Reusability And Hydrocarbon Rocket Engines
Relevant US Industry Experience

Aerojet Perspective

Presented To The

National Research Council

Aeronautics And Space Engineering Board

16 February 2012

Jim Long

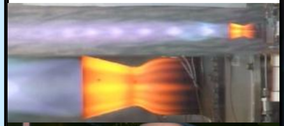
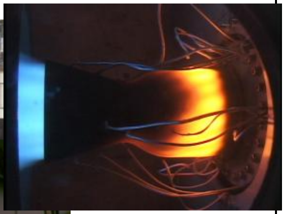
Hydrocarbon Rocket Engines

- **Purpose / Scope**
  - **Provide An Overview Of Aerojet Relevant Experience – ORSC Focus**
  - **Focus Is On HC Engines For RBS**
  - **Elected NOT To Share Technical / Future Plan Details Openly – ITAR, Competition**

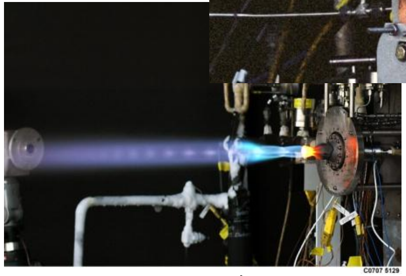
- **HC Experience Summary**
  - **Titan 1**
  - **HC Boost Technology Demonstrator (HBTD)**
  - **N1 (NK 33) – Russian Experience**
  - **Aerojet Experience**
    - **Kistler**
    - **Antares**

Aerojet Has Nearly 50 Years Of Experience With Hydrocarbon Propellants

	Ethanol	Methane	Kerosene
1960 1970 1980		• Characterization as a Coolant • 40 klbf Injector • GOX/GCH4 Igniter • Igniter • Preburners, Gas Generators • Thruster	• Titan I • High Density Fuel LOX/RP-1 Igniter • 40K LOX/RP-1 • Fuel-Rich Preburner • Carbon Deposition
	GOX/HC Ignition Investigation		
			• Pressure Fed LOX/RP-1 Injector (NASA)
	LOX/HC Injector Characterization Program (Design All, Hot-Fire Kerosene)		
1990 2000 2005 Today	• GOX/Ethanol Igniter/RCE • Kistler OMS LOX/Ethanol • LOX/Ethanol Igniter and 870 lbf RCE With 25 lbf Vernier Mode	• Gox/CH4 X-33 RCS • 870 lbf Thruster Pulse Test • Igniter Optimization • 870 lbf Injector Optimization • CH_4 Regen Cooling Study (CMBD) • 870 lbf RCE Tests • 870 lbf APSTB System Tests • NASA 100 lbf RCE Development, Test • NASA AME 6000 lbf • LOMET TPA	• NK-33 Hot-Fire • AJ-26 (Americanized NK-33) Development and Hot-Fire • LOX/RP-2 Ox-Rich Igniter • Hydrocarbon Boost Tech Demo • Antares Booster Engines

