

**U.S. Department of Energy
Cooperative Agreement Number:
DE FC02-36CH11080**

**Advanced Natural Gas Reciprocating
Engine Program**

Peer Review
December 2, 2003

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Waukesha

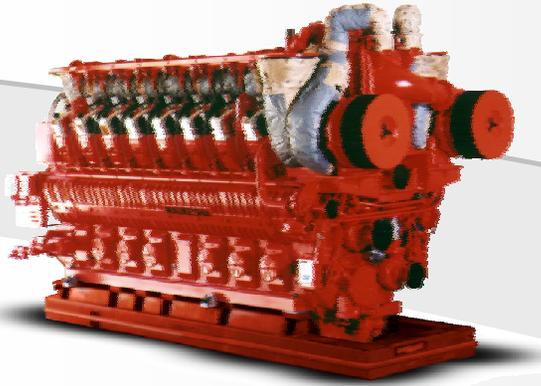


Peer Review Topics

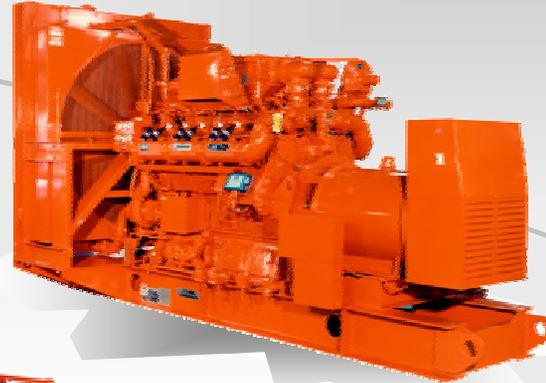
- Waukesha Engine & ARES Objectives
- APG Overview & Partners
- APG R & D Approach
- Technical Accomplishments & Progress
- APG Design Verification & Production
- Future Research Activities



Waukesha Engine Products



ATGL



VGF



CFR



VSG



VHP



**Waukesha
Genuine Parts**

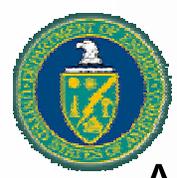


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Waukesha Power Systems



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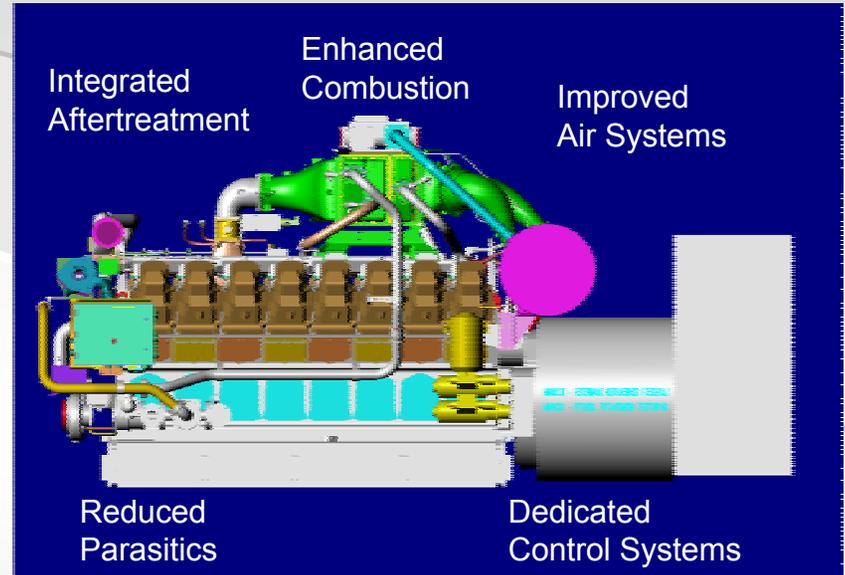


ARES Program



A multiyear cooperative agreement between the US Dept of Energy and Industry to create a 50% efficient natural gas powered reciprocating engine system with a 95% reduction in NOx emissions by the year 2010

- ▶ Multiple Phases
- ▶ Ongoing Market Verification
- ▶ Partnerships with Labs / Universities
- ▶ Pre-Commercialization Demos
- ▶ Full Commercialized Production
- ▶ Awards Announced Nov 2000
- ▶ Contracts Signed April 2001
- ▶ Program Launch September 2001
- ▶ Phase 1 Complete 2004-5
- ▶ Final Phase Complete 2009-10



