Technical Path Evaluation for High Efficiency, Low Emission Natural Gas Engine

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Southwest Research Institute

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Southwest Research Institute

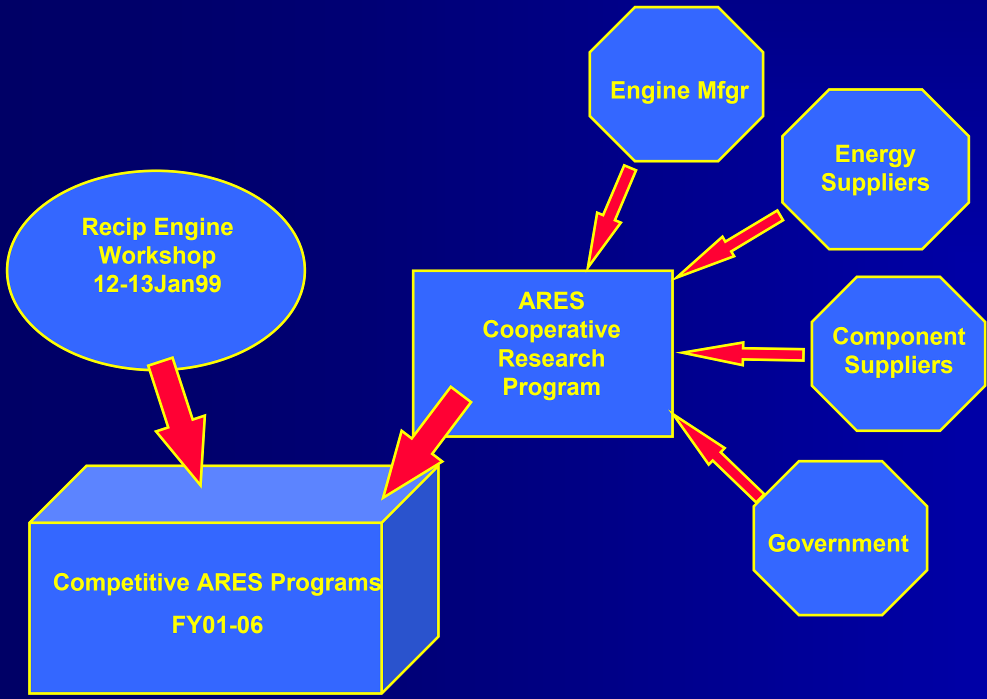
- Founded as an independent, non-profit, R&D organization in 1947
- Located on 1200 acres in San Antonio, TX, 3000 employees

Presentation Outline

- SwRI ARES Program Description
- SwRI ARES Objective and Scope
- Technical Barriers to High Efficiency
- Pathway to High Efficiency
- Summary

Advanced Reciprocating Engine Systems (ARES)

ARES was formed (Nov 1998) as a cooperative research program with funding from industry and government.



Program Structure

ARES Program Members

Department of Energy (OPT and NETL)
Gas Research Institute
Caterpillar Inc Engine Division
Cooper Energy Services
Cummins Engine Company
Waukesha Engine Division
Southern California Gas
Altronic
Federal Mogul - Champion
Woodward Governor