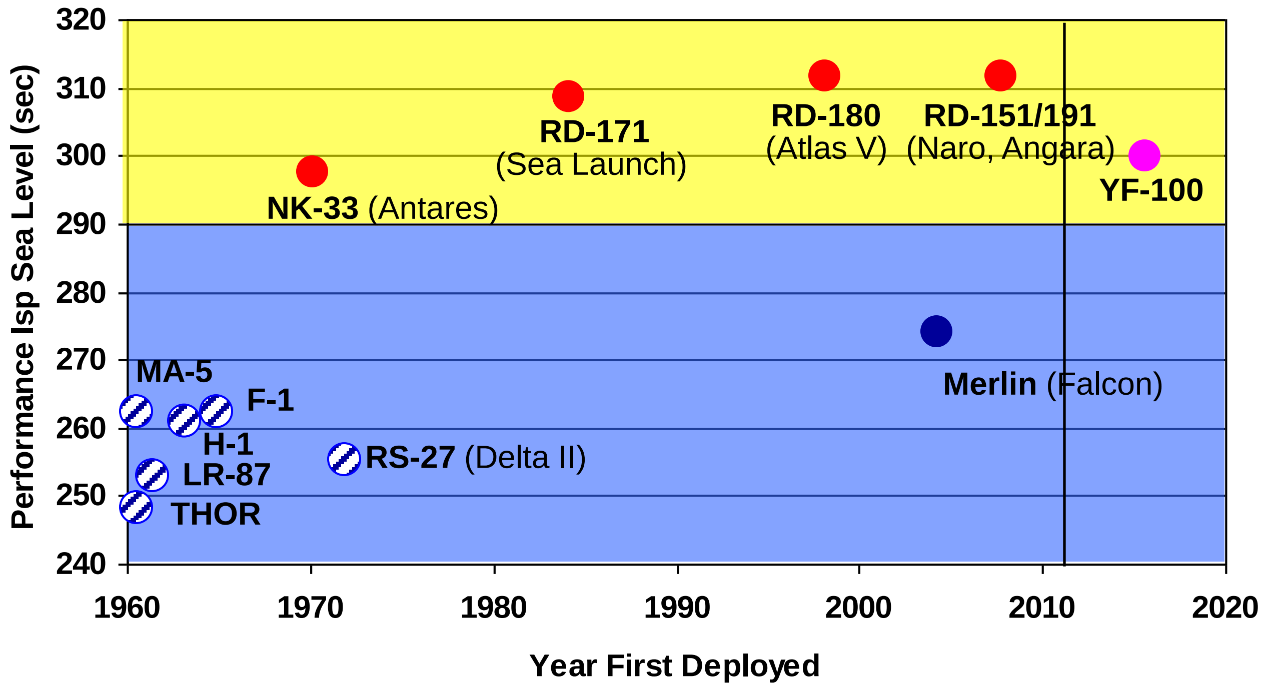








Ox-rich Staged Combustion Provides Higher Performance Than Gas Generator

Hydrocarbon Booster Engines



Foreign
Modern Technology
Ox-Rich Staged
Combustion Cycle

USA
Old Technology
Gas Generator Cycle

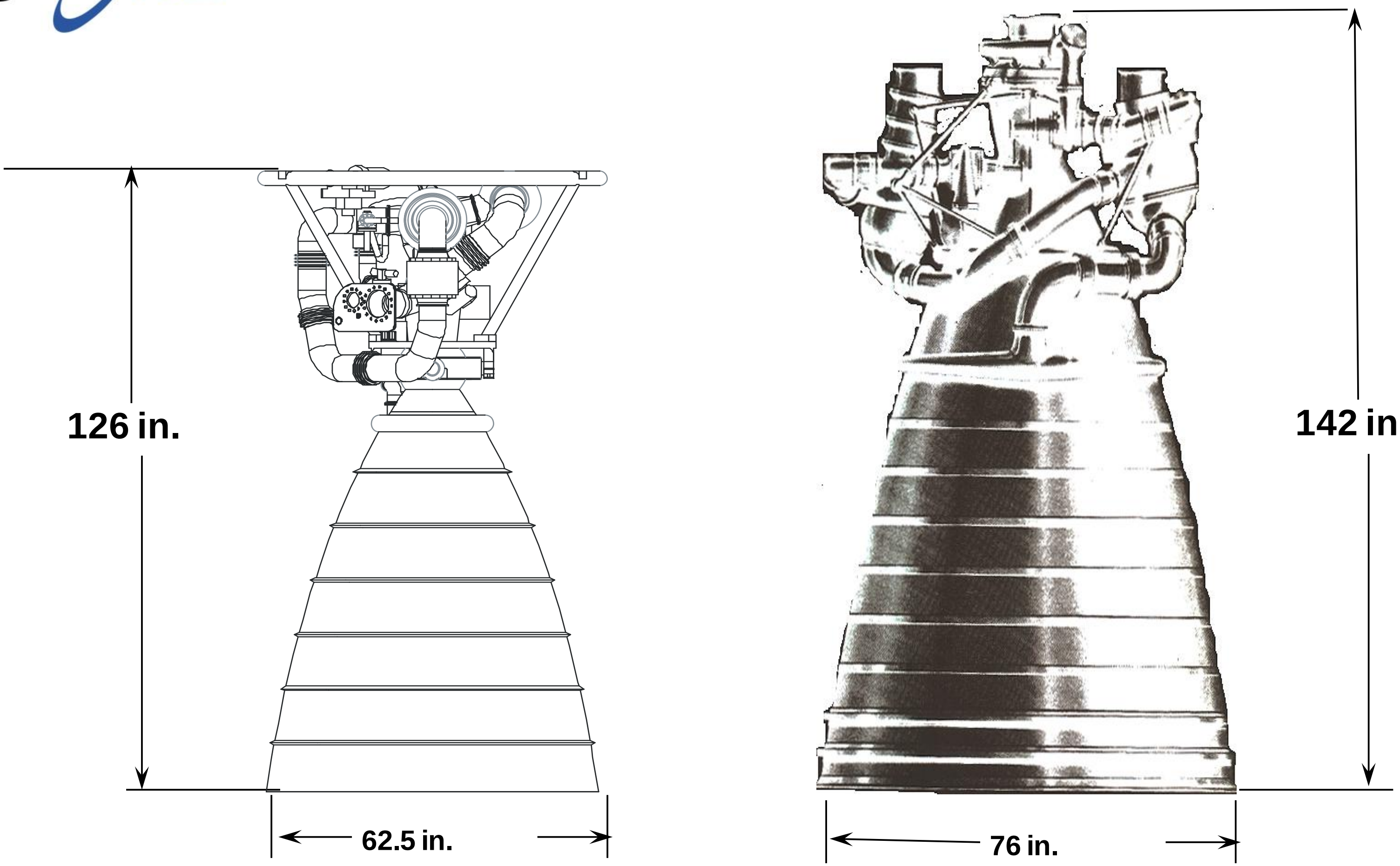
- U.S.
- Russia
- China
- U.S., out of production