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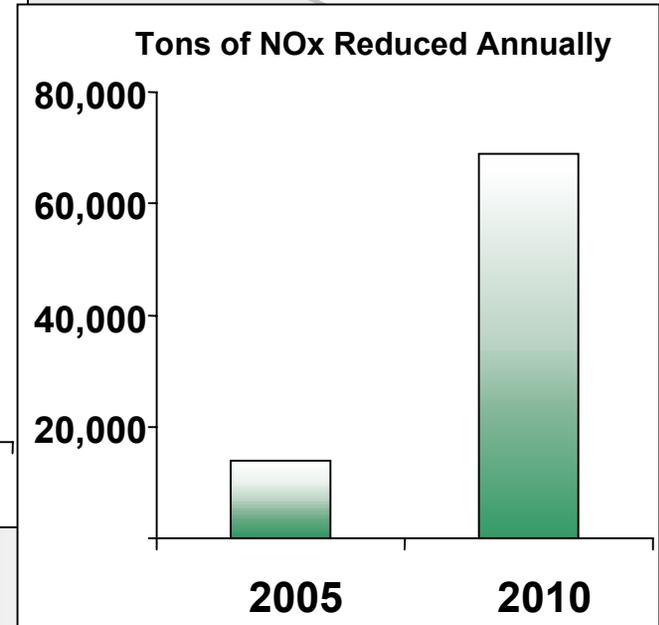
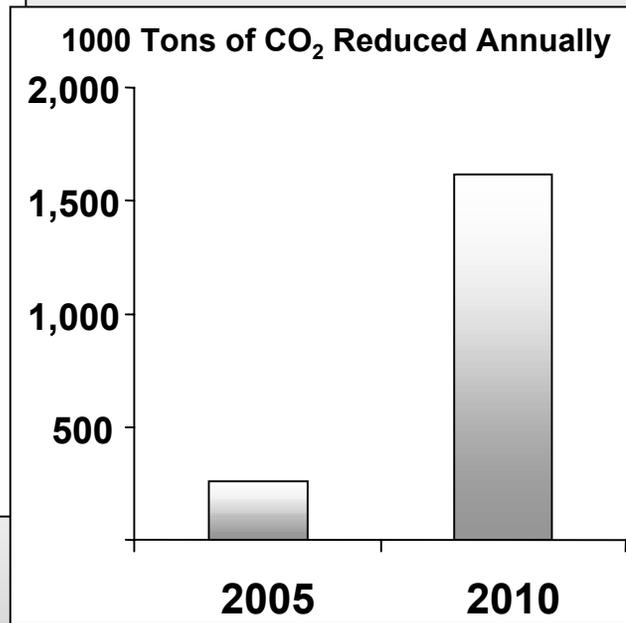
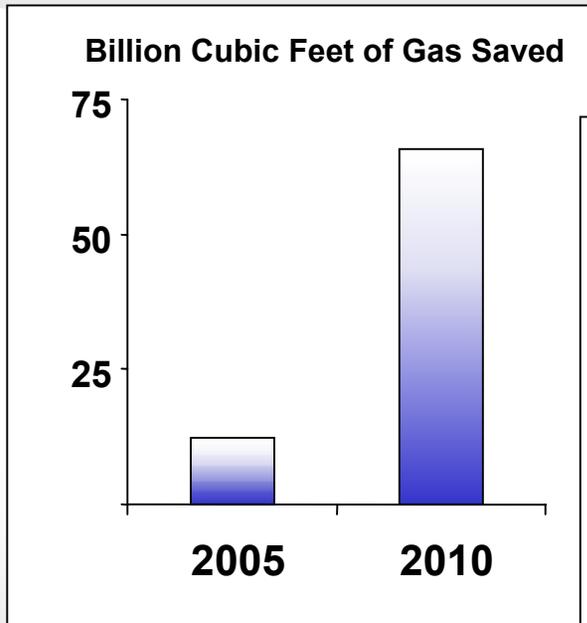
ARES Benefits to Society



Provide power for 10 Million new homes,
and save enough natural gas to heat
500,000 of those homes.
EVERY YEAR

Remove the Carbon Dioxide emissions
of 3.0 million automobiles
EVERY YEAR

Remove the NOx emissions
of 6.5 million automobiles
EVERY YEAR



ARES Program Milestones

Typical Introduction by Phases: Staged Introductions
Faster Time to Market
Quicker Program Results

