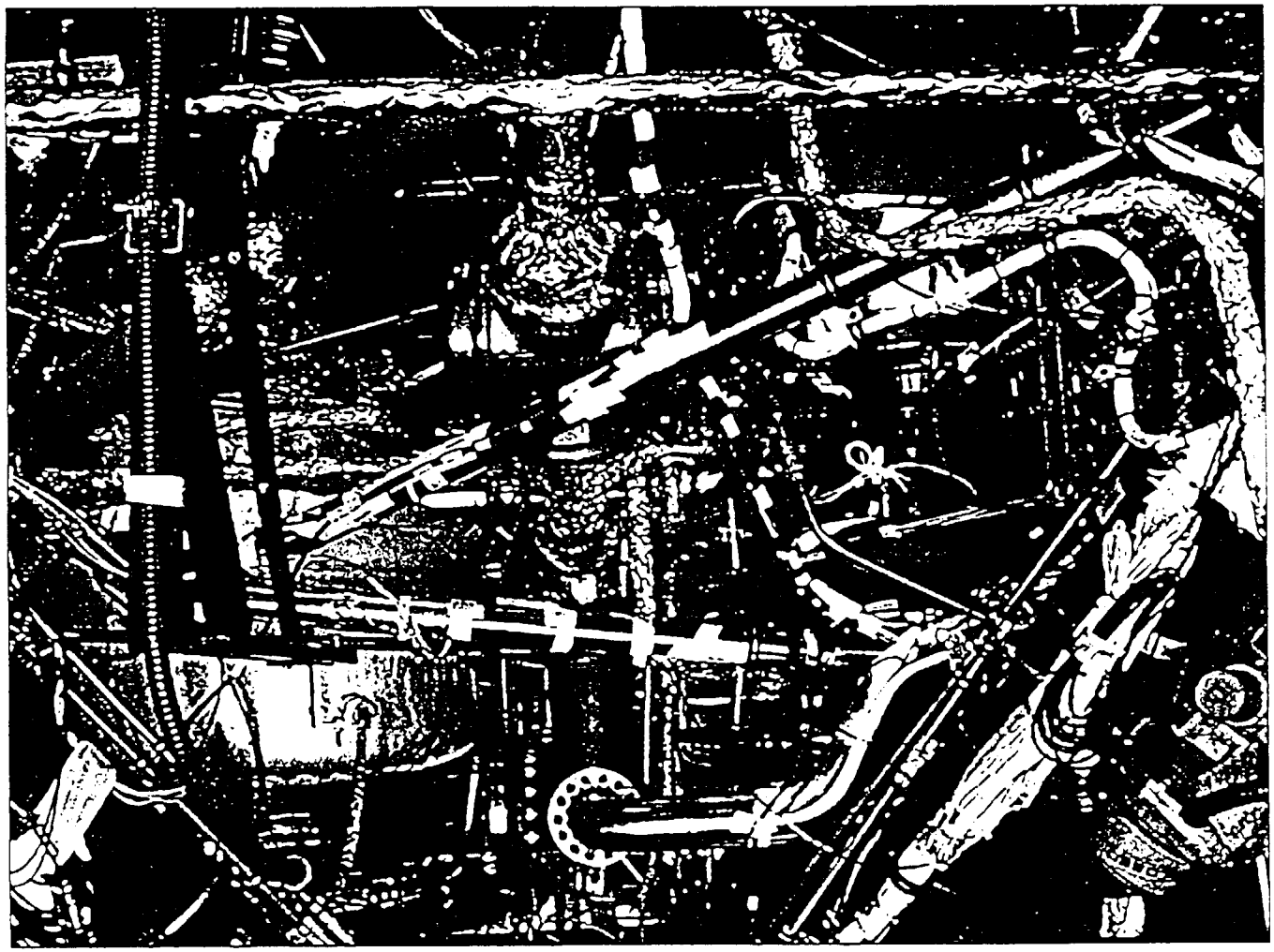
AC

Turbomachinery Full Scale Cold Flow Test



AC

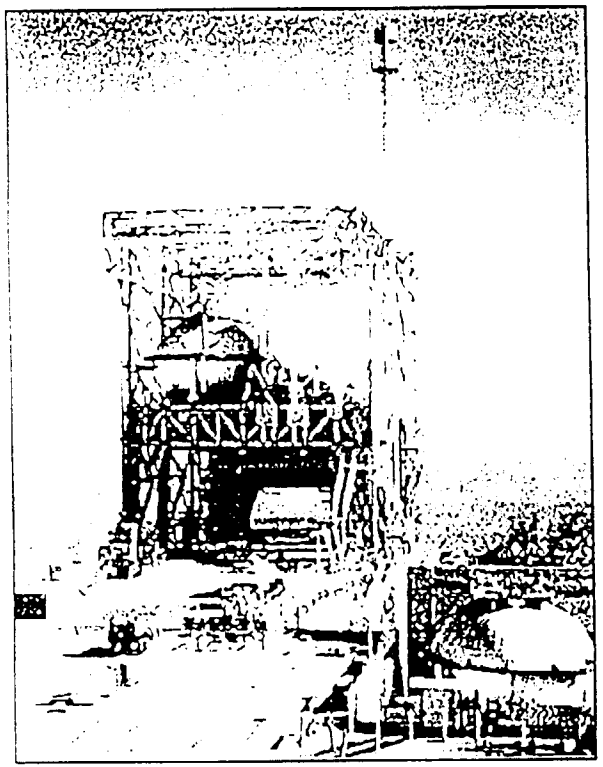
Full-Scale Powerpack Hot-Fire Testing



TC

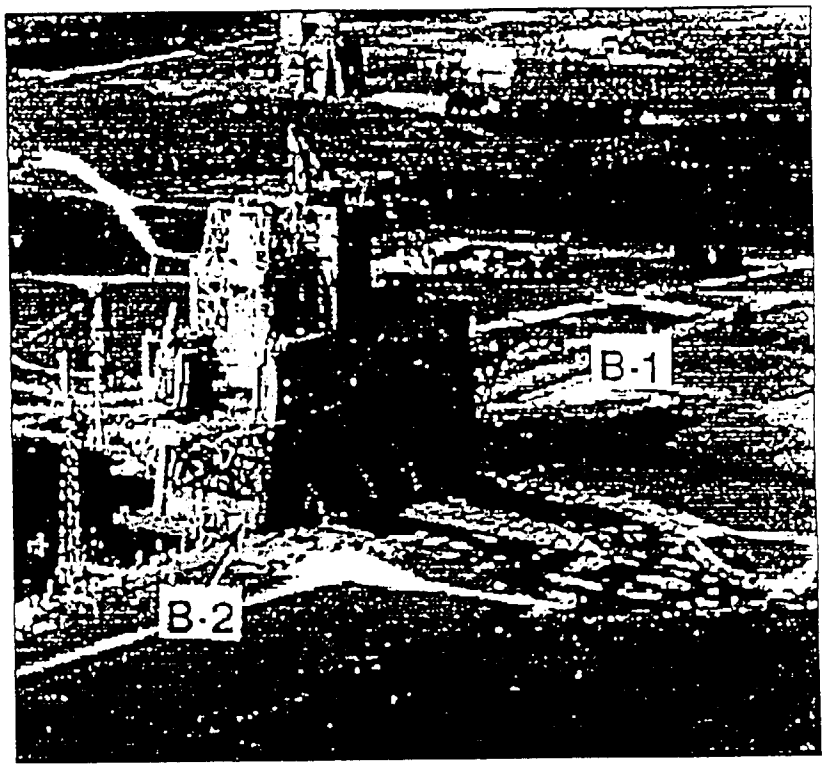
RS-68 Test Facilities

Development



Stand 1-A
AF Research Lab

Certification/Production



Stand B-1
Stennis Space Center

SSL

Test Stand Capability Supports Remaining Test Program

Stand	Capability
1-A	• High LOX inlet pressures • POGO pulsing • 120 sec duration at 100%
B-1A	• Thrust/thrust vector measurement • Inlet flow/MR • Mission duration • Gimbaling
B-1B	• Thrust/thrust vector measurement • Inlet flow/MR • Mission duration
B-2	• Stage tankage • Stage integration • POGO verification

ST

Minimum Power Level Achieved on 1st Engine

Start

Ignition

Mainstage (60% power level)

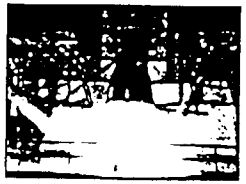
Engine 10001

Total Tests	7
Total Sec	36

AC

Engine 10202 Tests

-013: Start
7 sec



-014: Transition
13 sec

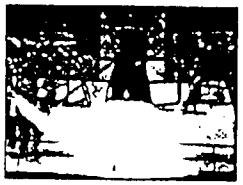
-015: 60% S-S
6 sec (facility cut)

-016: 60% S-S
18 sec

-017: 60% S-S
38 sec

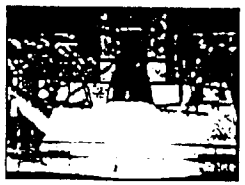
-018: 60% S-S
68 sec

-019: Stability
6 sec



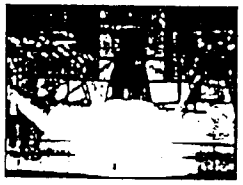
-020: Stability
78% ramp
18 sec

-021: Stability
6 sec

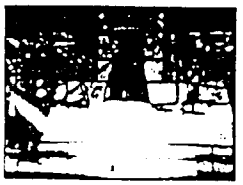


-022: Stability
8 sec

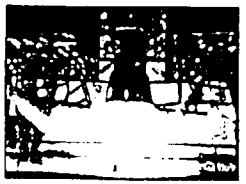
-023: Stability
83% S-S
14 sec



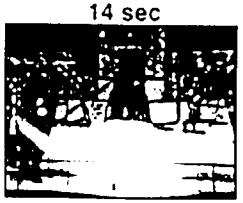
-024: 93%
Ramp
9 sec



-025: 93% S-S
15 sec



-026: 60%/93%
68 sec



-027: 100% Ramp
8 sec

-028: 102% Ramp
11 sec
(Redline cut)

Demonstration Objectives

- Start/shutdown
- Ignition
- Bootstrap
- Injector stability-60%
- Nozzle dynamic environment
- Mainstage 60%
- Purge development
- Bleed valve characteristics
- Drying verification
- Config. - 60% power level

Risk Mitigation

- High power (96%) steady-state
- 100% start transient

Rocketdyne
Propulsion & Power

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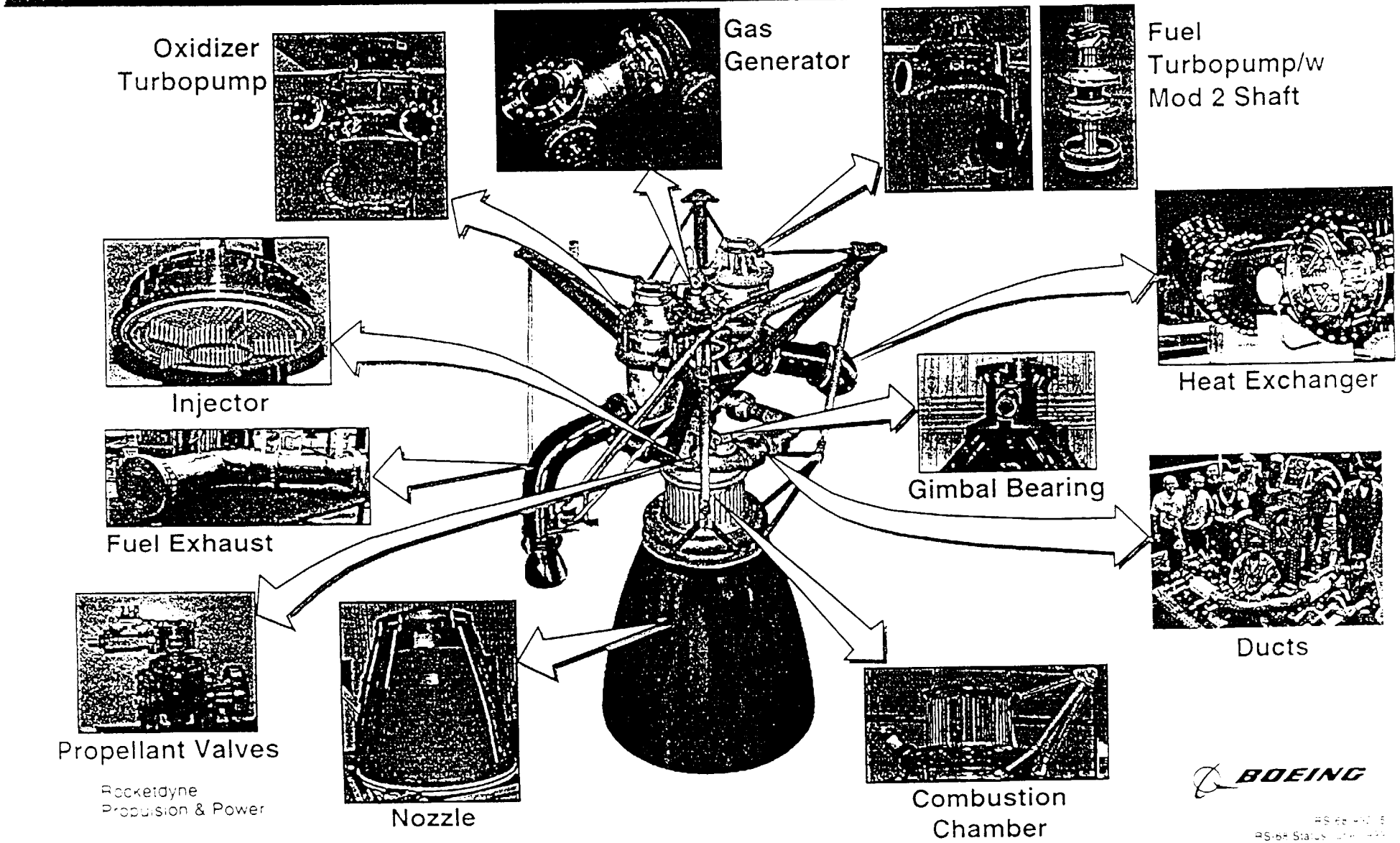
RS-68 943-29
Aerospace Corp