The International Community Is Using High Performance HC Engines

HC Engines Are In Transition In The US

- Initial HC Engines In Both US And USSR Used Gas Generator (GG) Cycle
- Soviets Switched To Oxygen-Rich Staged Combustion (ORSC) In 1960's
  - Since Then, All HC Engines Developed Outside USA Have Been ORSC
    - At Least Eight Different ORSC Designs Fielded By USSR Or Successor Countries
    - At Least Two ORSC Engines Now Qualified In China (YF-100, YF-115)
    - ORSC Engines Under Study Or Development In India, South Korea And Europe
- The US Meanwhile Has Abandoned HC Gas Generator Engines
  - Except Falcon 9
  - Imported ORSC Engines Used On Atlas V And Antares
  - But, Has Never To Date Completed An ORSC Design
  - Hydrocarbon Boost Technology Demonstrator (HBTD) Currently Underway

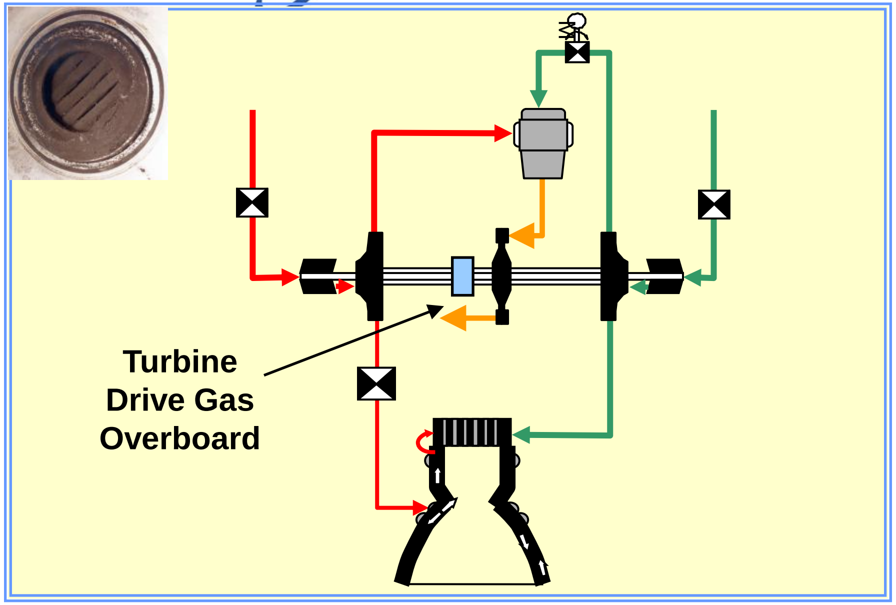
ORSC Engines Are More Compact And Lighter Than GG Engines – Important On Fly Back

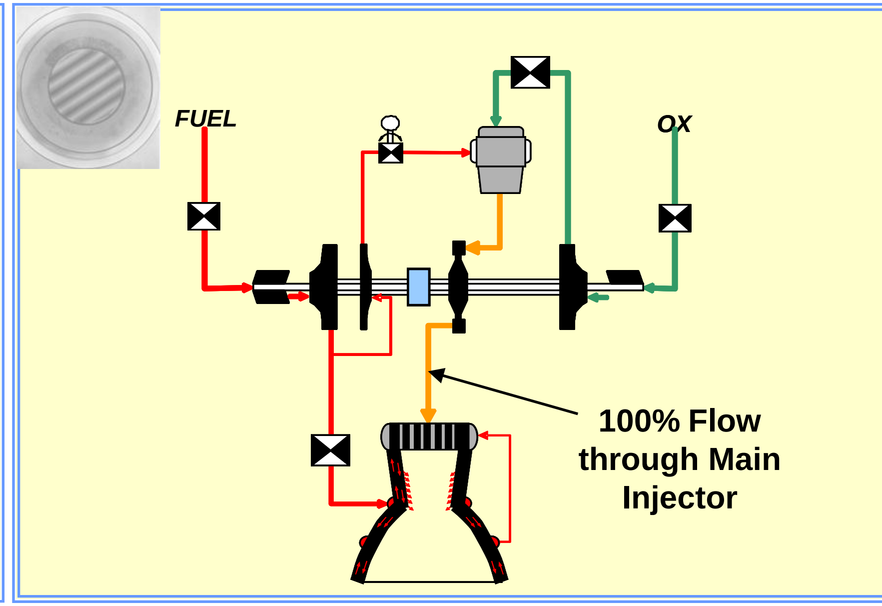


	ORSC	Gas Generator
Sea Level Thrust, klbf	506	506
Sea Level Isp	306	282
Vacuum Thrust, klbf	552	575
Vacuum Isp	337	321
Mixture Ratio	2.8	2.29
Mass - lbm	4200	7784