Current 38-40% BTE, 2 g NO_x

Phase I 44% BTE, 0.25g NO_x

Phase II 47% BTE, 0.1g NO_x

Phase III 50% BTE, 0.1g NO_x

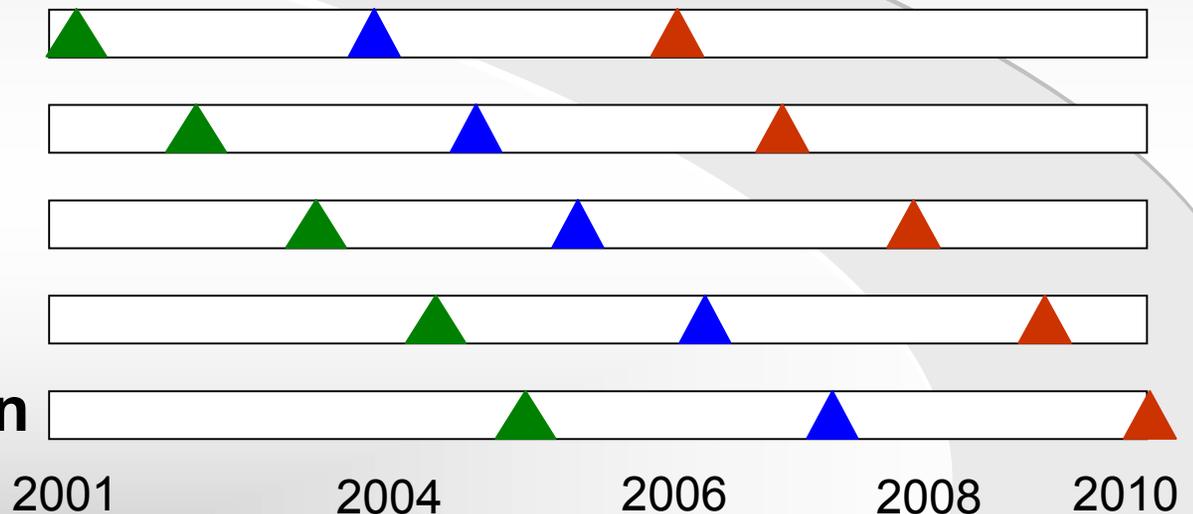
Concepts

Technical Base

Platform Base

Field Demos

Commercialization



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APG Overview & Partners



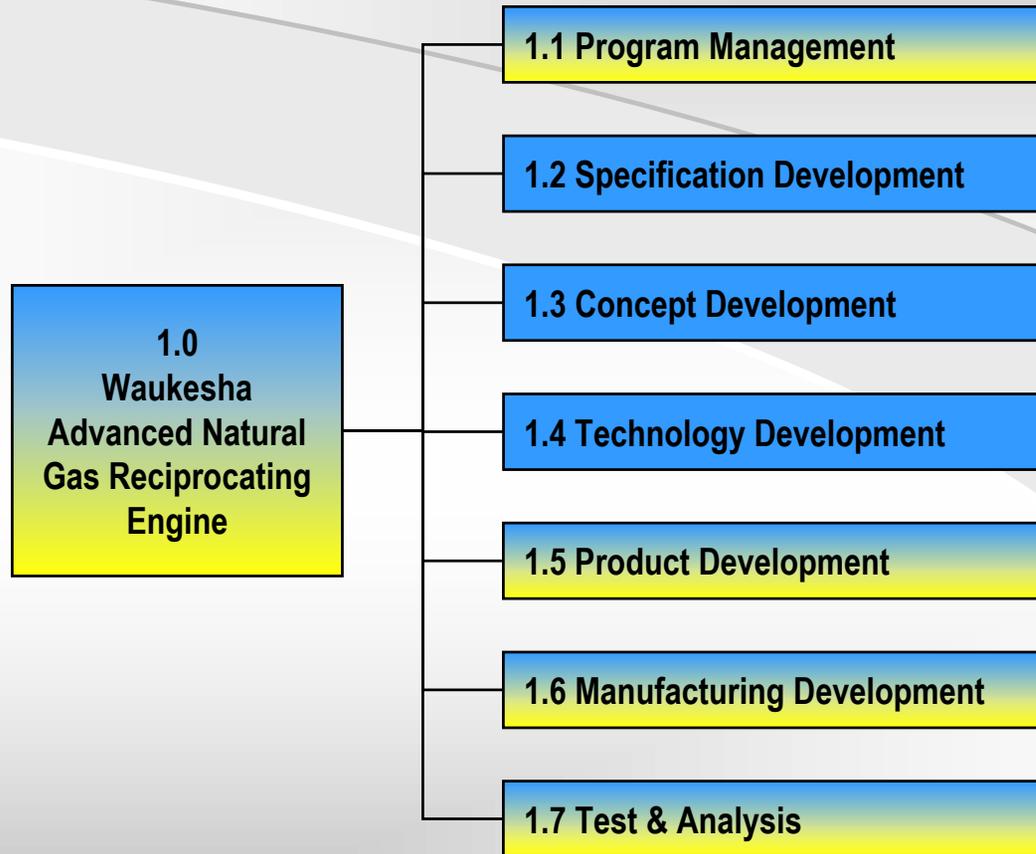
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Waukesha Phase I: APG