3rd Engine in Assembly



Rocketdyne
Propulsion & Power

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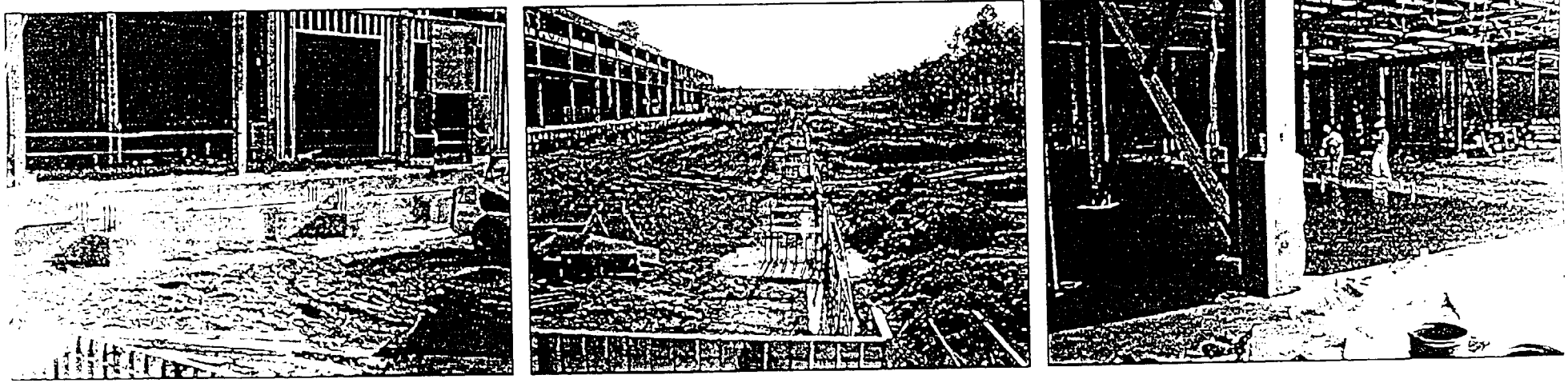
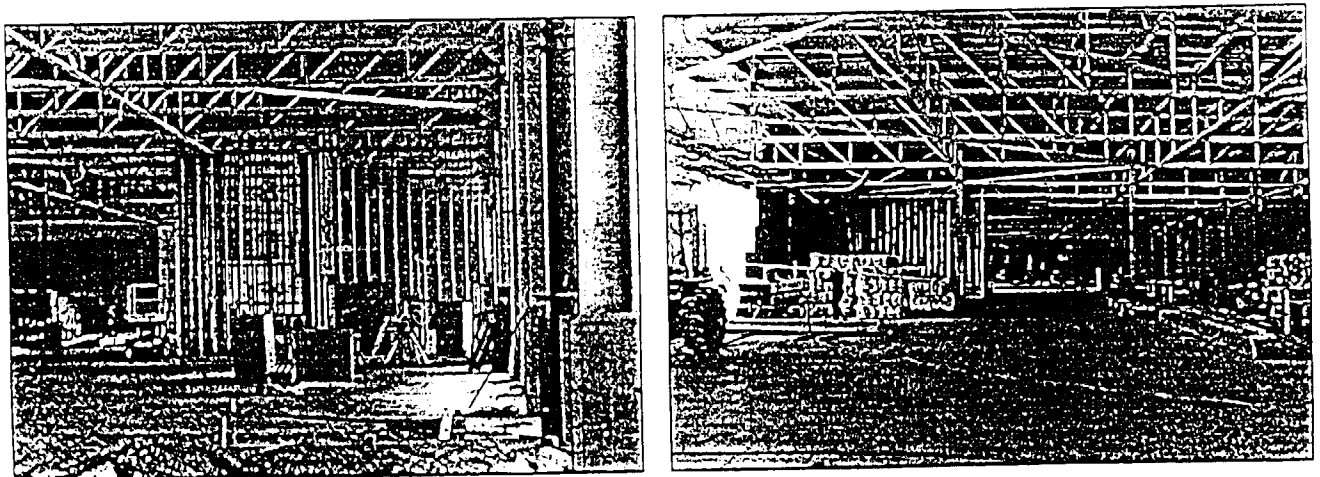
SSC Production Facility at Stennis



High Bay Area

UPDATE



Staging

Assembly

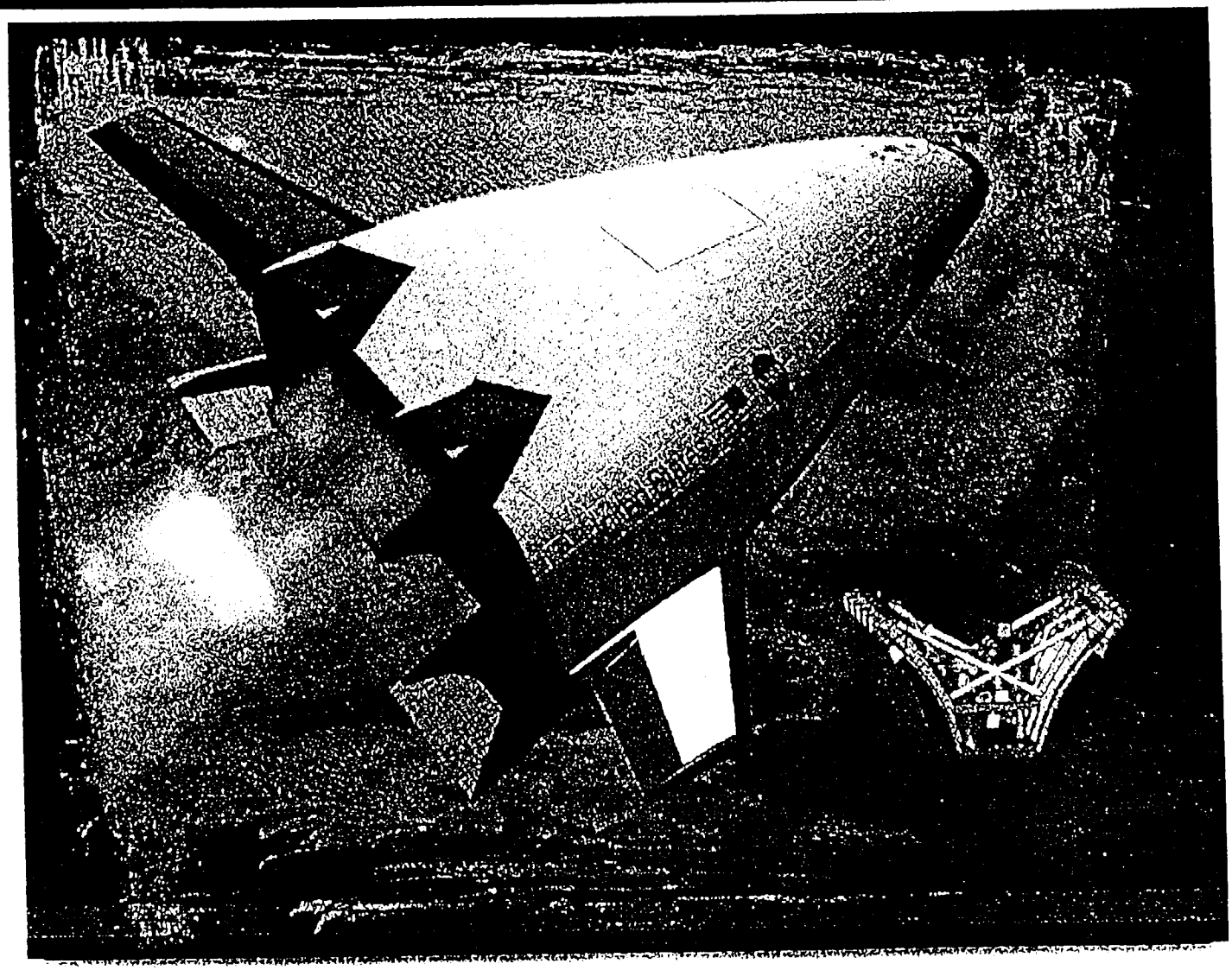
BOEING

Rocketdyne
Propulsion & Power

Summary

X-33 Linear Aerospike Engine

Program Overview



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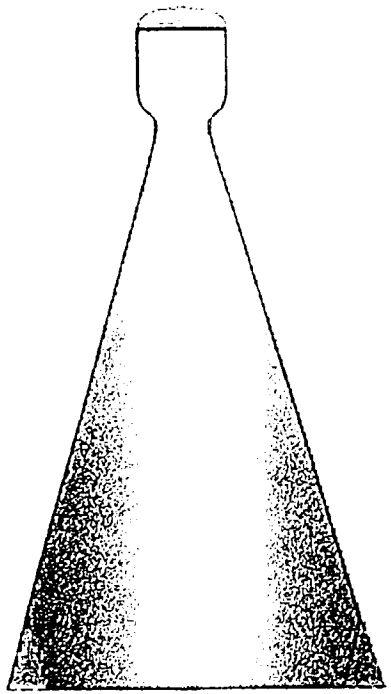
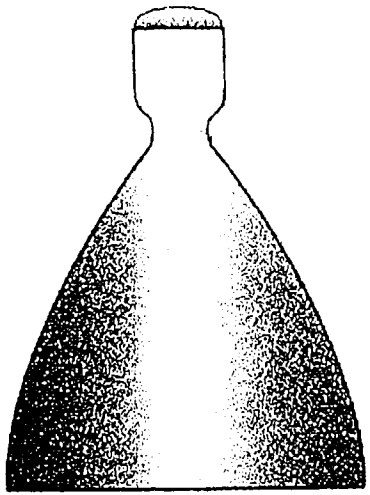
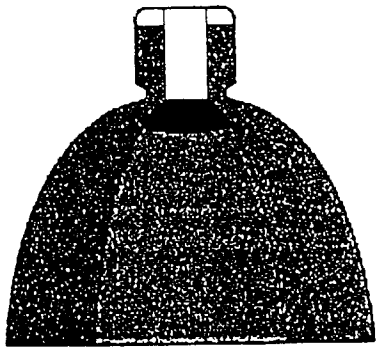
Aerospike One of Many Nozzle Shapes