Two Engine Cycles Used For LOX/Kerosene Boosters

AEROJET 70 YEARS





Fuel Rich Gas Generator Cycle:

- Open Cycle: Performance Loss Due to Overboard Propellant Flow
- Minimized Turbine Flow Results in High Turbine Drive Temperature, Limiting Engine Life
- Sensitive to Minor Mixture Ratio Variations
- Main Injector Mixes Ambient Fuel With Liquid Oxidizer, Making it More Difficult to Achieve Maximum Performance
- Liquid/liquid Injector More Susceptible to Combustion Instability
- Fuel-rich Gas Generator Requires Engine Cleaning Between Flights, Limiting Operability For Reusable Applications

Ox Rich Staged Combustion:

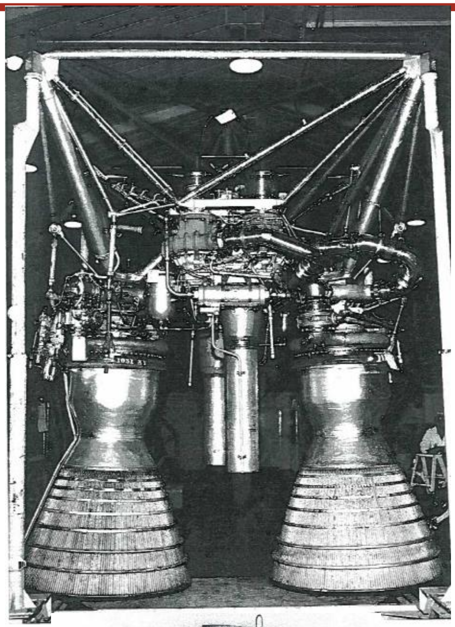
- Closed Cycle: Maximizes Performance Since All Propellant Used to Produce Thrust at No Penalty on Margins
- Increased Mass Flow Through Turbine Results in Reduced Temperature Requirement, Enhancing Engine Life
- Increased TPA Power Availability Enables Higher Chamber Pressure Engines, Resulting in Smaller/lighter Hardware
- Warm Ox/fuel in Main Injector Increases Engine Performance and Enhances Combustion Stability
- Requires High Strength Ox Compatible Materials
- Ox-rich Shutdown Minimizes Cleaning Between Firings, Optimizing Operability

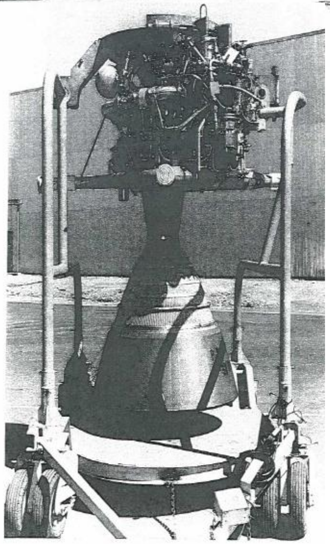
ORSC Engine Cycle Provides High Performance And Enables Reusability

Titan 1 Experience – HC GG Engines

AEROJET 70 YEARS

- **Developed For ICBM 1955-1959**
- **Stage 1 Lox / RP Two TCAs / 300klbf**
- **Stage 2 Lox / RP Single TCA / 80klbf**
- **Significant Test Program > 26,100 Total Tests**
  - **6900 Engine Tests;**
  - **5440 TCA Tests**
  - **3930 TPA Tests**
  - **9900 Misc Tests**
- **500 Engines Manufactured / Delivered 1956 - 1960**
- **First Flight 1959**
- **Titan Engines Were Converted To Storable Propellants But Retain Their GG Heritage**
  - **Titan Flew For 50 Years**





Aerojet Has Significant GG Flight Experience, But Is Investing For The Future In ORSC

HC Boost Program Objectives

- **Program Focused On Achieving IHPRPT Goals Including Operational Responsiveness**

  ISP +15% *T/W +60%* *Cost -30%* *Reusable*

- **Develop Vision Flight-type Engine And Critical Components To The Conceptual Design Level = HIVE**
  - **250 Klbf Thrust (Sea Level)**
  - **LOX/RP-2 Ox-rich Staged Combustion Cycle**

- **Demonstrate Critical Technology In A Hydrocarbon Demonstrator Engine (Hyde) To Achieve TRL 5 Maturity**
  - **Design And Fabricate Critical Components**
  - **Design, Fabricate/Integrate Demonstration Engine**
  - **Support Testing At AFRL For Components, Subsystems, And Engine**