- APG: Advanced Power Generation
- 1 MWe Engine and Enginator™
- Redesigned V16 Platform
- Advanced combustion system
- Advanced ignition system
- High efficiency
- Ultra-low emissions capability



APG Work Breakdown Structure



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Completed Tasks

In process Tasks

APG Project Tasks

Completed Tasks

Task 1: Component Development & Testing

Task 2: System Development & Testing

In-Process

Task 3: Engine Integration & Preparation

Task 4: Engine Fabrication & Proof Test

Task 5: Pre-Commercial Demonstration



APG Project Partners

Suppliers: Mahle Power cylinder & tech. support
TRW Valves & tech. support
Winsert Valve seats & tech. support

Consultant/Lab/University

CSU/MIT Friction reduction program
Digital Engines KIVA combustion modeling
MRI Manufacturing consulting
Rexnord Component durability testing
Ricardo Design analysis services
SWRI Concept testing

End Customers For Field Demonstration



APG R&D Approach



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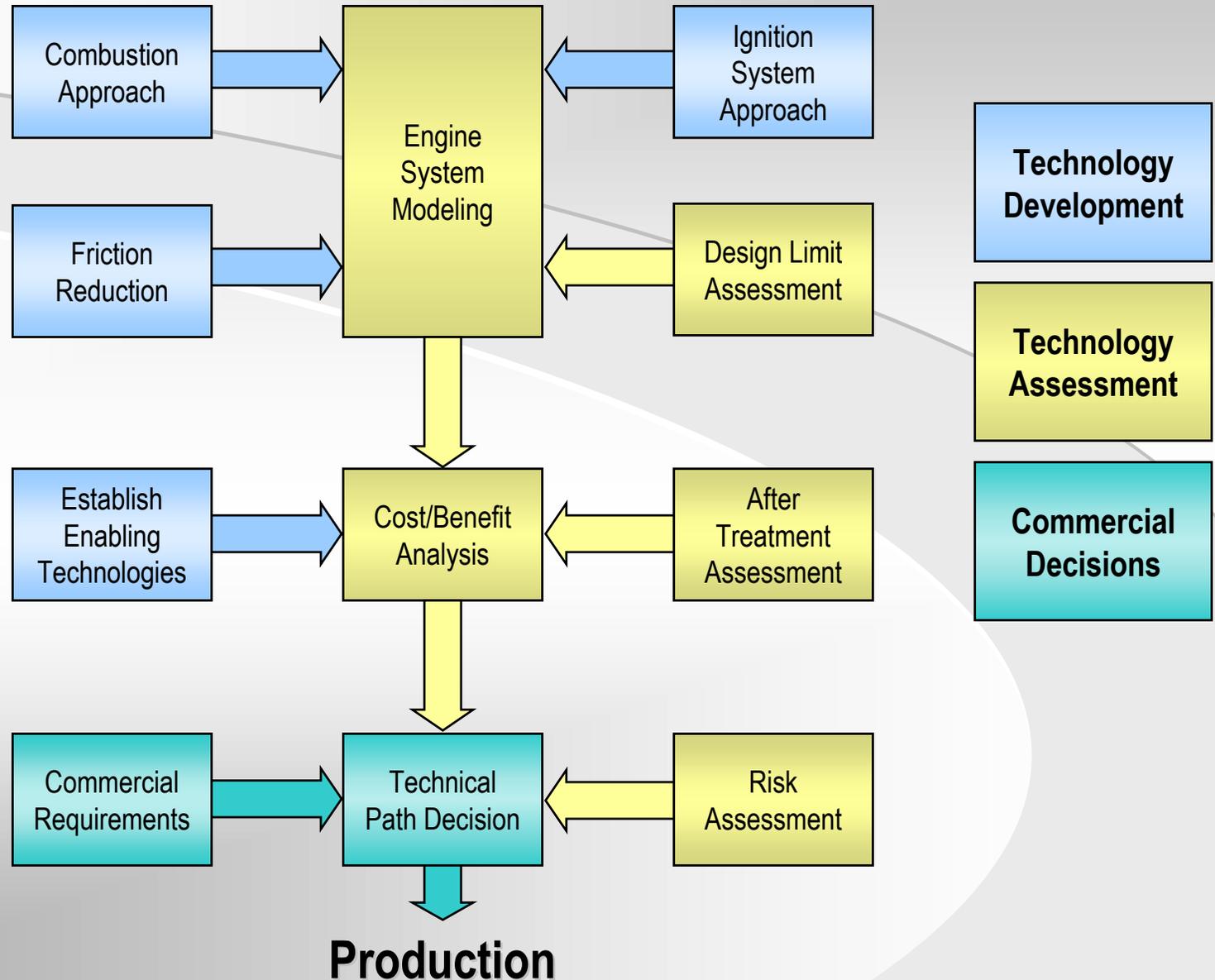
APG Technical Barriers