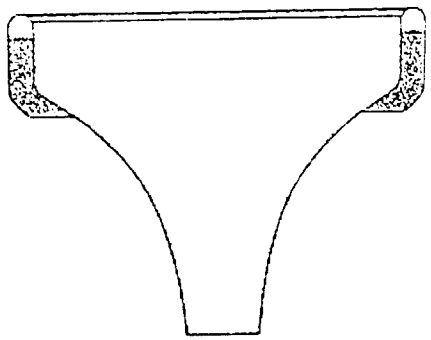
Cone



Bell



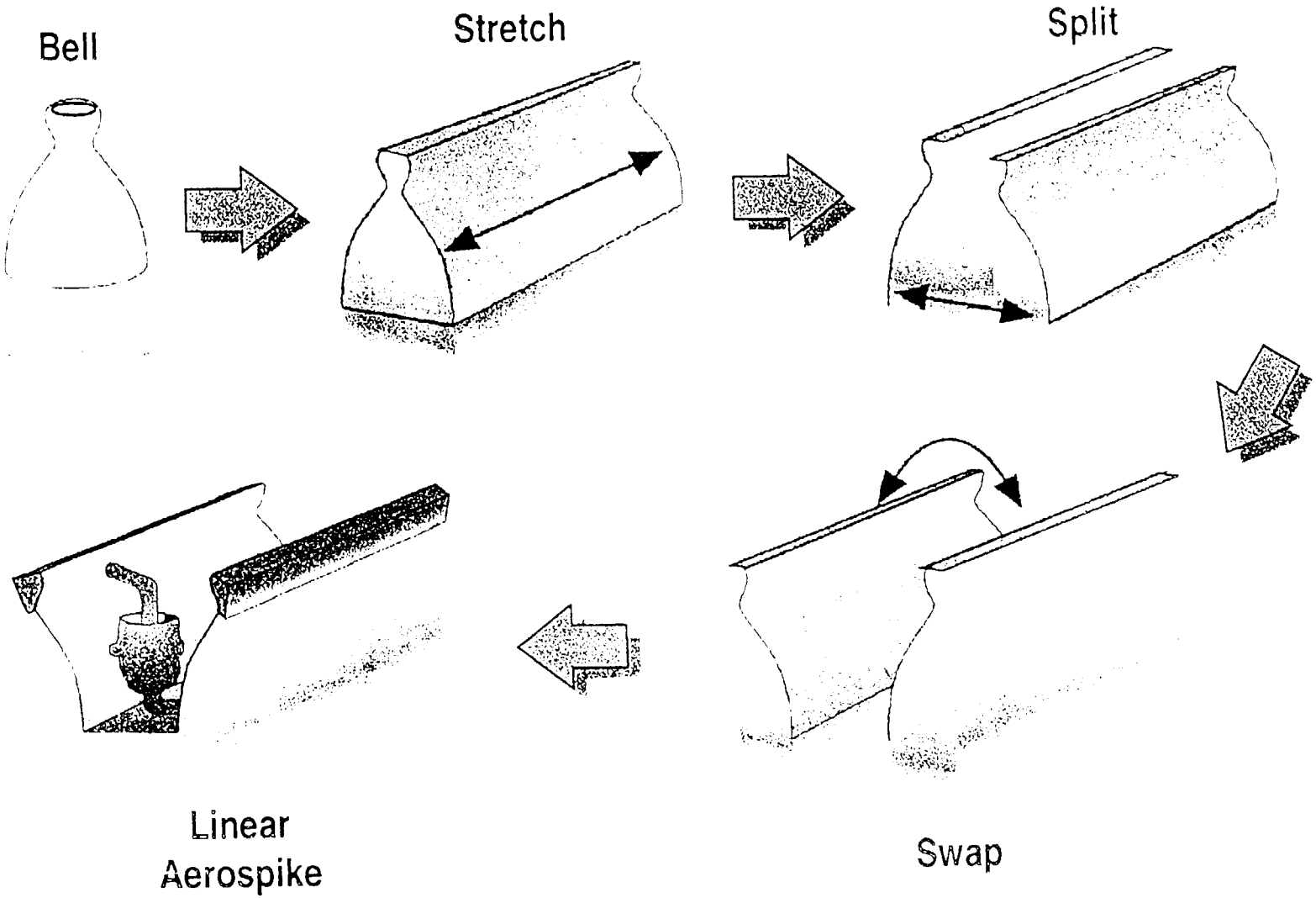
Expansion Deflection



Aerospike

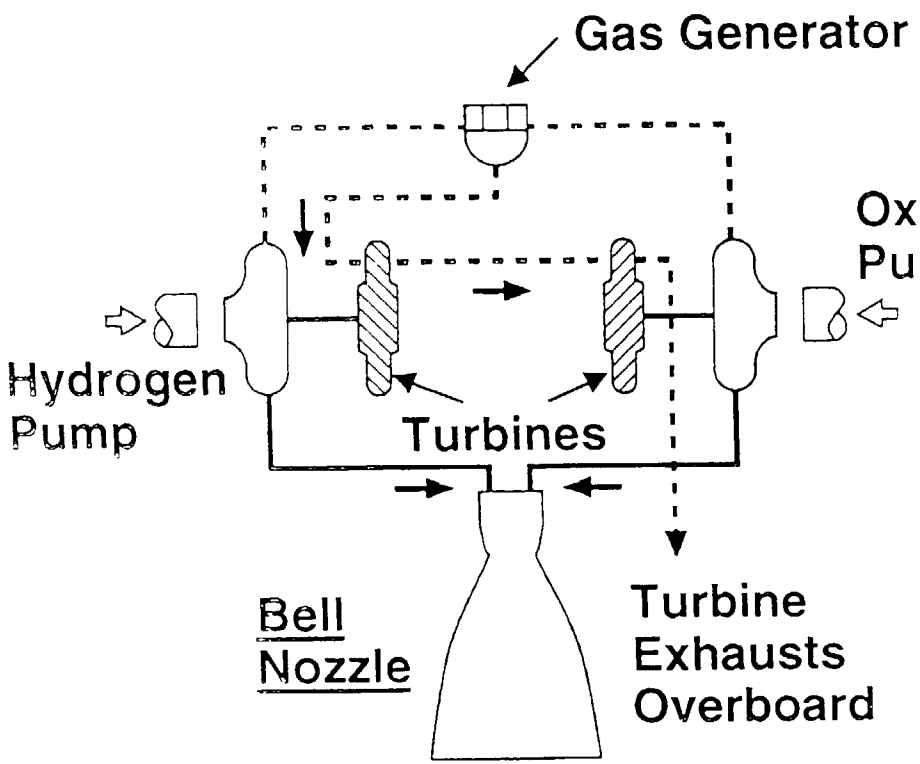
All four shapes produce the same thrust

What's a Linear Aerospike

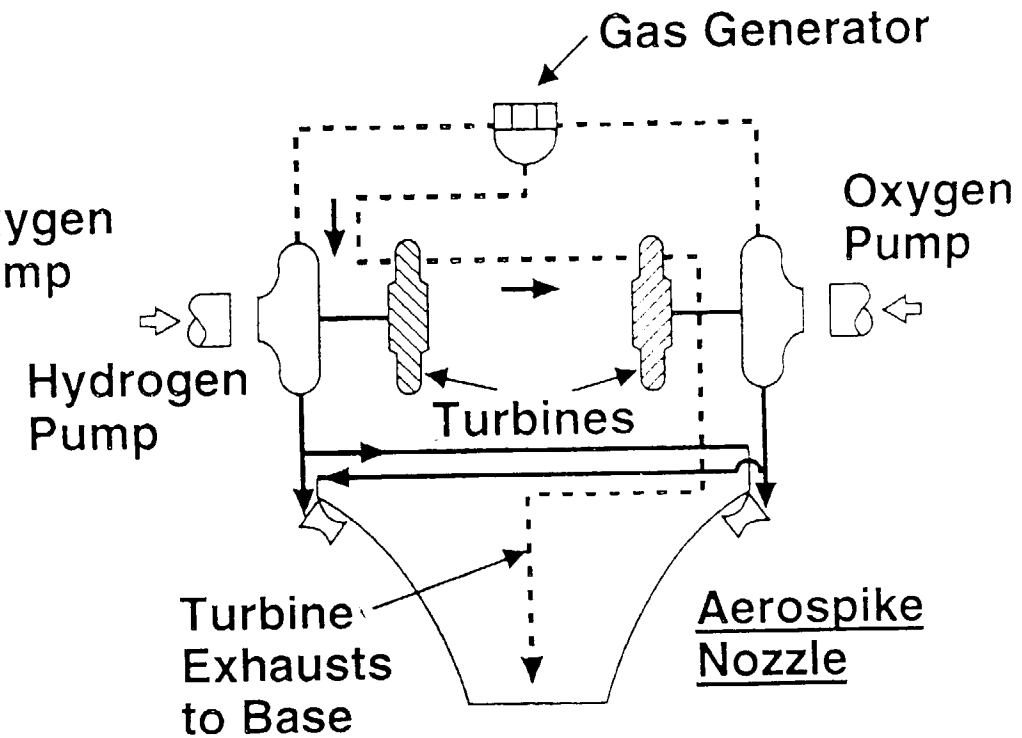


Bell Nozzle vs Aerospike

Gas Generator Cycle Bell

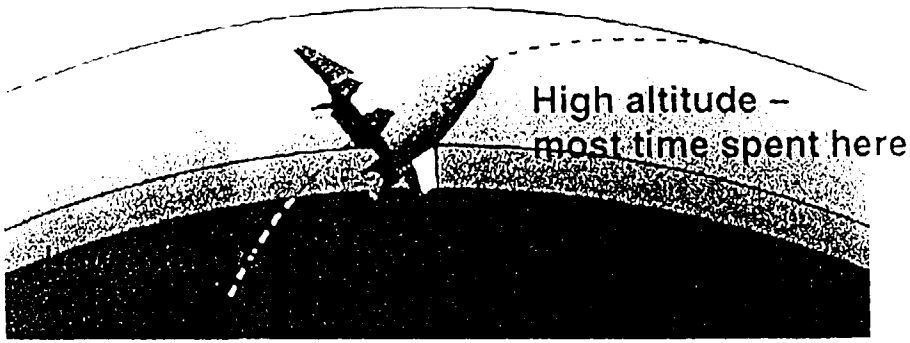


Gas Generator Cycle Aerospike

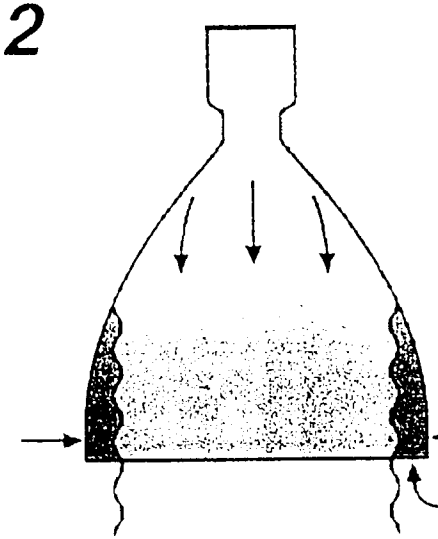


SSTO Demands on Propulsion

1 High altitude performance drives engine requirements – prefer a large area ratio nozzle



2



Large area ratio nozzles at sea level cause flow separation, performance losses, high nozzle structural loads

High Loads

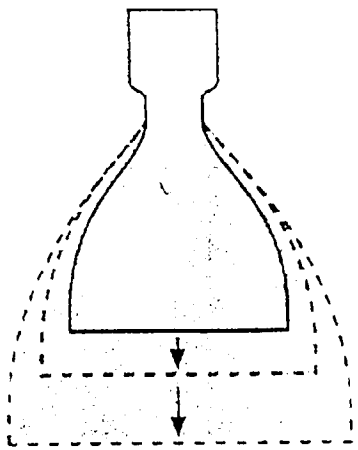
Pexit < P∞ ⟹ thrust loss

3

$$F \simeq \dot{m}V_{exit} + A_{exit}(P_{exit} - P_\infty)$$

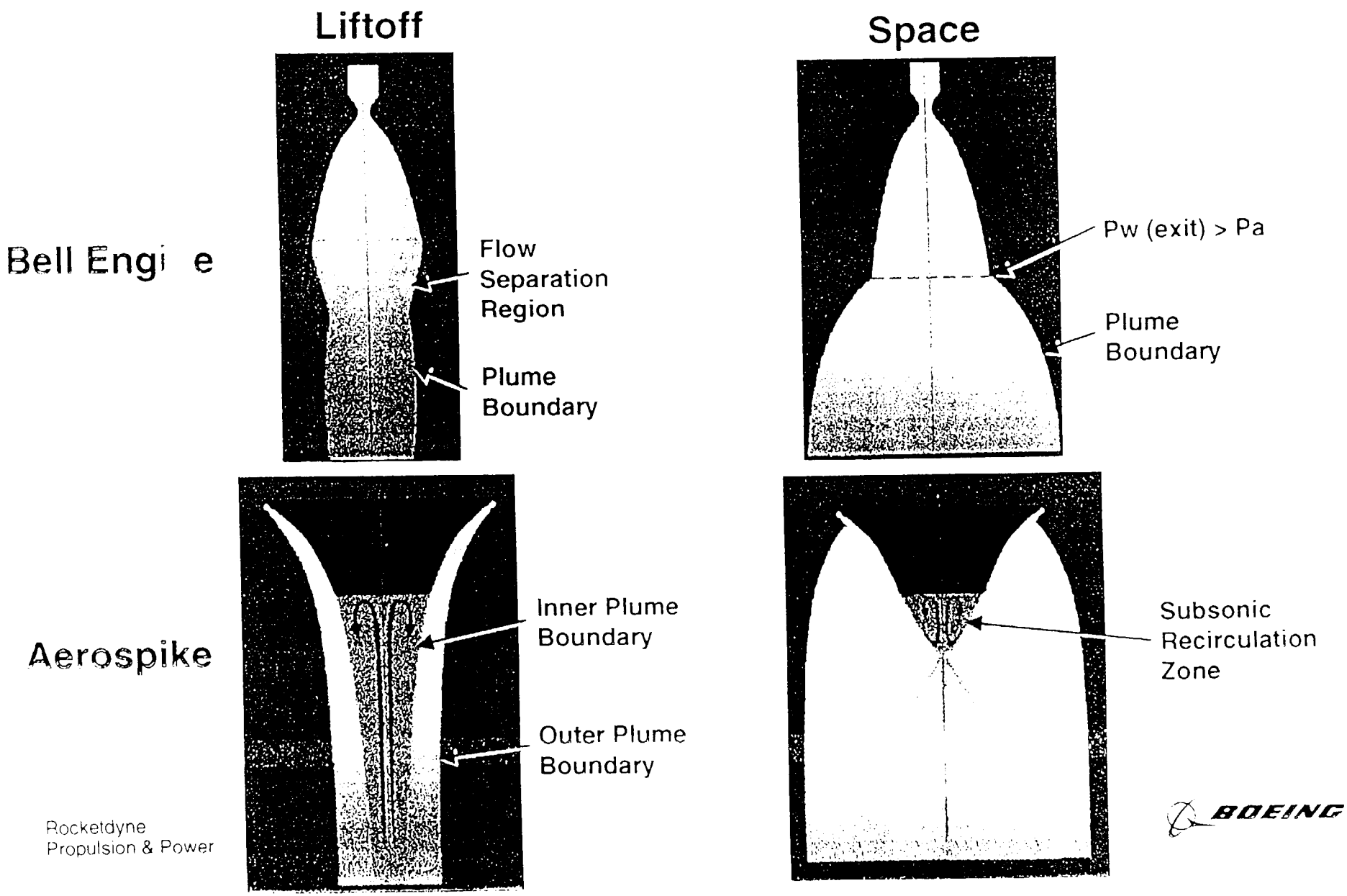
Optimum performance occurs when $P_{exit} = P_\infty$ at all altitudes

4



Variable nozzle required to get $P_{exit} = P_\infty$ at all altitudes, but design is not feasible

Aerospike Performance Advantage



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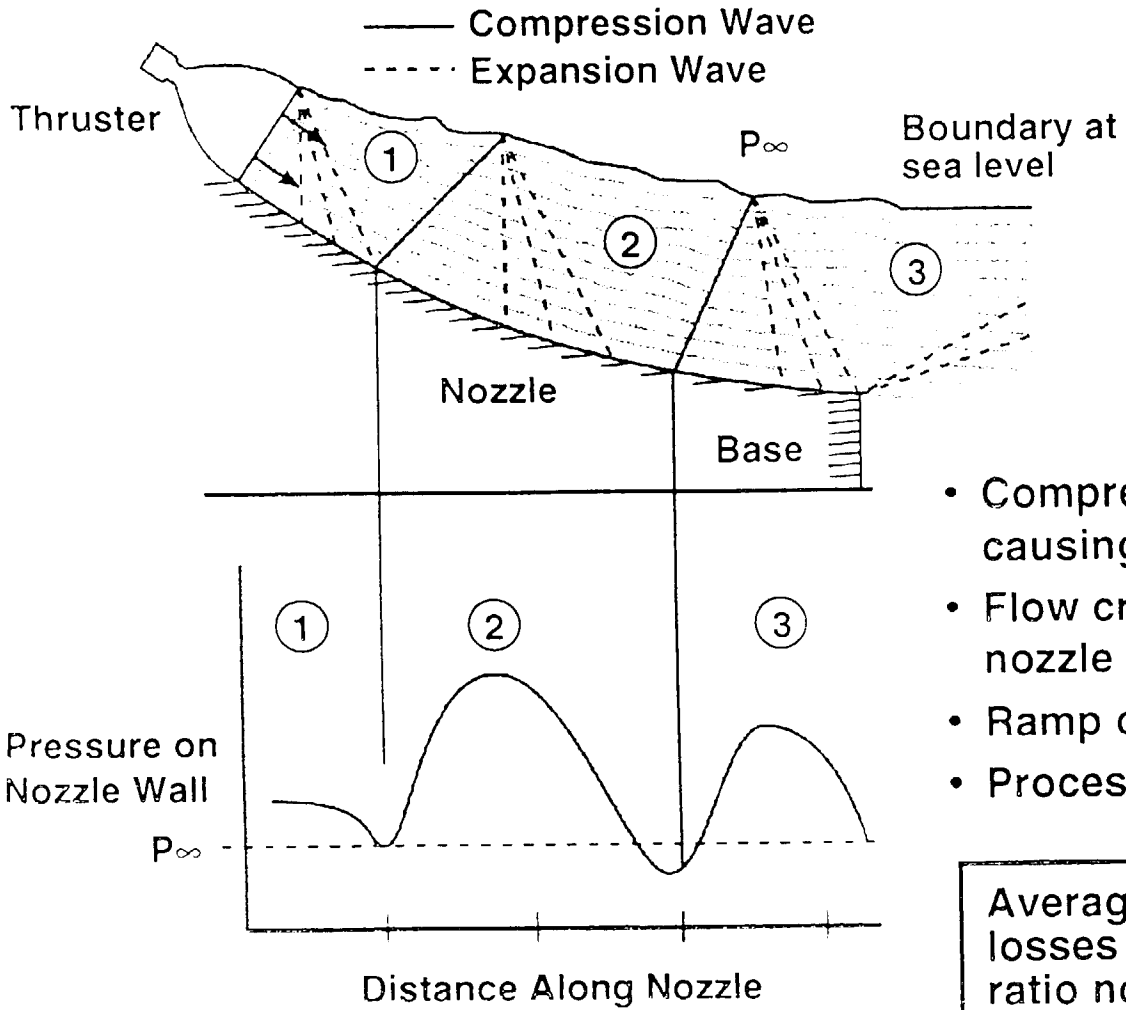
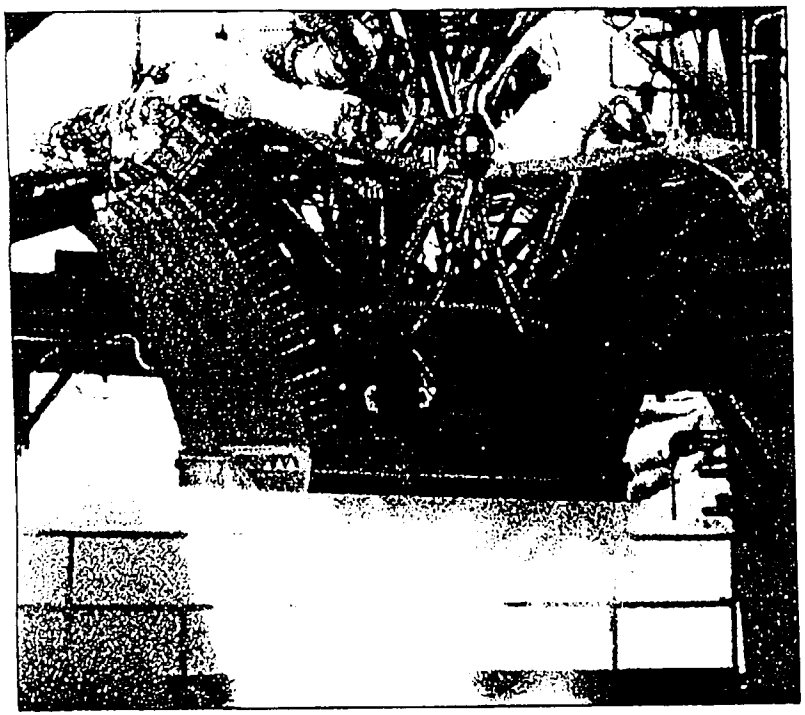
Aerospike Nozzles Avoid Bell Nozzle Problems