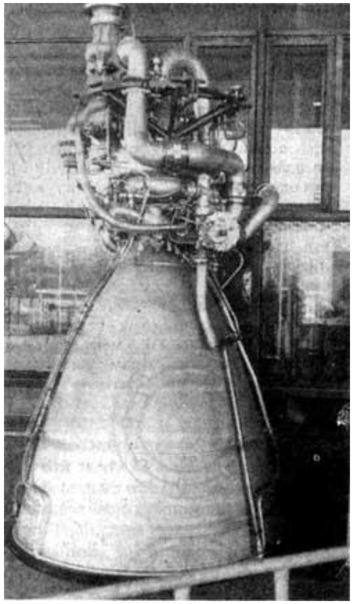
HBTD Is Developing The Next Generation Technologies For ORSC And Reusable Engines

History Of The NK-33

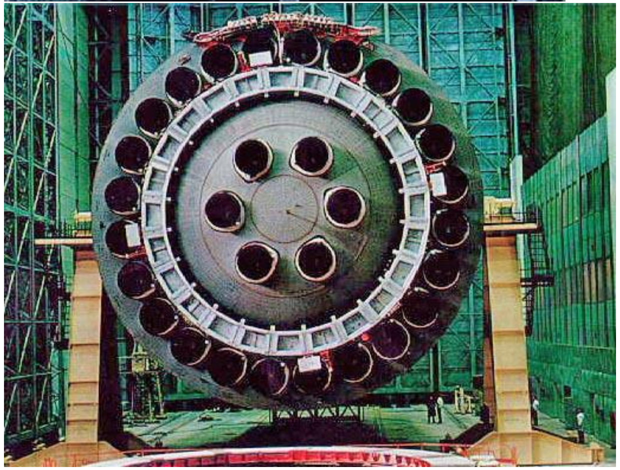
N-1 Vehicle Was Being Developed To Carry Men And Cargo To The Moon

Comparable in size to Saturn V

- Korolev Wanted Non Toxic Propulsion For N-1
- Energomash Was Developing Storable Propellant Engines For ICBMs At The Time
- N.D. Kuznetsov Was Contacted
    - Primarily Gas Turbine Engine Developer
    - Initiated Ox Rich Staged Combustion Research In 1959 With The NK-9 Engine
    - Initiated NK-15 Development In 1963
    - NK-33 Development Completed In 1972
- All Engines Use Ox-rich Staged Combustion Cycle With LOX/Kerosene Propellants
    - First Stage – 30 NK-15/33
        - 154 Metric Tons (339,500 Lbf)
        - 331 Seconds (27.7:1 Ar)
    - Second Stage – 8 NK-15V/43
        - 179 Metric Tons (394,600 Lbf)
        - 346 Seconds (79.7:1 Ar)
    - Third Stage – 4 NK-39
        - 41 Metric Tons (90,400 Lbf)
        - 353 Seconds (114:1 AR)
    - Fourth Stage – 1 NK-31
        - 41 Metric Tons (90,400 Lbf)
        - 353 Seconds (114:1 AR)



N1 Vehicle On The Transporter And In The Assembly Bay And The Launch Pad



NK-33 Features And Performance

Engine Cycle Features

- Ox-Rich Staged Combustion (ORSC) Cycle
- Single Liquid/Liquid Preburner
- Moderate Turbine Temperature
- Single Turbopump Assembly
- Single Chamber/Nozzle

Engine Performance (100% Throttle)

• Thrust (vac/SL), klbf	377 / 338
• ISP (vac/SL), sec	331 / 297
• Main Chamber Pressure, psi	2,109
• Main Chamber Mixture Ratio	2.6:1
• Throttle Range	50 - 100%
• Preburner Mixture Ratio	59
• Turbine Inlet Temperature, °F	670
• Nozzle Area Ratio	27.7:1
• Weight, lbm	2,985
• Thrust/Weight (vac/SL)	126 / 113

NK-33 Was Developed As A Booster Engine For The N-1

Test History

	NK-15	NK-33	NK-43	Total
Total Engines Built	581	208	42	831
Development	199	101	5	305
Serial Production	382	107	37	526
Total Engine Tests	832	575	92	1,499
Development	450	350	13	813
Serial Production	382	225	79	686
Total Test Duration, sec	86,000	99,400	8,608	194,008
Development	40,200	61,651	969	102,820
Serial Production	45,800	37,749	7,639	911,88
Total Engines Flown	120	0	0	120
Development	0	0	0	0
Serial Production	120	0	0	120

- Tests Of 30 Engines With Augmented Thrust To 114%
- Five Engines At Lower Thrust Ratings To 50%
- 22 Engines Tested At 122-130% Of Rated Power
- 49 Engines Without Removal From Test Stand In The Range Of 4-17 Successive Firings
- 75 Engines At Propellant Mixture Ratio In The Range Of 133…78 Percent Of Nominal Ratio