SwRI ARES Objective

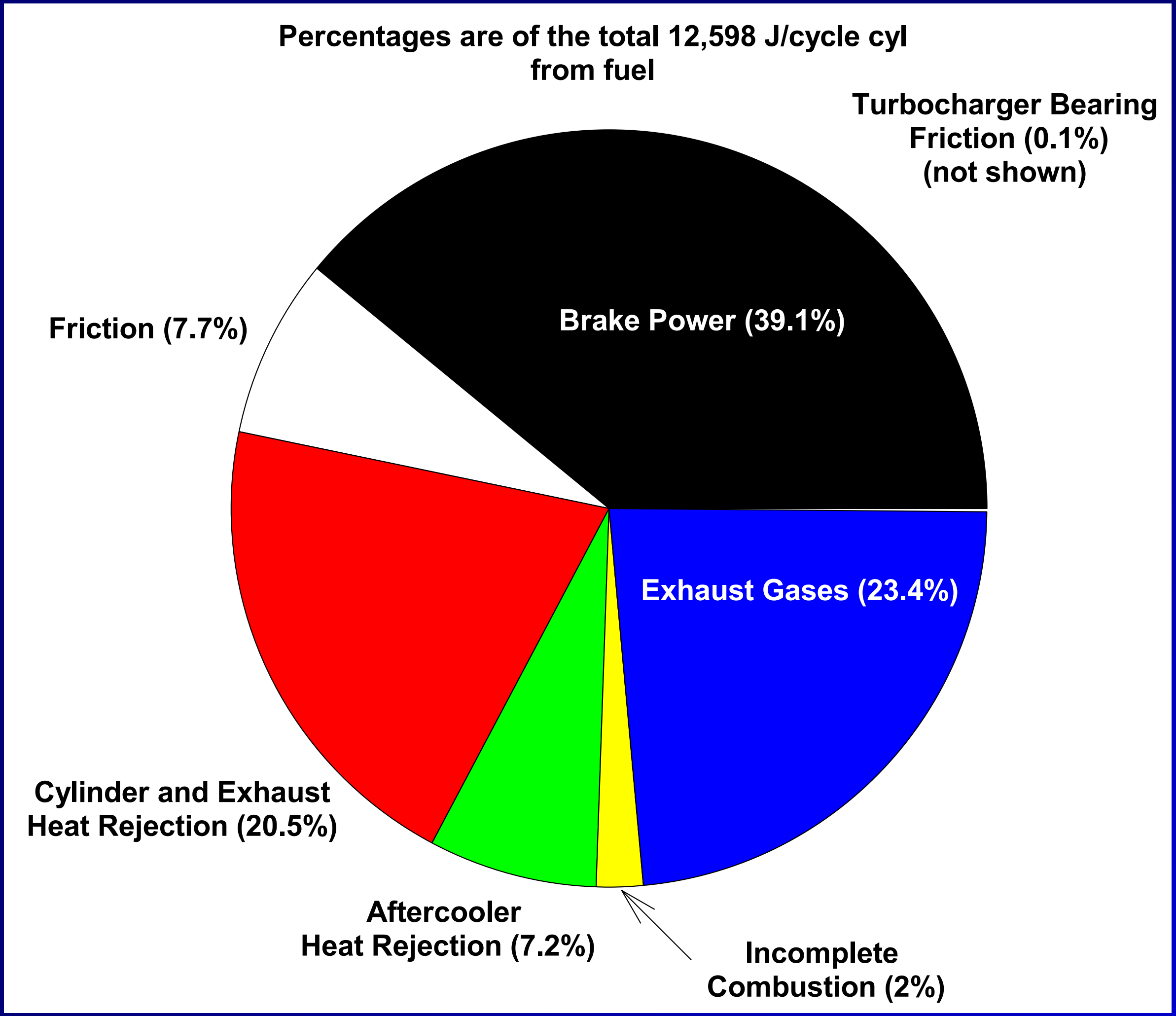
- Identify enabling technology for development of high efficiency, low emission, stationary natural gas engines
- Efficiency target: 50% Brake Thermal Efficiency
- NO_x emissions target: 0.1 g/hp-hr NO_x

Program Scope

Single Cylinder CAT3501 Research Engine

- Modeling and simulation to identify technical paths and barriers
- Bench scale and single cylinder engine testing to evaluate various technologies