- Thruster flow discharges to ramp
- Expansion waves turn flow axially
- Ramp curves, turns flow axially (at low altitudes)
- Turning causes compression wave from (1) to (2) – nozzle pressure increases
- Compression wave reflects off boundary causing expansion waves
- Flow crosses expansion waves in (2) – nozzle pressure decreases
- Ramp continues to curve and turn flow
- Process repeats (2) to (3)

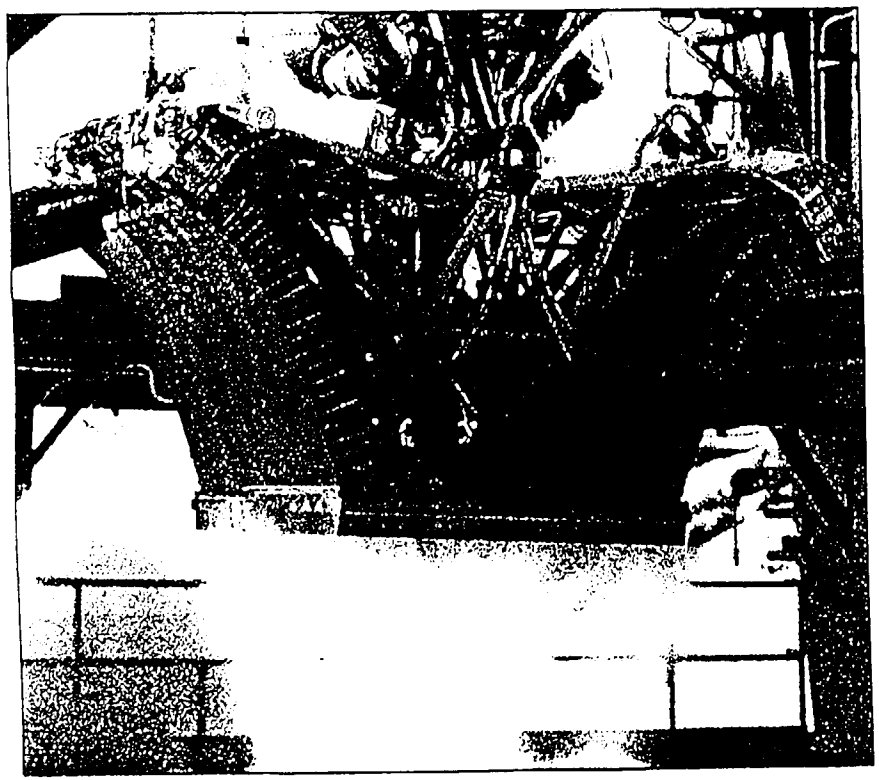
Average nozzle pressure >P∞, therefore no losses or separation, therefore large area ratio nozzle can be used, enabling SSTO

Aerospike Benefits



- Enables smallest, lowest cost vehicle
  - Smallest thrust take-out structure
  - No gimbal joints or actuators
- High installed performance
  - Altitude compensating
  - Lowers vehicle base drag
- Lowest development risk
  - Lowest risk cycle - gas generator
  - Parallel component development

Linear Aerospike Heritage



Two Linear Aerospike Engine testbeds built & testing in early 1970's

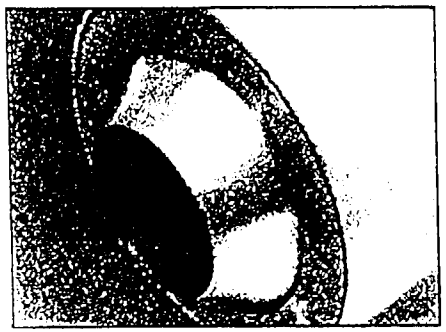
Testbed #1

- 44 starts
- 3,113 seconds

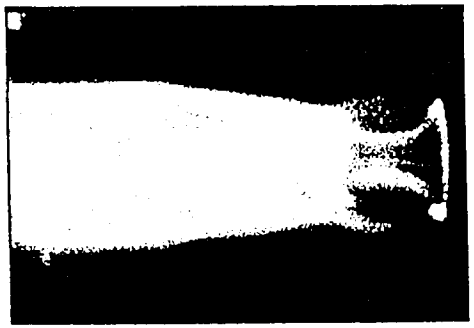
Testbed #2

- 29 starts
- 1,200 seconds
- Gimballing demonstration

Over $500M Invested in Aerospike

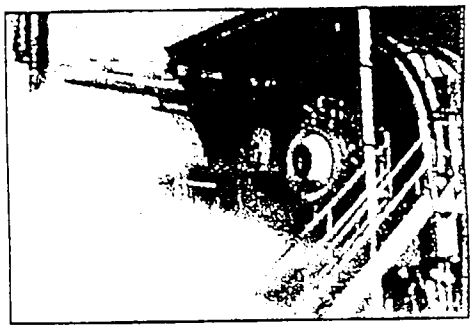


H2O2 (0.4K)
43 Tests at AEDC

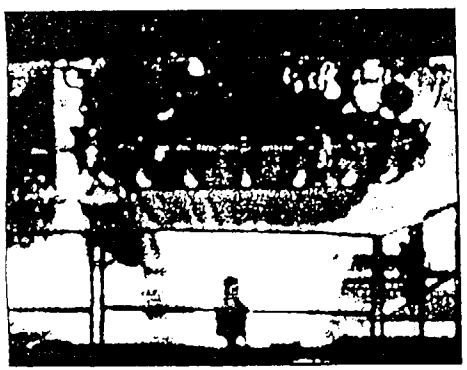


O2/RP-1 (8K)
9 Tests at PRA

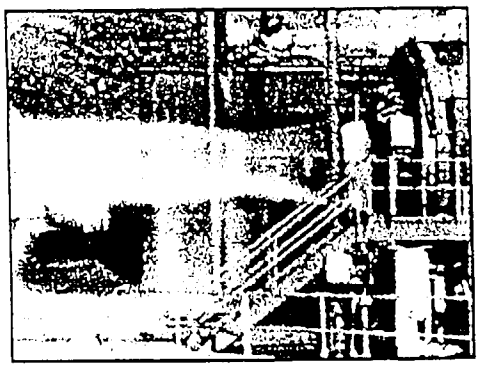
N2O2/50-50 (10K)
61 Tests at AEDC



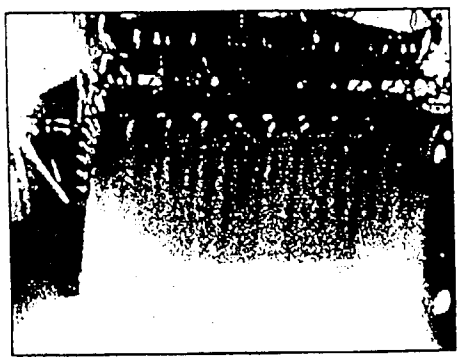
O2/H2 (40K)
24 Tests at NFL



O2/H2 (250K)
15 Tests at SSFL



O2/H2 (250K)
48 Tests at NFL



O2/H2 (250K)
44 Tests at SSFL

O2/H2 Linear (125K) Gimbaled
29 Tests at SSFL

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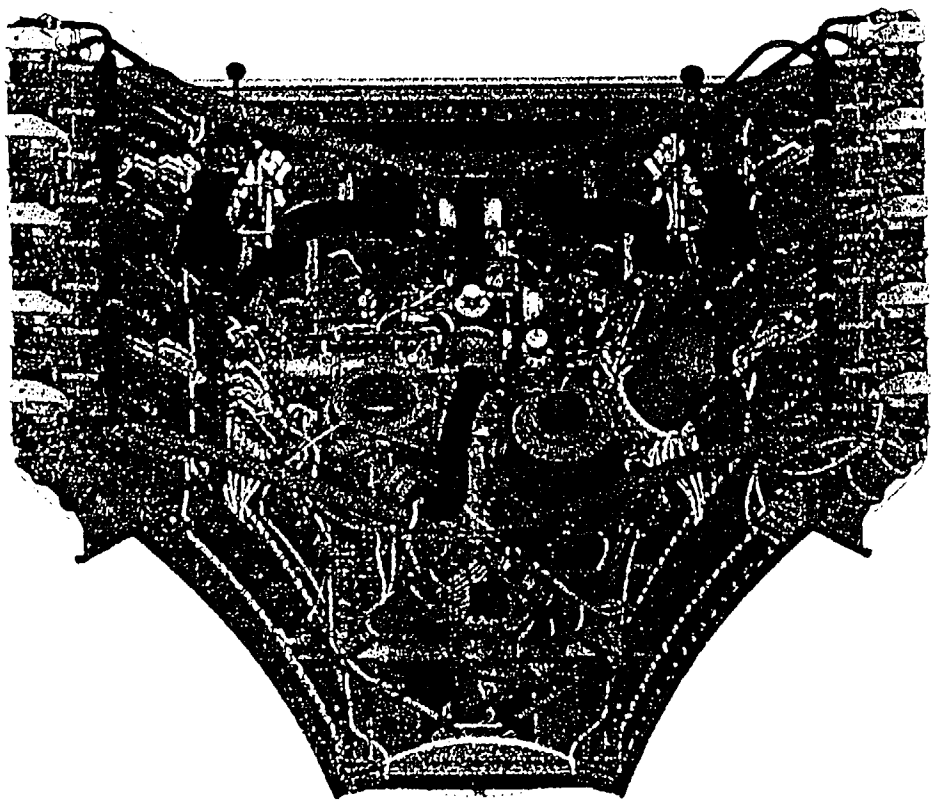
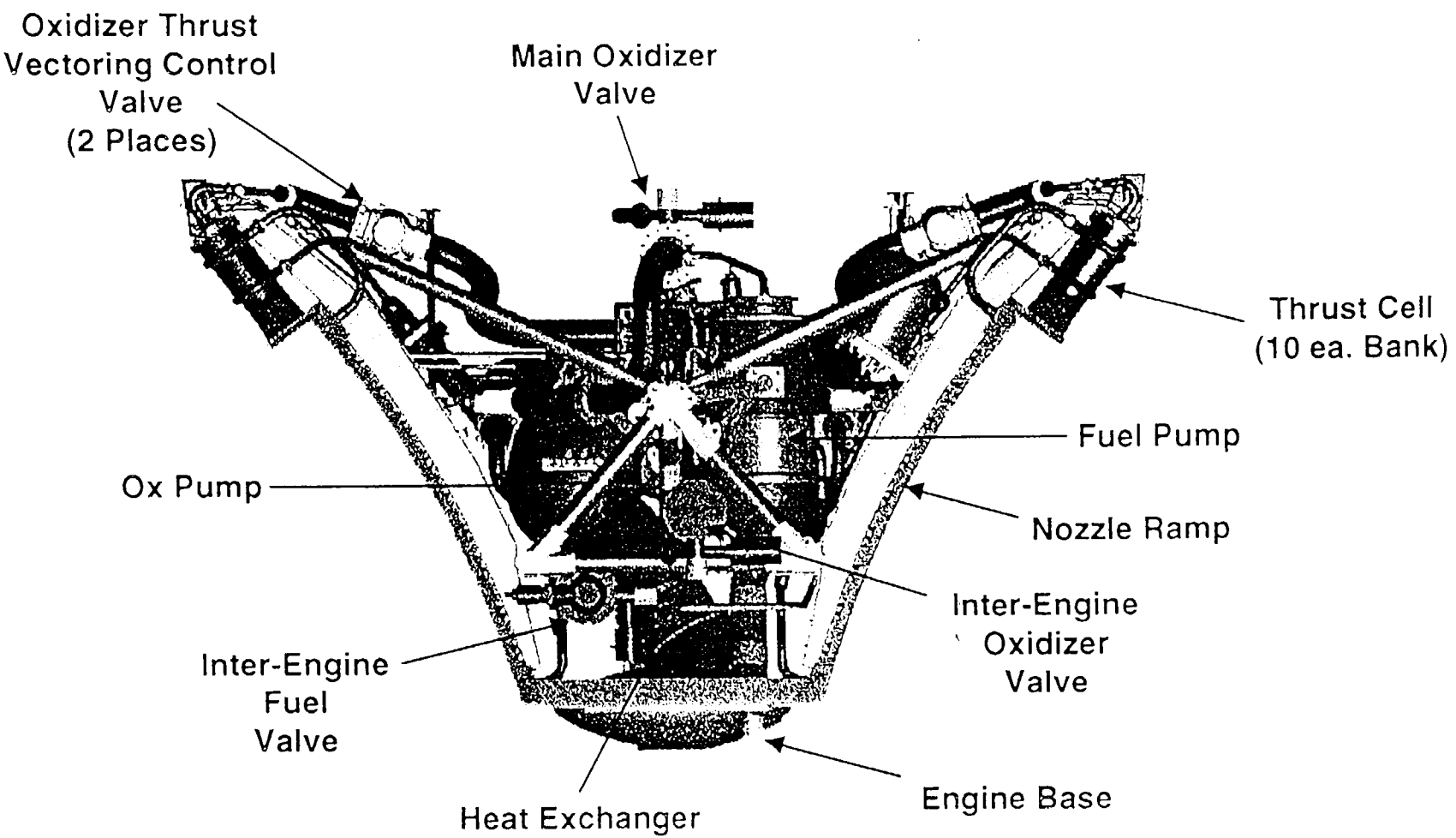
X-33 Linear Aerospike