Flight History

- First N-1 Test Flight (Designated 3L) Launched on 21 February 1968 (between Apollo 5 and 6)
  - Fire Started in First Stage Aft Bay Due to Hot GOX Line Failure From High Frequency Vibration
  - Mistakenly Shut-off all 30 engines at 68.7 seconds (12 km) into the flight
- Second N-1 Flight (5L) Launched on July, 3 1969 (2 weeks before Apollo 11)
  - At 0.25 Seconds into Flight, the LOX Pump of Engine Number 8 Ingested Debris (likely a bolt) and exploded
  - Control System Detected the Inoperative Pump and Was Suppose to Then Shut off the 180° Opposite Engine to Cancel out Pitch/Roll Moment but Instead Shut off the other 28 Engine of the 30
- Third N-1 Flight (6L) Launched on June 24, 1971 (between Apollo 14 and 15)
  - During Ascent, the Vehicle Developed a Roll That the Control System was Unable to Compensate for
  - Appears That the Roll Thrusters Were Wired Backwards
  - Control was Lost 50.2 seconds After Liftoff, and Controllers Activated the Self-Destruct System
- Fourth (and Final) N-1 Flight (7L) Launched on November, 23 1972 (2 weeks before Apollo 17)
  - Normal Operation Until 106.3 seconds into Flight
  - To Reduce G Levels the Stage I Shutdown Sequence First Shut 6 Center Engines off and Then a Few Seconds Later the Remaining 24 Engines Were to Be Shut off
  - The Center Engines Were Shutdown Causing a Water hammer that Failed the Feed lines on Engine 4 in The Out Ring of 24 Engines Resulting in an Explosion and Disintegration 7 seconds prior to Stage 1 Burnout

NK-33 Testing Successfully Demonstrated a Reusable HC Engine using the ORSC Cycle

AJ26/NK-33 Knowledge Base Program

Kistler

Through

Orbital Sciences Corporation"s
Antares Launch Vehicle

A Comprehensive Product Integration Effort Has Been Performed On The NK-33

NK-33 Heritage

- Flight qualified
- Thrust (SL) 338,000 lbf
- Isp (SL) 297 sec
- 831 engines built
- 1,499 hot fire tests
- 194,000 sec firing
- 0.9985 demonstrated benign-shutdown reliability

Aerojet Modifications

- Gimbal
- TVC attachment
- Thrust frame
- Solenoid valves
- EMAs
- Harnesses
- Controller

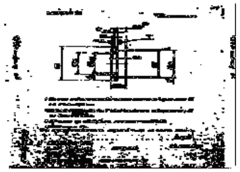
Americanized Engine

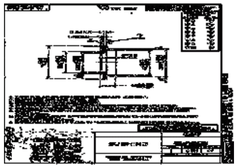
Kistler Proven Operability

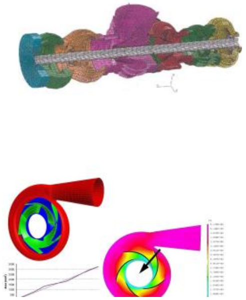
- 23%-115% thrust
- 78%-133% mixture ratio
- 5,870 sec before overhaul
- 10 firings before overhaul
- 6 firings after overhaul

Orbital Antares Requires One Use

Aerojet Design and Analysis Capability







- Acquired and converted complete set of design drawings, specifications, and process instructions
- Conducted analyses to confirm fluid flow conditions
- Conducted analyses to replicate design data for stresses, frequencies, and dynamic and static loads

Aerojet Manufacturing and Assembly Capability

- Acquired Manufacturing License Agreement
- Demonstrated ability to reproduce key processes and capabilities in US
- Trained by Russian engineers in engine assembly and disassembly

Aerojet Engine Availability

- 38 NK-33's
  - 20 for use on Orbital's Antares after inspection and repair of OEM material defects
  - Remaining 18 being inspected for OEM defects
- 9 NK-43's
- Aerojet-owned / In Sacramento

Aerojet Engineers Were Trained By NDK Developers On The Design And Operation Of The NK-33

Aerojet Has Made Significant And Continuous Discretionary Investments In The NK-33 Product Line

• **1993 – 2008 Efforts**	**$72M**
–Engine MLA, Acquisition, Drawings, IP, Tooling, Testing	
• **2009 Efforts**	**$3.65M**
–Engine Inventory Health Check	$200K
–Engine Disassembly And Inspection	$150K
–Refurbishment Kit Development	$50K
–Knowledge Base Development	$250K
–Duty Cycle Margin Demonstration Test	$3000K
• **2010 Efforts**	**$1.58M**
–Continue NK-33 Knowledge Base Development	$1.2M
• Data Mining And Electronic Database Development $383K	
• Engine/Component Performance Models $181K	
• Engine/Component Structural/Dynamic Models $631K	
–Valve Testing And Disassembly	$107K
–Samara Test Data Detailed Analysis	$277K