(Ref: April 2001 Peer Review)

- Combustion stability with high diluents
- Ignition system reliability, durability, and cost
- High cylinder pressure
- Friction reduction
- After treatment efficiency and cost



APG Technology Path (R&D Approach)



Technical Accomplishments & Progress



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APG Technical Accomplishments Combustion

Improved COV IMEP by >50%

Reduced burn duration >30%

- 3-D combustion modeling using KIVA
- Genetic optimization technique
- Optimized intake port swirl
- High kinetic energy piston bowl design
- Optimized piston squish area and height



APG Technical Accomplishments

Ignition

Reduced 5% MFB Std Dev. by 40%

Improved lean limit ~6%

Long life design

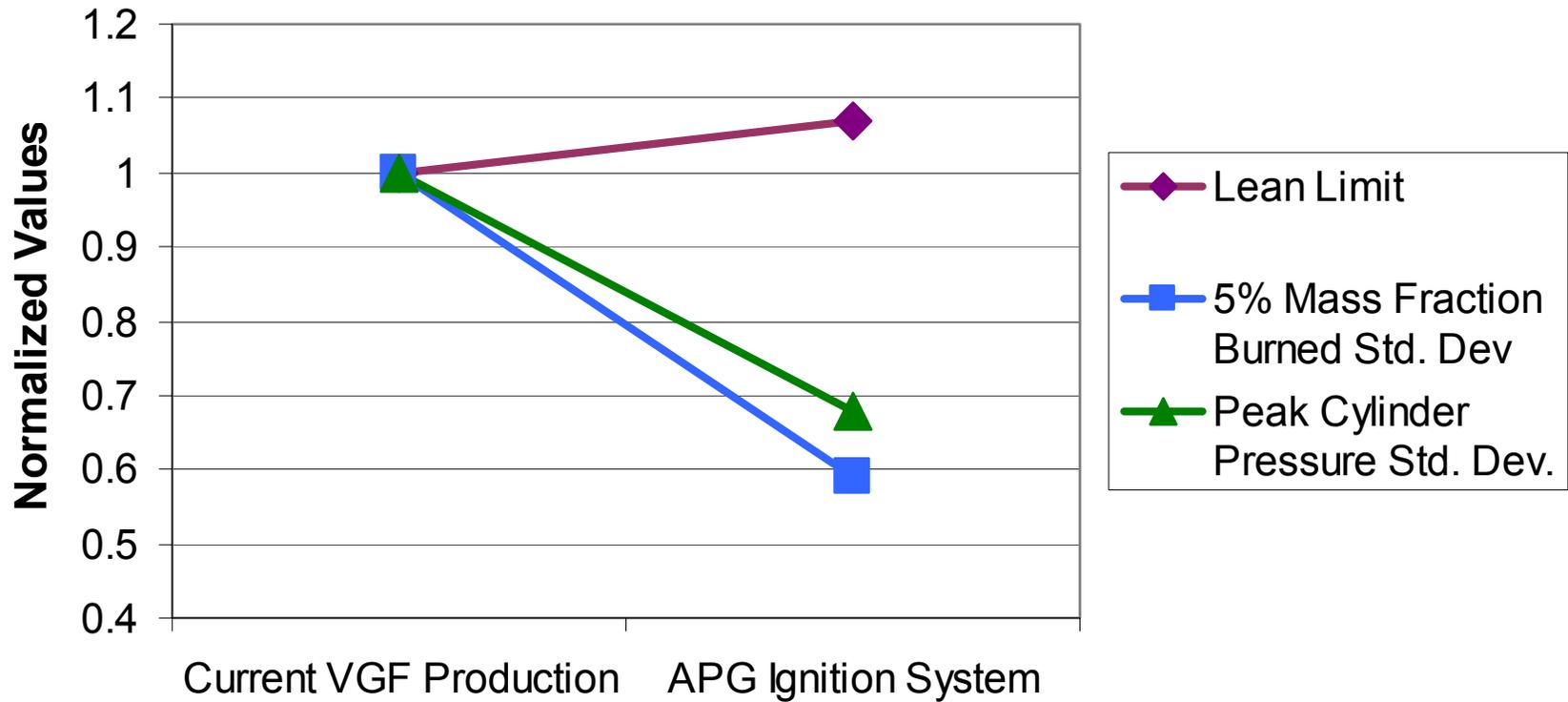
- Optimized ignition system in conjunction with combustion system
- Shielded spark plug design
- Reduced demand voltage