Baseline Engine Energy Balance



Known Barriers to High Efficiency for Natural Gas Combustion

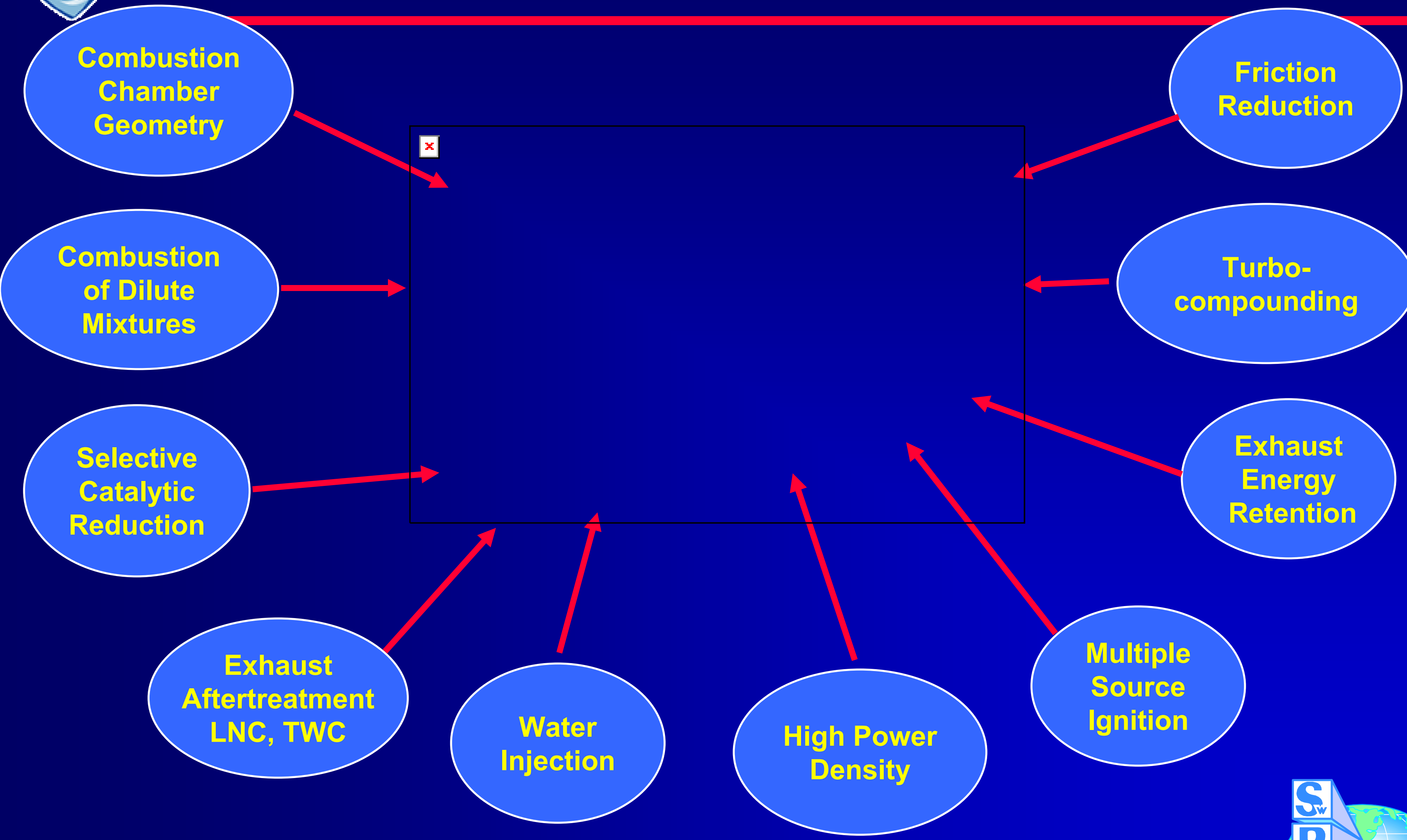
- Knock (uncontrolled combustion)
- NO_x emission regulations
- Structural limitations
- Combustion efficiency (unburned fuel)
- Combustion rate (slow reactions at low temperature)
- In-cylinder heat loss
- Frictional losses
- Pumping losses
- Exhaust port and manifold heat loss
- Efficient exhaust energy recovery