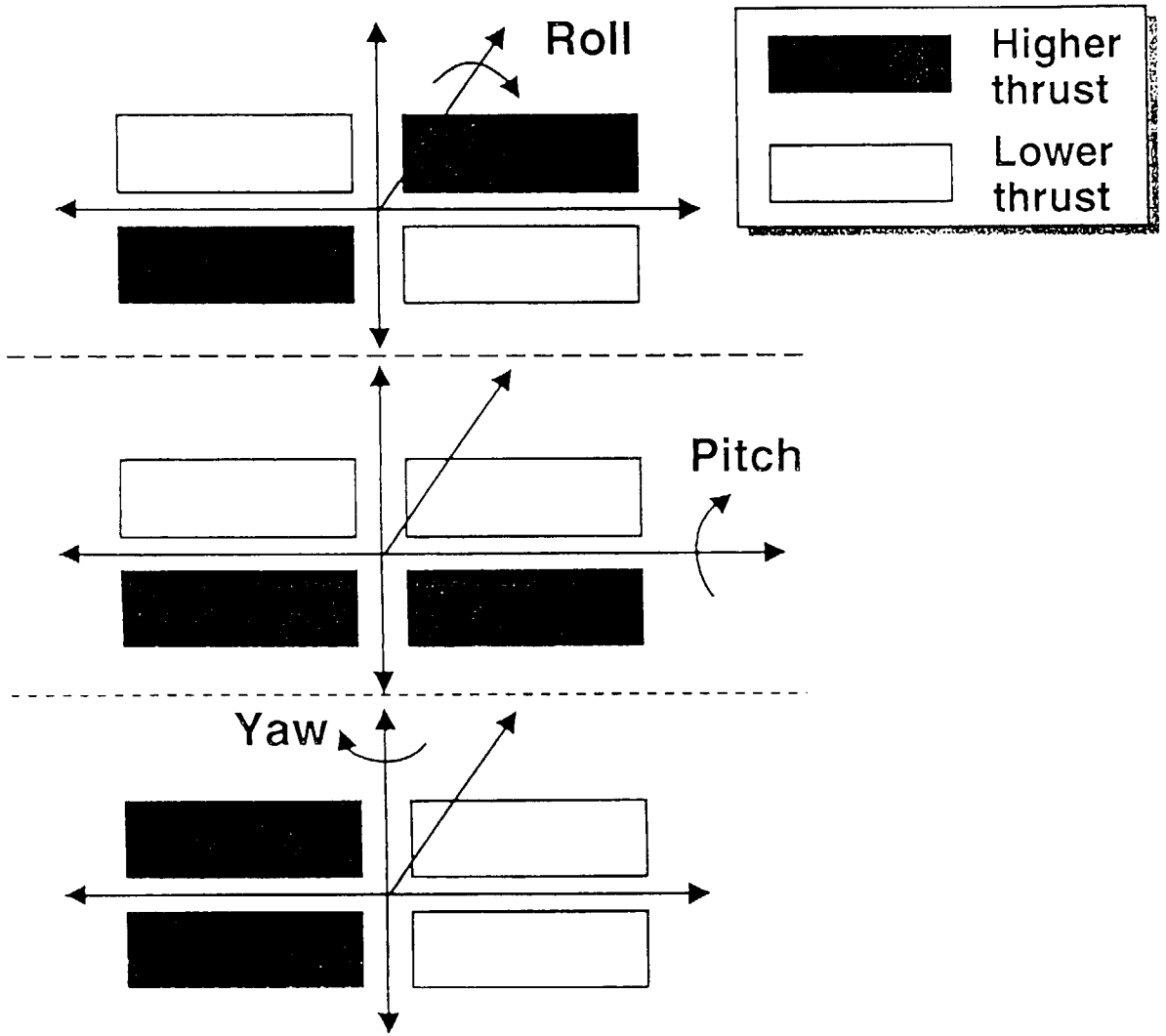


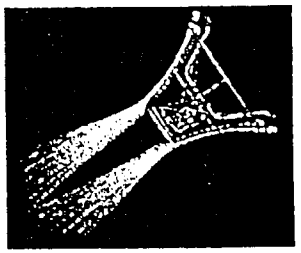
F, sea level/vacuum, Klbf.	206.2/266
Isp, sea level/vacuum, sec.	340/429
Chamber pressure, psia.	854
Area ratio	58
Thrust cells	20
Propellants	Ox/hydrogen
Mixture ratio, o/h	5.5
Cycle	Gas generator
Throttling, % thrust	57 - 102
Thrust/weight	35
Dimensions,	inches
Forward end	133w x 88ℓ
Aft end	46w x 88ℓ
Forward to aft	79

X-33 Engine Major Components

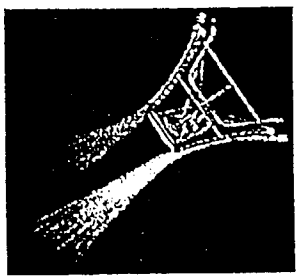


X-33 Two Engine Thrust Vector Control

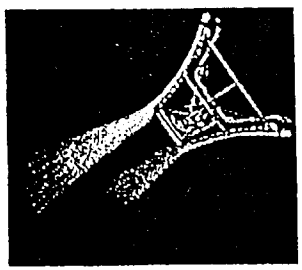




Level Flight



Pitch Up



Pitch Down

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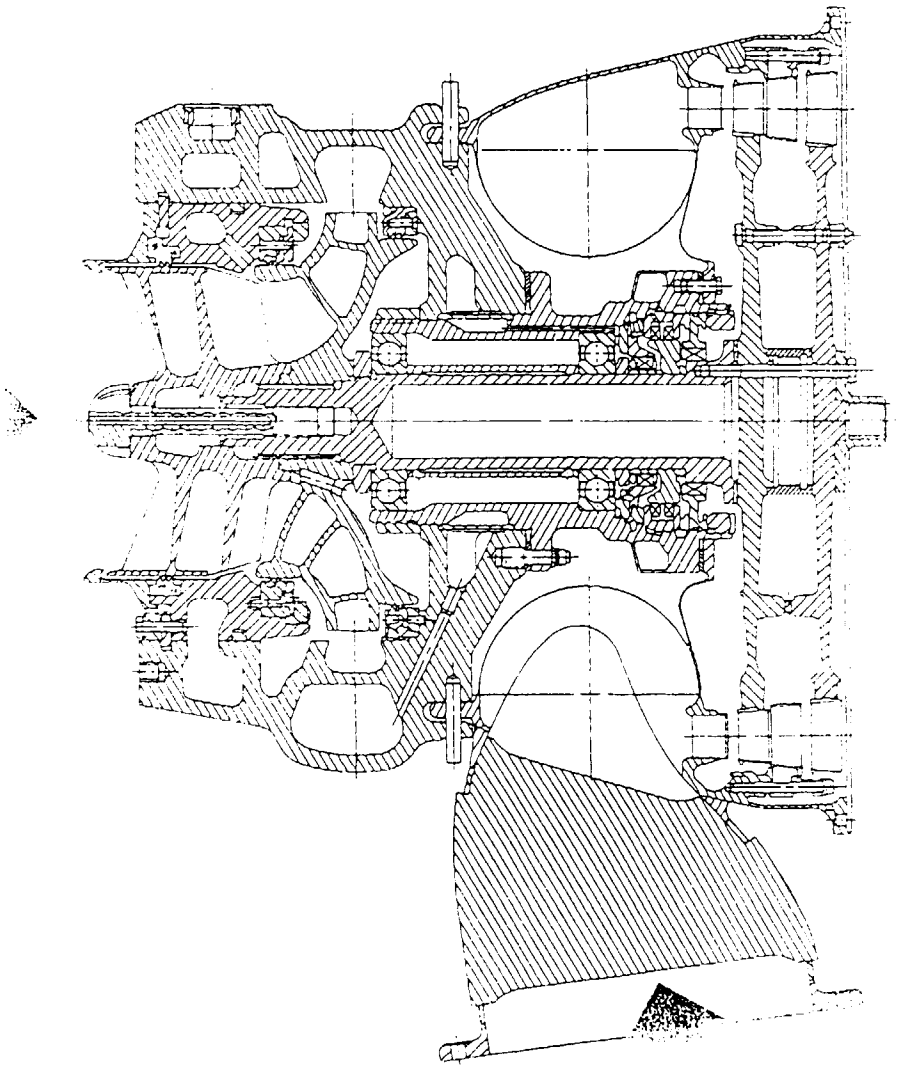
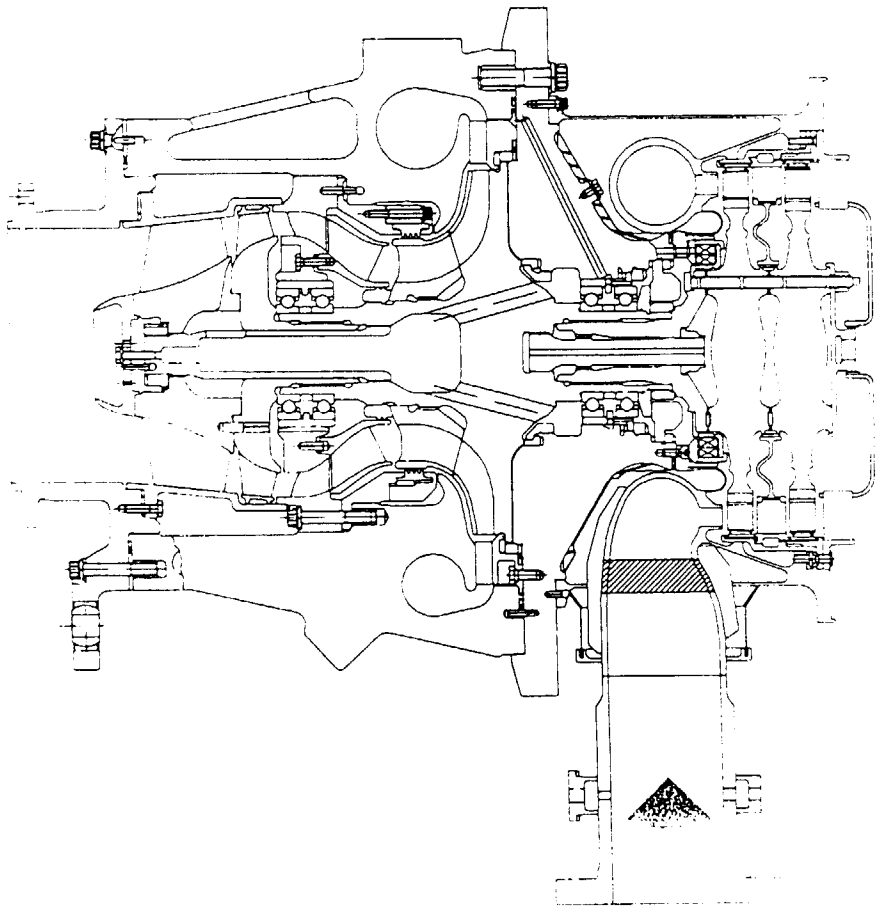
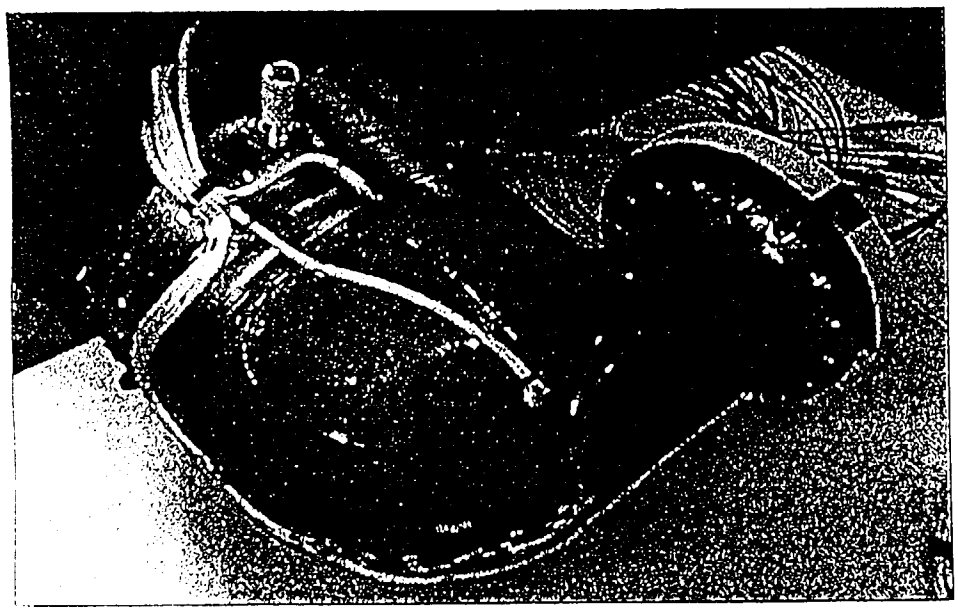
X-33 LOX Turbopump