APG Technical Accomplishments

Ignition

APG Ignition System Performance



APG Technical Accomplishments

Pumping & Friction

Reduced pumping work

Reduced power cylinder friction

- Optimized air flow through modeling, CFD analysis, and flow bench testing
- Optimized piston skirt guidance and piston ring pack



APG Technical Accomplishments

High Cylinder Pressure Capability

Increased platform strength >25%

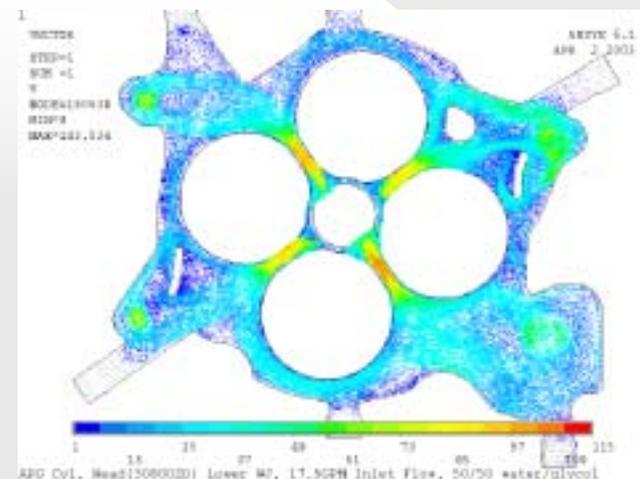
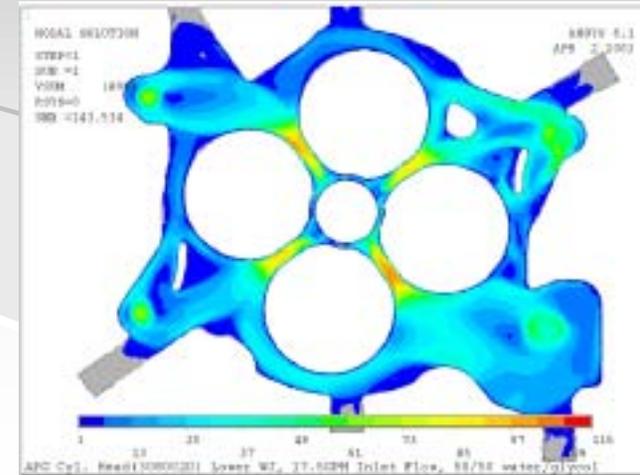
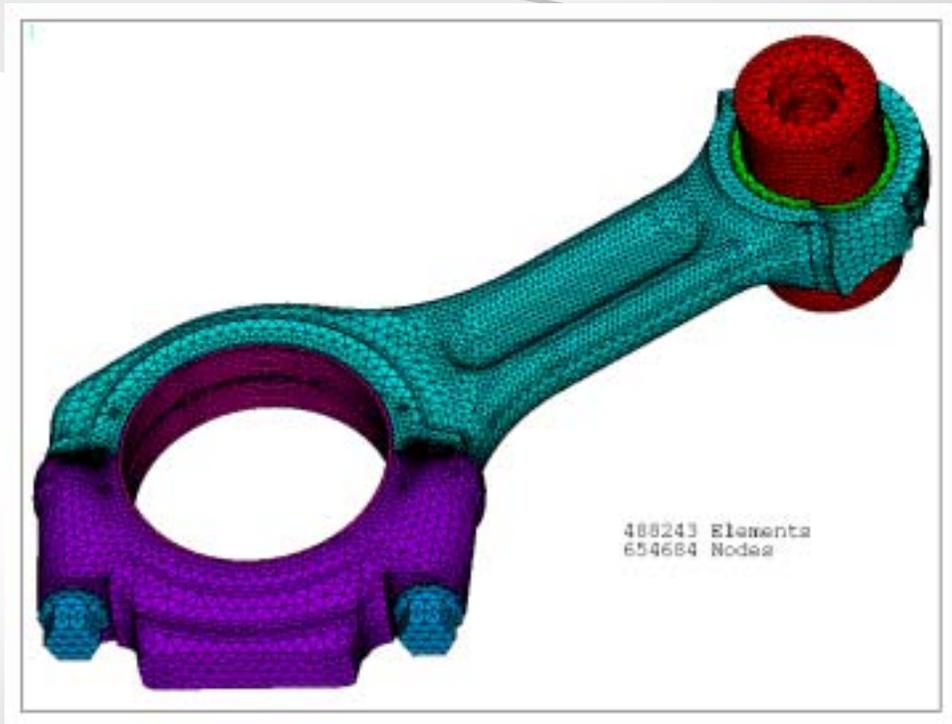
Maintained or improved high cycle fatigue safety factors