Total Investment From Inception (1993-2010) > $80M

Aerojet Test History

	Purpose	Tests	Results	Notes
1995 Aerojet	Demonstrate Performance for EELV Competition	5	•Total Duration 408 sec •Repeat of original ATP •“end-of-mission” test with warm LOX •Atlas duty-cycle test up to 103% power level •EELV max-power test up to 113% power level	All Objectives Met
1998 Aerojet	Veriify Engine Modifications for Kistler	6	•Total Duration 525 sec with 415 sec at Full Power •Various Ox and Fuel Temperature Ranges •Various Throttle and MR Settings •Tested with Low Inlet Tank Pressures to Demonstrate Altitude Start	All Objectives Met
2009 Samara	Demonstrate 2x Duty Cycle for Orbital Sciences Corporation’s Antares Launch Vehicle	2	•Total Duration 362 sec •Thrust levels from 81% to 113% with MR excursions to explore Pc/MR box	Test Failed 154 sec into second test. Attributed to Test Stand feed line
2010 Samara	Demonstrate 2x Duty Cycle for Orbital Sciences Corporation’s Antares Launch Vehicle	3	• Total Duration 619 sec •95 sec test up to 108% power •287 sec test up to 108% power •235 sec test at 100% power level and below	All Objectives Met
2010 Stennis	Verify Engine Modifications for Orbital Sciences Corporation’s Antares Launch Vehicle	2	•Total Duration 65 sec •10 sec checkout test up to 108% power level •55 sec Acceptance Test Profile with1° engine gimbal, up to 108% power level	All Objectives Met
2011 Stennis	Verify Engine Modification for Orbital Sciences Corporation’s Antares Launch Vehicle	6	Total Duration 277 sec 55 sec acceptance test profile with engine gimbal, up to 108% power	**1 test failure attributed to OEM material defect All other objectives met
	Totals	**24**	**1783 sec**	**No Anomalies Attributed to the Cycle**

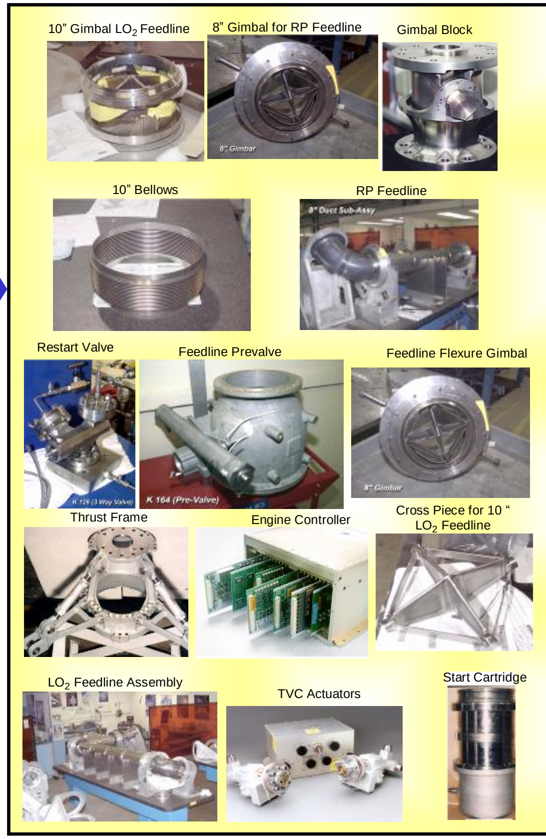
**All engines required inspection and repair to correct age-related material defects"

Evolution Of NK-33 To AJ-26 Engine Configuration

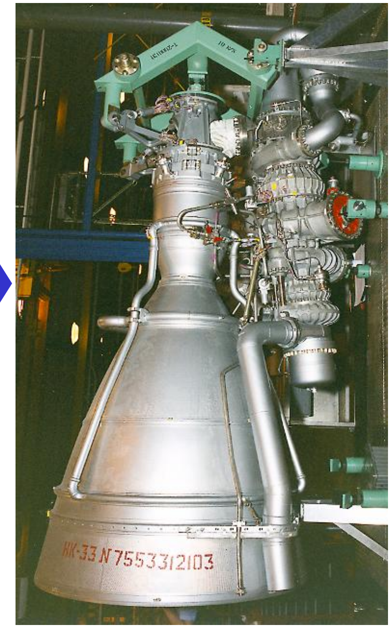
NK-33 Heritage

- Flight qualified
- High Performance
- High Reliability
- 831 engines built
- 1,499 hot fire tests
- 194,000 sec firing

Aerojet Adaptations for Kistler



AJ26 Reusable Engine



Demonstrated Operability**

- Deep throttling capability
- Non-coking
- Up to 17 firings before overhaul
- Up to 5 overhauls
- Up to 11 firings after overhaul
- Up to 25 total firings
- Up to 20,000 total sec hot fire