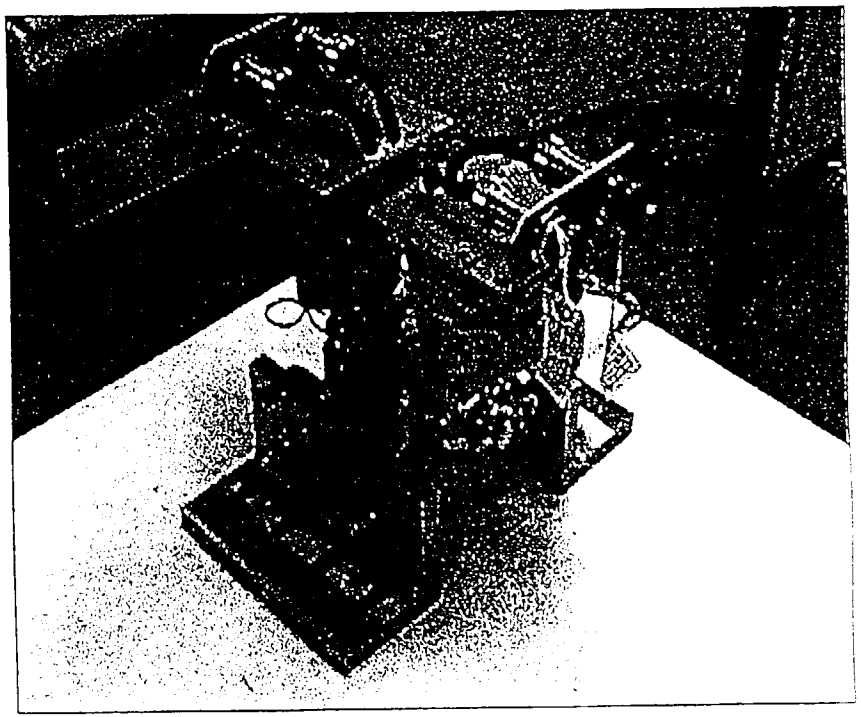


X-33 Fuel Turbopump

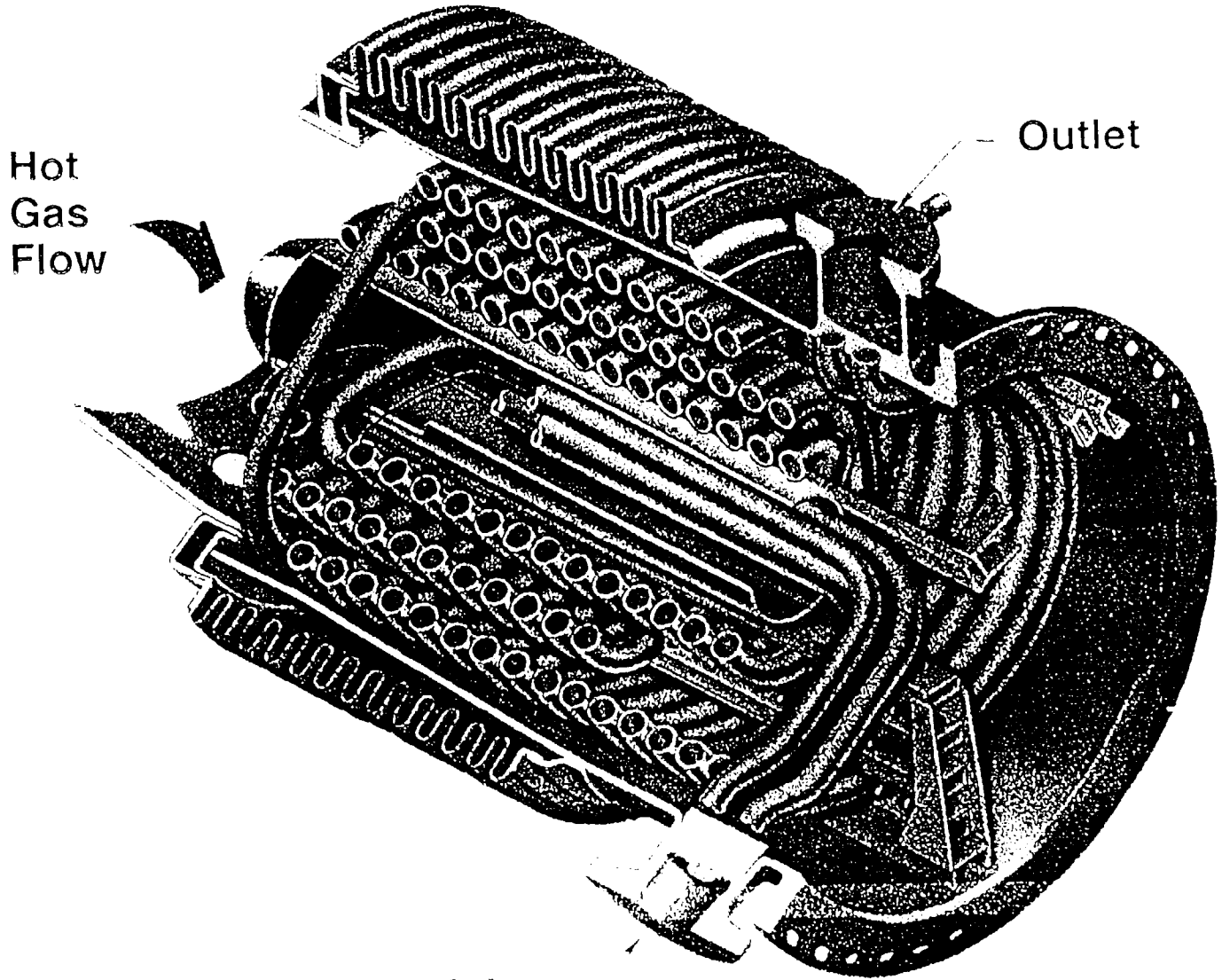


X-33 Gas Generator

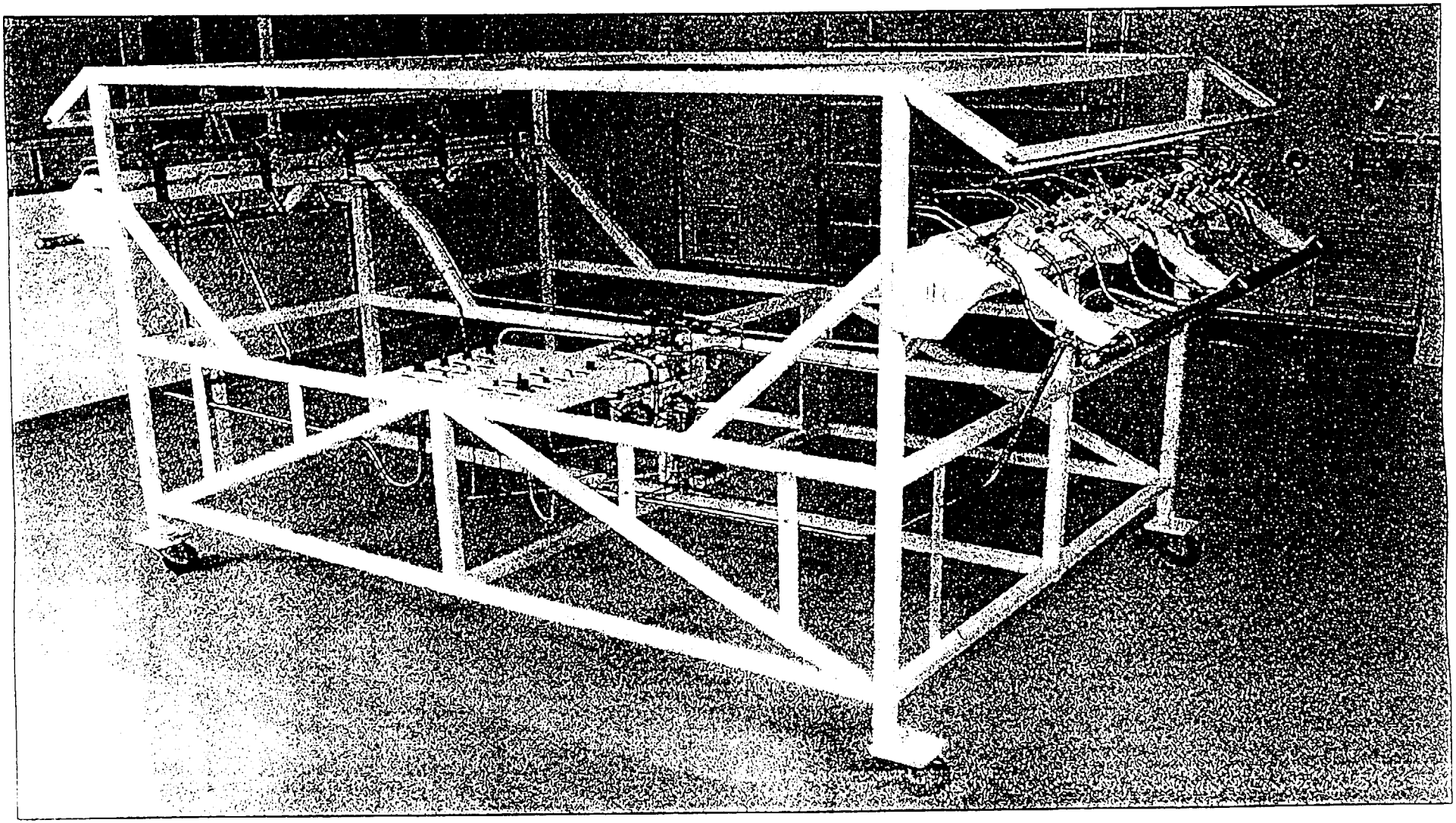




X-33 Heat Exchanger



Combustion Wave Ignition Spider Rig



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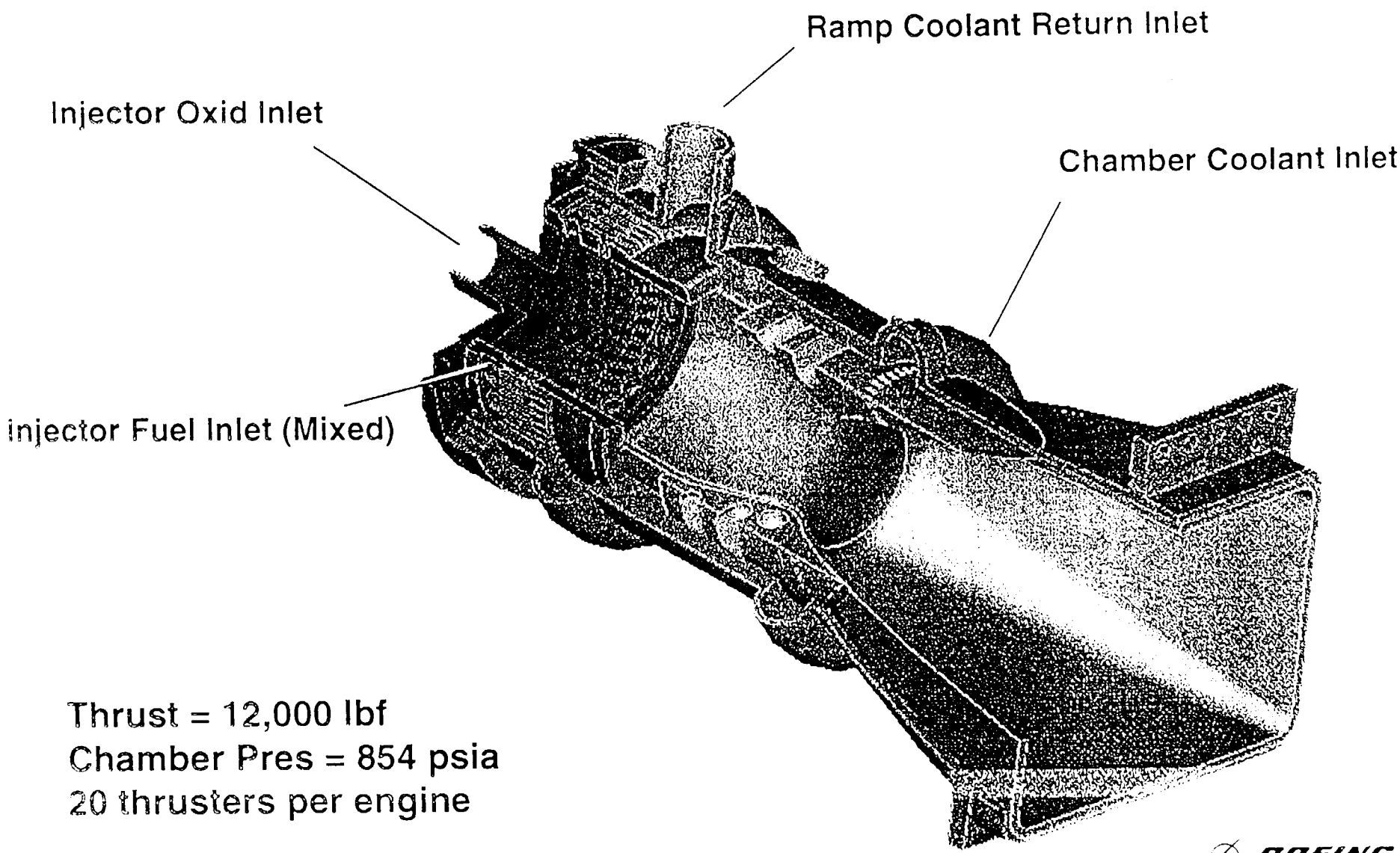
X-33 Leverages Universal MCC Technology



Thrust = 12,000 lbf
Chamber Pres = 854 psia
20 thrusters per engine

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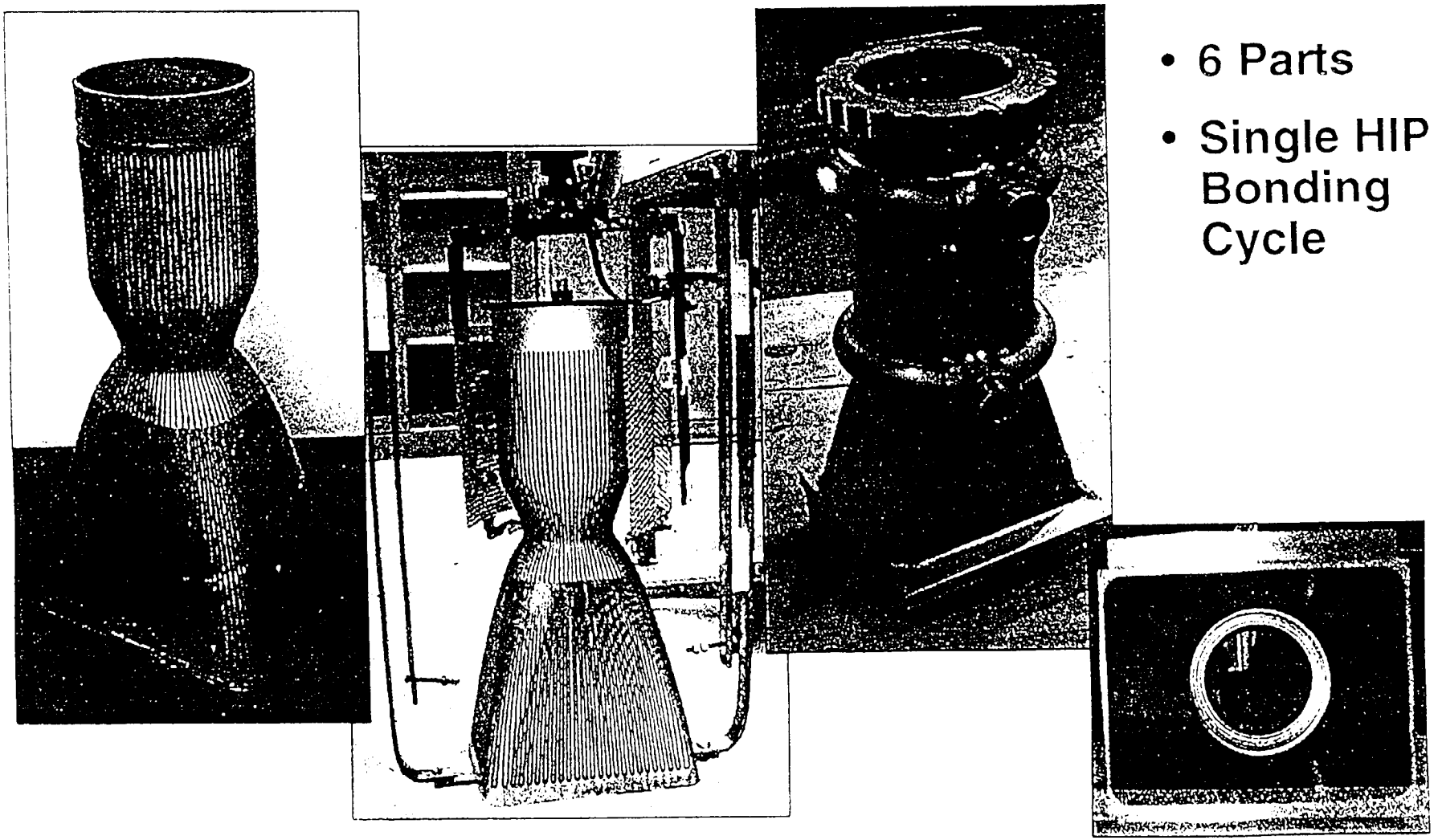
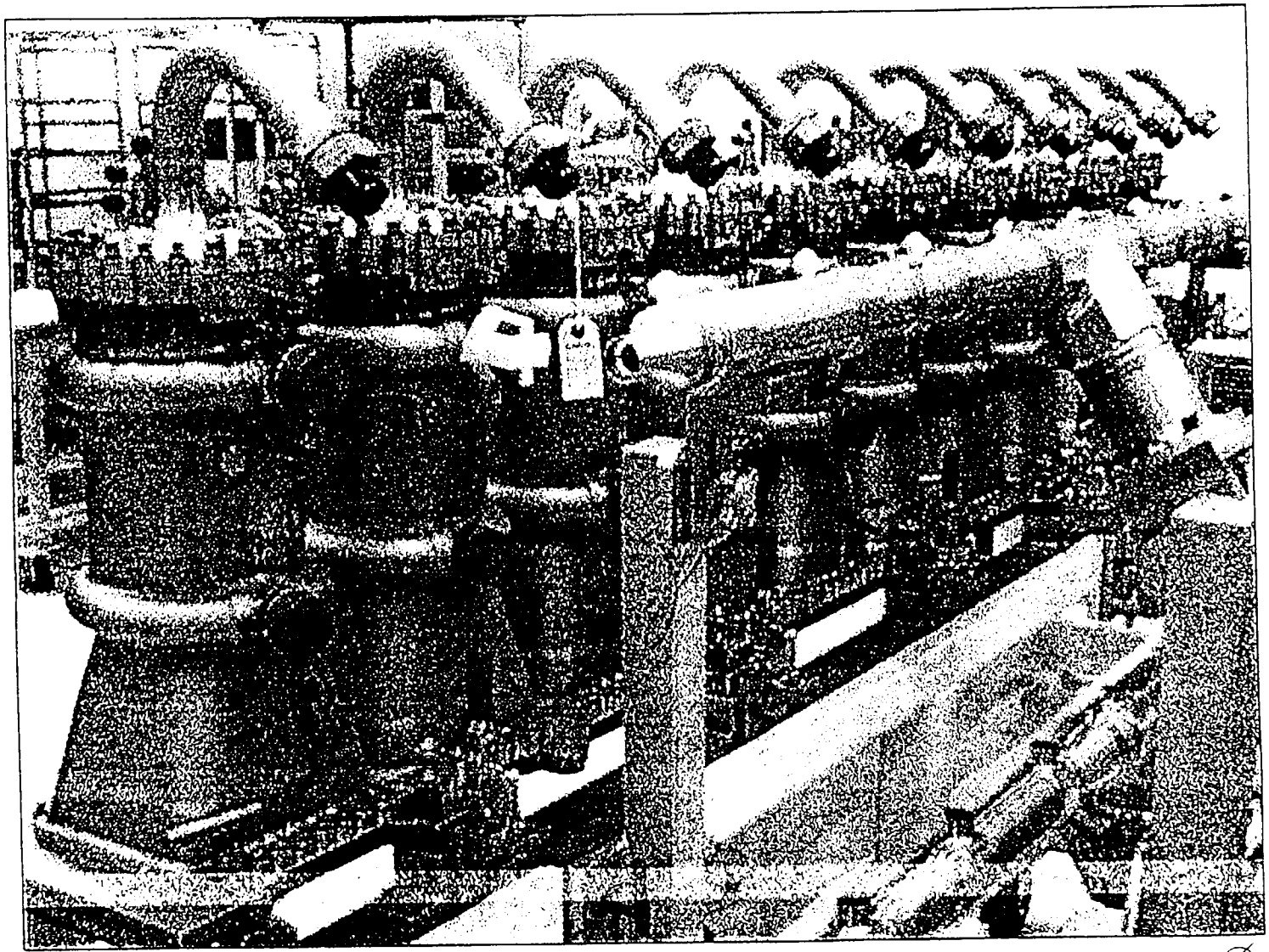
X-33 Aerospike Thrust Cell