- Complete FEA optimization
- Upgraded materials
- Improved component cooling through CFD



APG Technical Accomplishments

High Cylinder Pressure Capability



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APG Technical Accomplishments Enabling Technologies

New ESM engine control system

Improved fuel system

- ESM provides full engine diagnostics with expert help system
- Ignition provides spark prognostics
- Improved fuel system perform while reducing air side pressure drop



APG Technical Accomplishments Completed Milestones

- Completed Technical Specification
- Completed Subsystem Development
 - Combustion
 - Ignition
 - Power Cylinder
- Technical Path Selection
- Technical Committee Review



APG Technical Accomplishments Completed Milestones

- Completed Control System Design
- Completed Core Engine Design
 - Crankcase / Geartrain
 - Crankshaft / Connecting Rods
 - Cylinder Head / Valvetrain
 - Power Cylinder
 - Intake / Exhaust / Turbocharger / I/C



APG Technical Accomplishments Completed Milestones

- Manufacturing Readiness Plan
- Marketing & Service Plan
- Supplier Selection
- Quality Plan
- CNC Programming & Routing
- Tooling / Fixturing

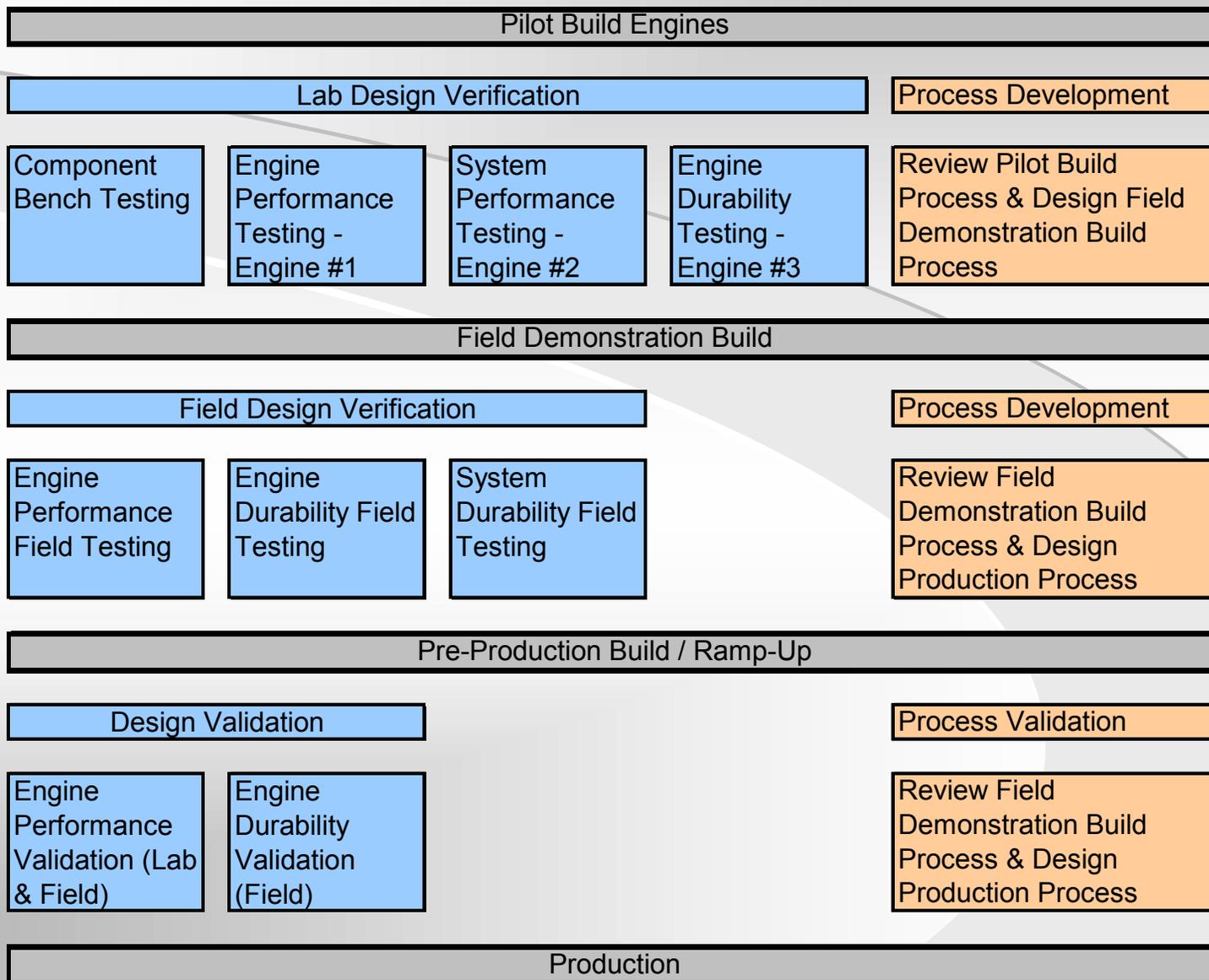


APG Design Verification & Production



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APG Design Verification



APG Design Verification Milestones

- Complete Engine & System Performance Testing
- Pre-Commercial Demonstration Build & Field Test Start-Up
- Pre-Commercial Demonstration Post Test Analysis
- Final System Technical Review
- Full Production Availability



APG Design Verification

Remaining Technical Risks