**Based on Russian Test History
Excludes Antares

38- AJ26/NK33's at Aerojet

Hot-Fire Test At Aerojet's E-zone

Kistler Program Invested $120M in NK-33 Conversion

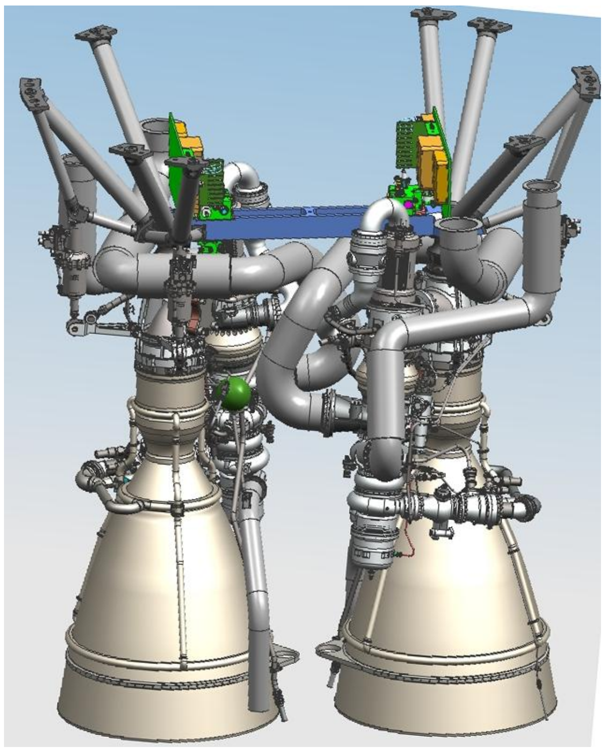
Orbital Sciences Corporation's Antares Launch Vehicle Program Added Additional Vehicle Integration Hardware And Established A Production Line

338,000lbf (SL)Thrust
297 ISP
831 engines Built
1499 Hot fire Tests
194,000 sec
0.997 Reliabilty

NK-33

- U.S. Pyro Valves and Initiators
- U.S. Moog EMAs to Actuate Control Valves
- Aerojet-Manufactured solid Start Cartridge
- Aerojet-Manufactured Gimbal Bearing and Thrust Mount
- Aerojet-Manufactured Main Chamber Igniters
- New U.S. Electrical Harness and Instrumentation
- Digital Controller/Sequencer
- U.S. Moog TVC System
- Aerojet Manufactured Lines
- US Sourced Propellant run lines
- U.S. Sourced Aft Closure
- Aerojet TEA-TEB Cartridge

776,866lbf (SL) Thrust
301.6 ISP
37 Engines For Conversion
11 Hot Fire Aerojet Tests
0.988 Reliability



AJ26-62

Aerojet Has Complete Technical Responsibility For NK-33 Derivates In The US

- **Aerojet Has Been Developing An AJ26/NK-33 Engine Knowledge Base For Over 15 Years**
  - **1993: Initial Contacts With NDK And Transfer Of Information**
  - **1995: Engine Test At Aerojet In Support Of EELV Proposal And Developed First U.S. Production Manufacturing Plan**
  - **1995 Received Manufacturing License Agreement**
  - **1996-1998: Kistler Program Included Multiple Technical Interchange Meetings (TIM) In Russia And Sacramento**
  - **1997-1999: Aerojet Expanded 1995 U.S. Build Program To Detailed Manufacturing Processes And Included Multiple Tims**
  - **1998-2001: Japanese J-I Upgrade Program Included Technical Interchanges With NDK**
  - **2002-2008: Various AJ26 Marketing Efforts Conducted, Some Knowledge Base Development**
  - **2008-present: Antares Program Includes Significant Technical Interchange Meetings With NDK**

Successfully Demonstrated Our Knowledge Gain Through Application To Kistler And Antares

Path To RBS

Aerojet's Experience With HC Engines Has Prepared Us To Develop And Produce A US Built ORSC Booster Engine

- **ORSC Is The Answer For RBS**
  - Reusable
  - High Performance
- **Our Ongoing Experience With HC Engines Has Prepared Us To Develop An ORSC Engine For RBS**
  - Understanding The ORSC Cycle
    - Transfer Of The Technical Characteristics Of The NK Engine
    - HBTD Expanded Our Knowledge Base Relative To The Cycle
  - Understanding The Operational Characteristics Of The ORSC Engine
    - Complete Technical Cognizance And Responsibility In The US For NK Derivatives
    - Hardware Test Experience
    - Integration Of The AJ 26 Into Launch Vehicles
    - Adapting The NK Engine To US Standards
  - Understanding The Hardware Fabrication
    - Investments In Manufacturing Process/Parts Manufacture
  - Understanding The Design And Mastering The Technologies
    - Modern Analysis Of NK Engine
    - HBTD Is Developing The Next Generation Technologies For ORSC And Reusable Engines

RBS Ultimately Requires A New, Reusable Engine

Aerojet & USG Investments Provide Path To New US ORSC Engine