- 6 Parts
- Single HIP Bonding Cycle

First X-33 Thruster Array



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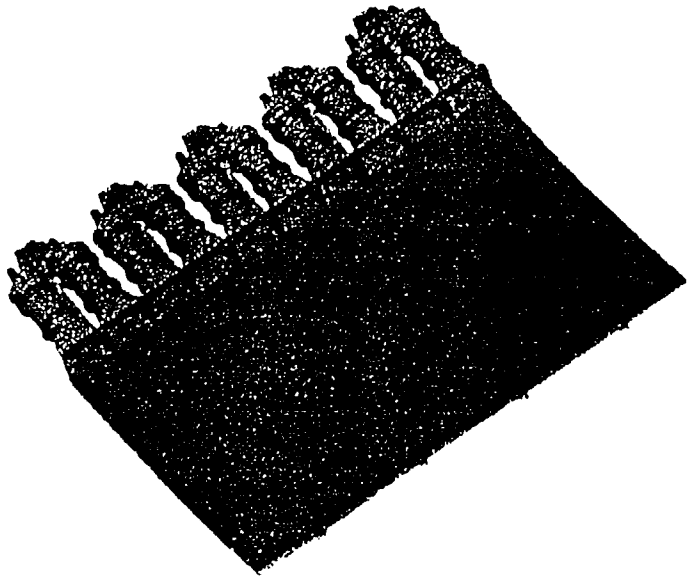
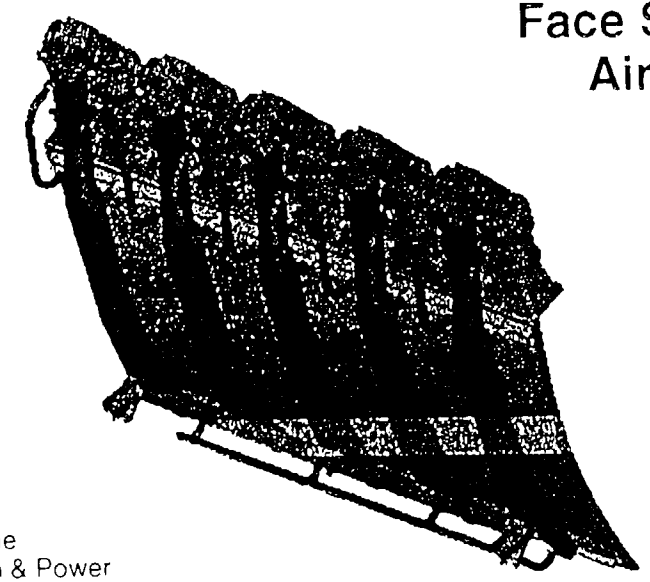
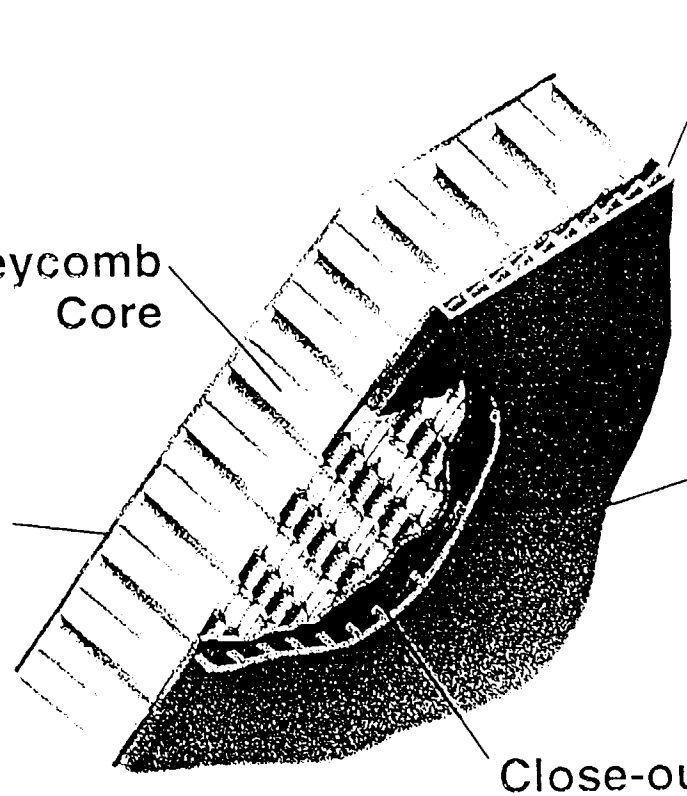
Thrust Ramp Design







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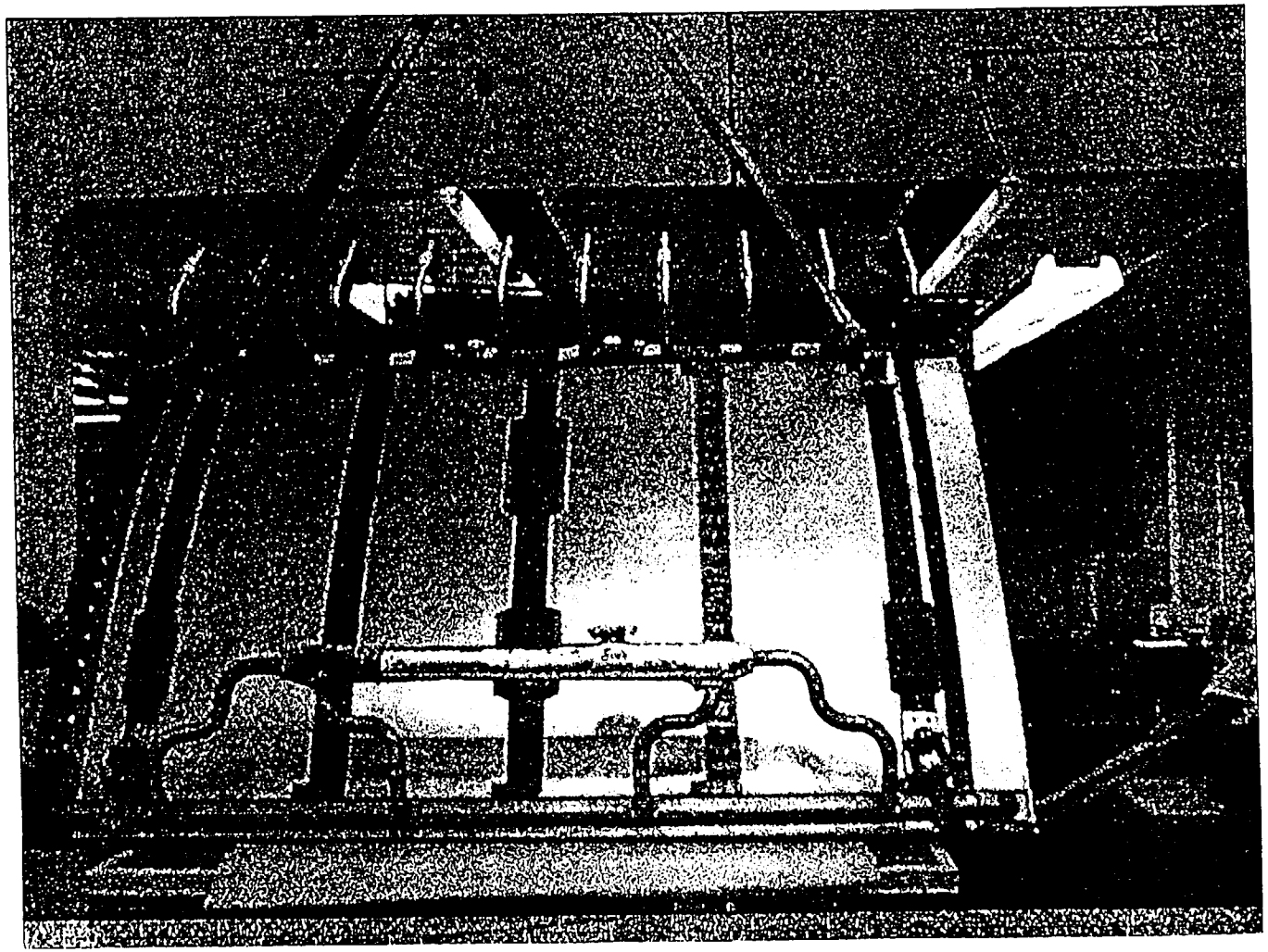
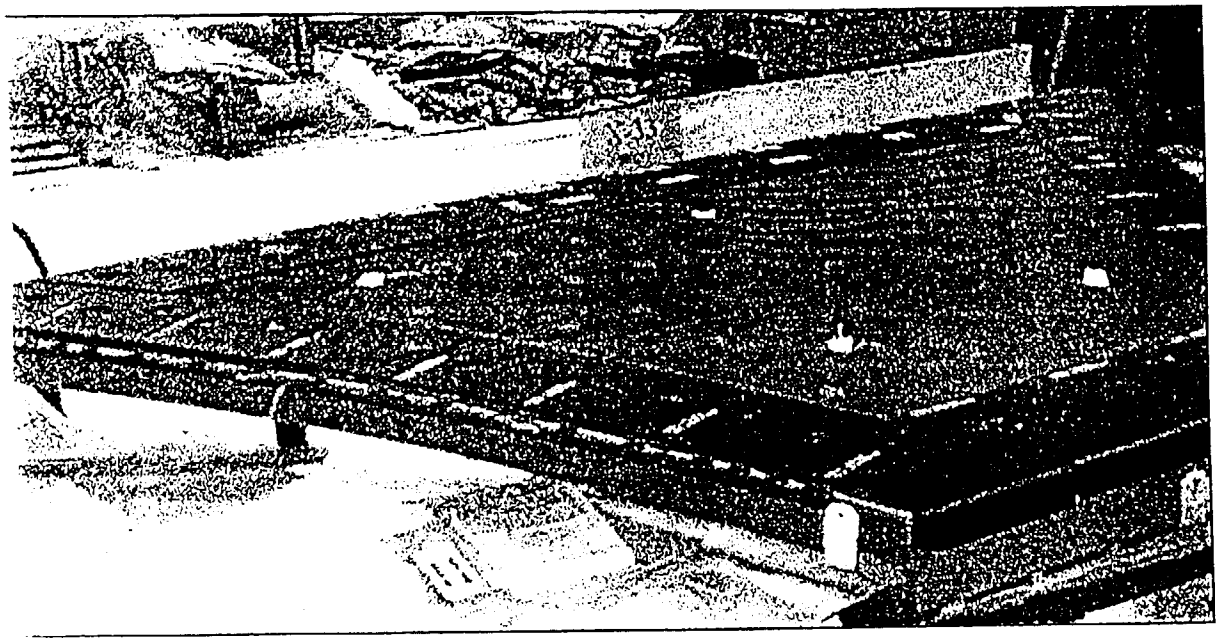
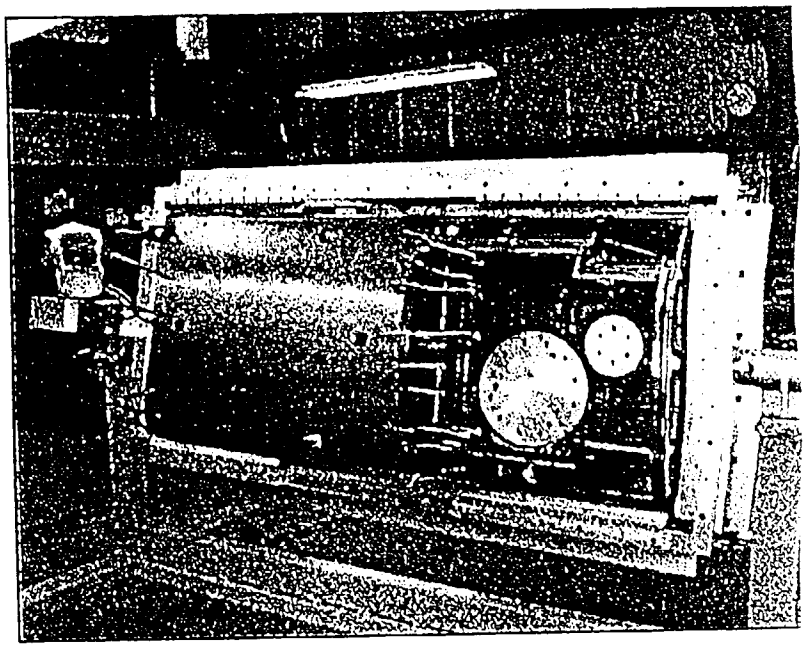
X-33 Thrust Ramp - Final Assembly