- Confirm all system performance requirements
- Durability / Life Cycle
 - Oil consumption & change interval
 - Spark plug life
 - Valve lash setting interval
 - Top end overhaul
 - Bottom end overhaul



Future Research Activities



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Future Research: 50% BTE Goal

Primary Research Areas

- High Energy Ignition
- Faster Combustion
- Friction & Parasitic Loss Reduction
- Turbo Eff. & Reduced Pumping Work
- Advanced Control Systems
- Waste Heat Utilization
- Catalysis and Aftertreatment



Future Research: DOE Roundtables

- Ignition
- Emissions
- Friction & Parasitic Losses
- Catalysis and Aftertreatment
- Turbo Machinery
- Sensors Capability
- Controls Integration
- HCCI Combustion



Future Research: ARICE Program

- Cooled-EGR w/ 3-Way Catalyst
- Focus on NO_x, CO, NMHC, THC, and formaldehyde reduction
- Co-funded by California Energy Commission to address 2007 proposed emissions standards
- Partners: CEC, Miratech, SRI, SoCal Gas



APG Technology Accomplishments

- High Confidence Technical Path Selected
- Improved COV IMEP by $>50\%$
- Reduced burn duration $>30\%$
- Reduced 5% MFB Std Dev. by 40%
- Improved lean limit $\sim 6\%$
- Advanced, long life ignition design



APG Technology Accomplishments

- Reduced pumping work
- Reduced power cylinder friction Increased platform strength >25%
- Maintained or improved high cycle fatigue safety factors
- ESM engine control system
- Improved fuel system



APG Summary

- Task 1 & 2 activities completed
- Task 3, 4, & 5 activities in process
- No major technical barriers remain
- APG is on track to meet the project goals
- Future R&D areas identified to achieve 50% BTE