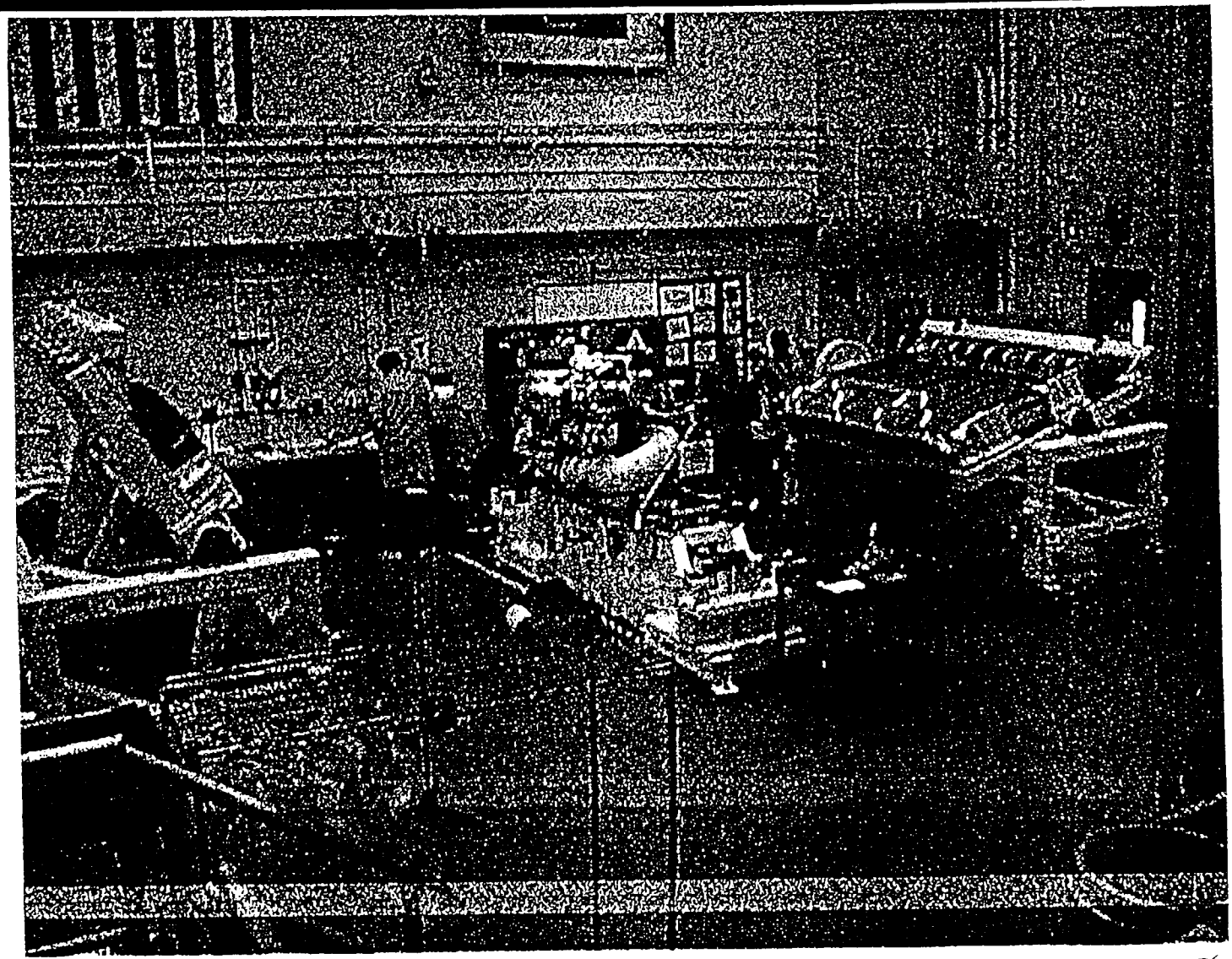


Base & EECO Hardware





X-33 Engine Assembly



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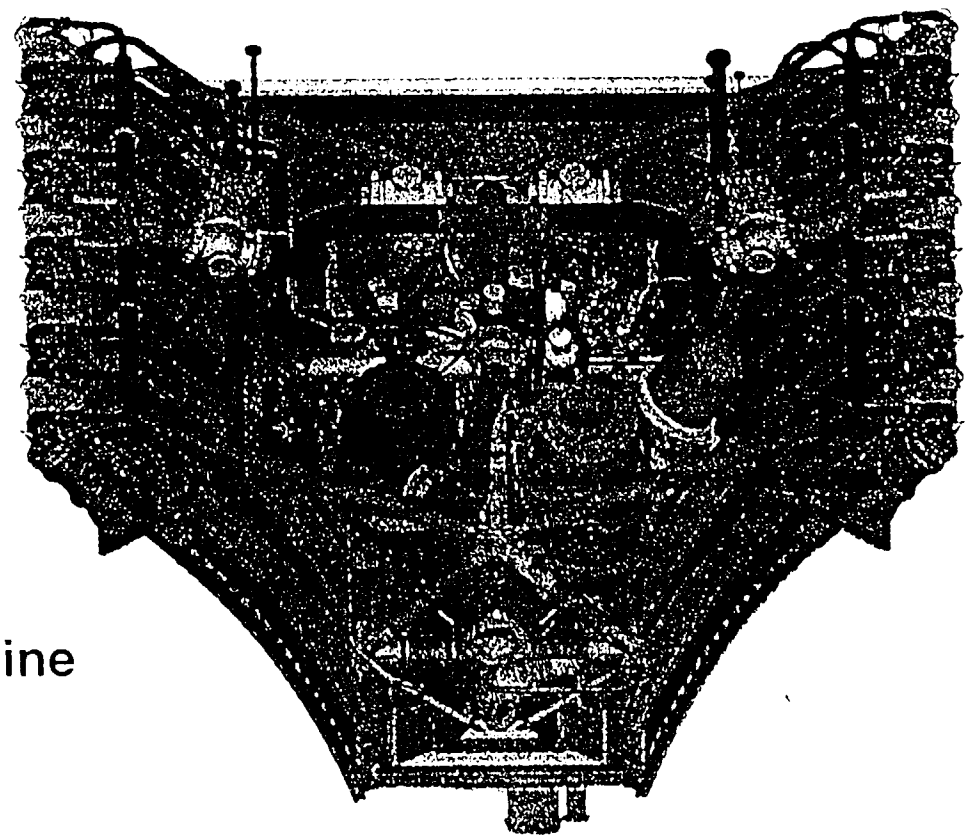
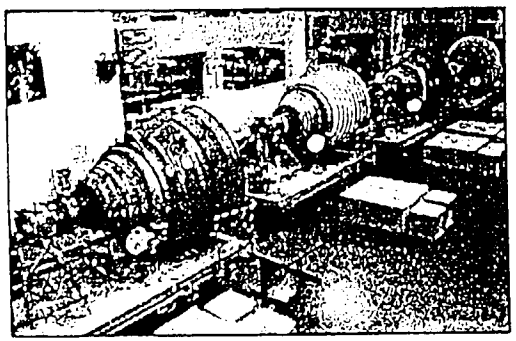
Most Significant Design Challenges

- Thermal Load Management
- Distribution of Thrust Loads

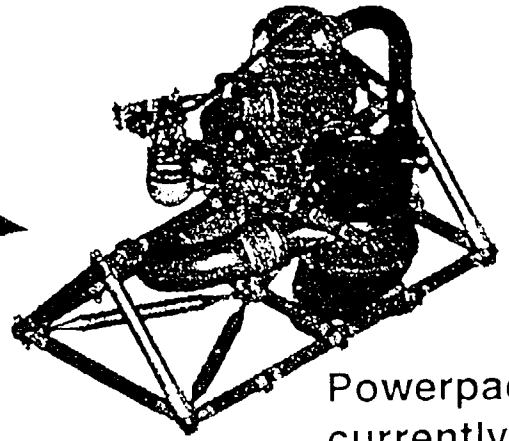


- Engine to engine interaction
- Packaging

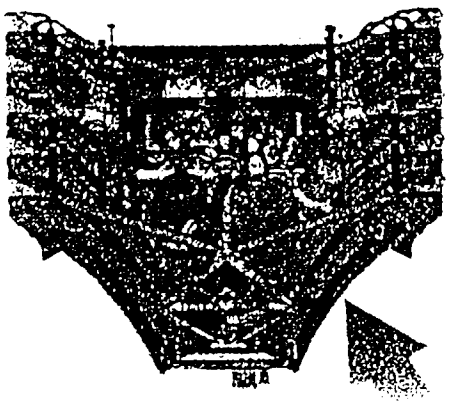
X-33 Engine Development



Apollo 18
J2 engine
powerpack
hardware
recycled

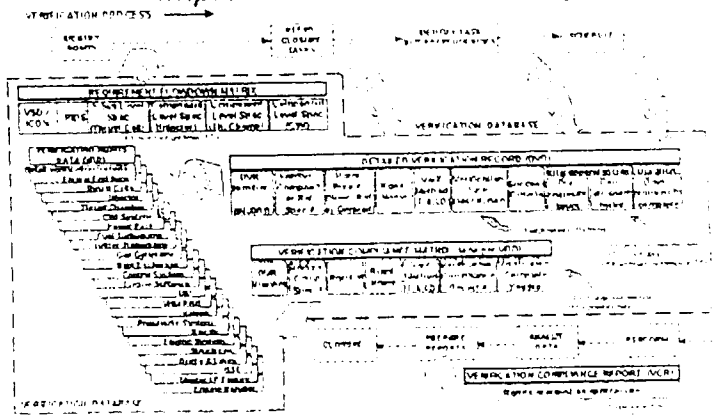


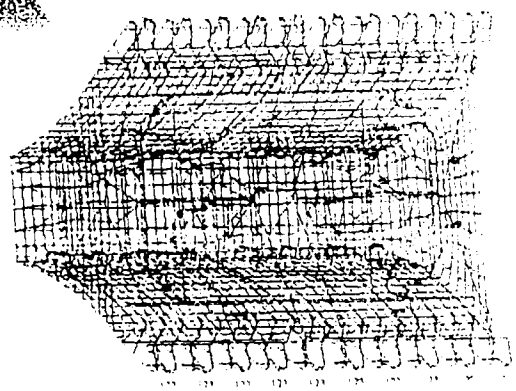
Powerpack #1
currently in test
at SSC



PRO-E design model
> 2 Gigabytes

XRS-2200 Verification
Implementation Methodology





- Structural analysis using Stardyne & ANSYS

- Component & subsystem margin tests
- 4 Engine to be tested

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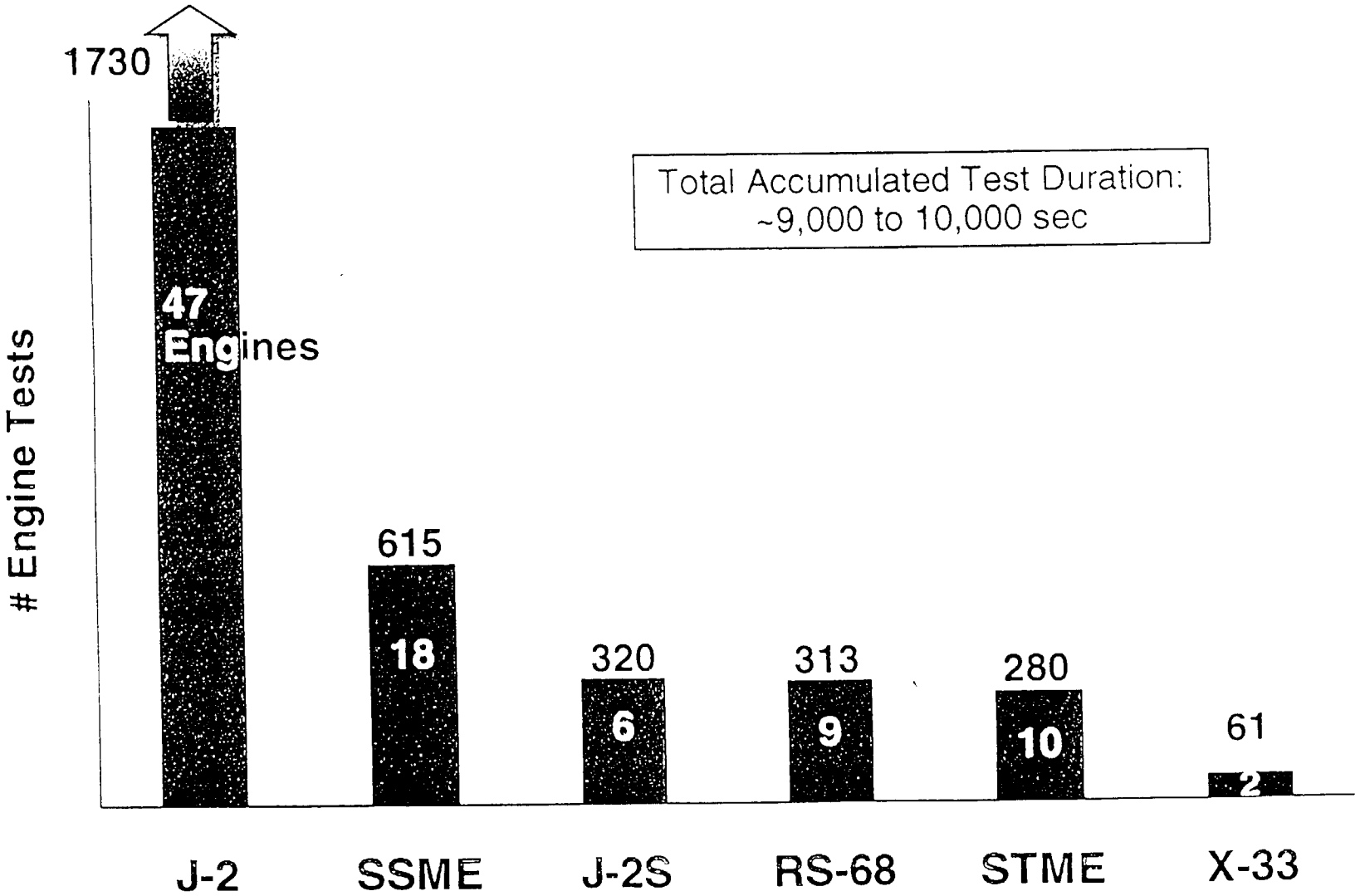
Test-to-Verify Development Goal



Total Accumulated Test Duration:
~9,000 to 10,000 sec

X-33 Powerpack Test

Test Unit	Test Start	Test End	No. Tests	Engine Cutoffs	Total Seconds
PPA 001	9/98	1/99	9	1	639.5
PPA 002	2/99	3/99	6	1	656.2
PPA 003	3/99	4/99	3	0	210.3
		Total	18	2	1506.0

Summary

- Aerospike rocket engine technology meets performance & integration needs for X-33/RLV
- Unique design & operational requirements demand high performance design, analysis & manufacturing tools
- Cost & schedule constraints demand high performance work teams & business management tools