ARES Technical Assumptions

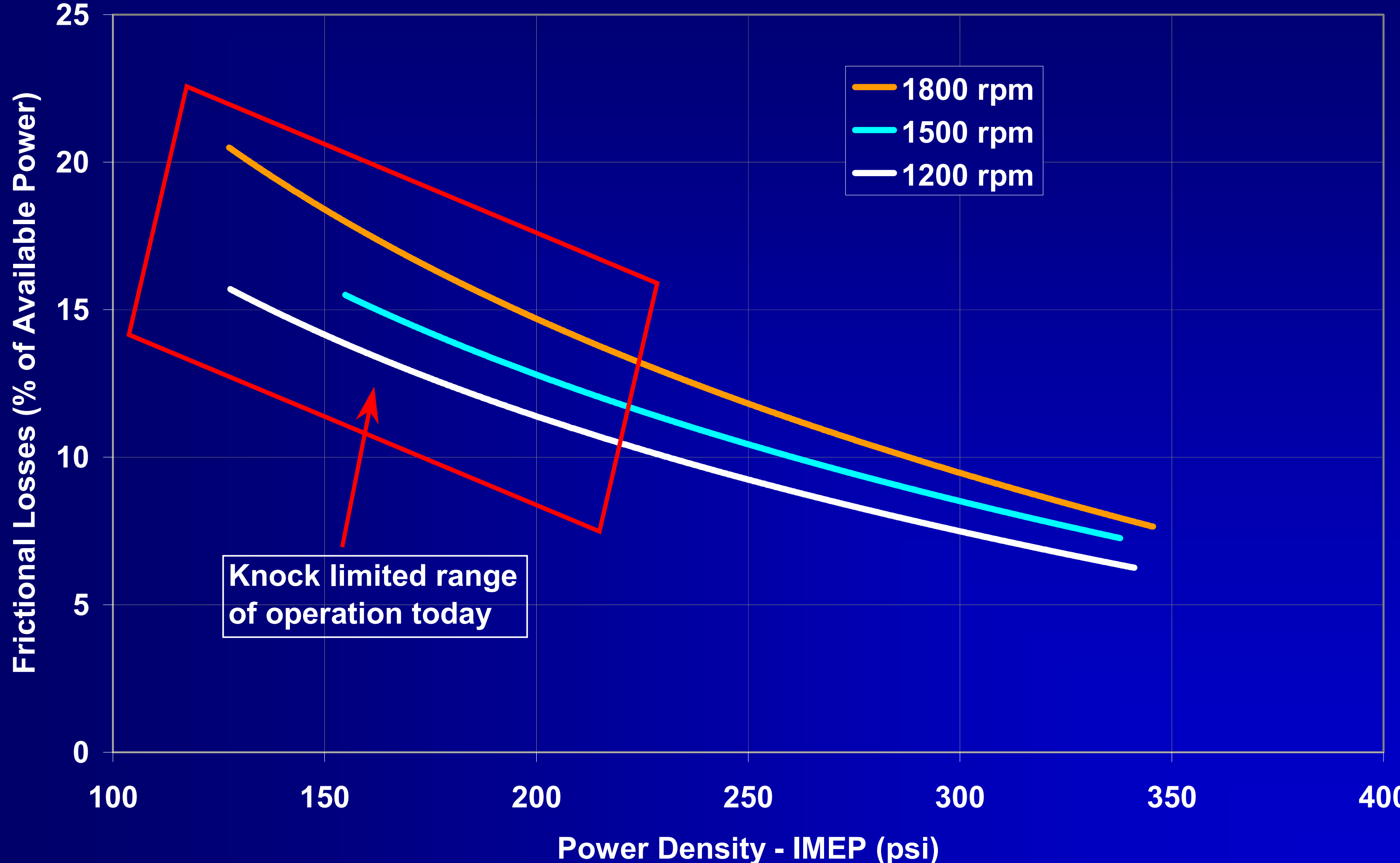
- High efficiency will require higher power density (BMEP)
- Knock limitations must be overcome to achieve higher BMEP
- Dilute air-fuel mixtures required for low NO_x - two alternatives
  - Lean air-fuel ratios plus lean NO_x aftertreatment
  - Stoichiometric air-fuel ratios plus high levels of exhaust gas recirculation (EGR) with 3-way catalyst
- Ignition and combustion of dilute mixtures a necessity
- Some type of aftertreatment required
- Exhaust energy retention for turbocharging is a key technology
- Minimized parasitic losses (friction, pumping, etc)

Multiple technologies will be required to achieve both efficiency and emissions goals!

ARES Technologies



Increased Power Density

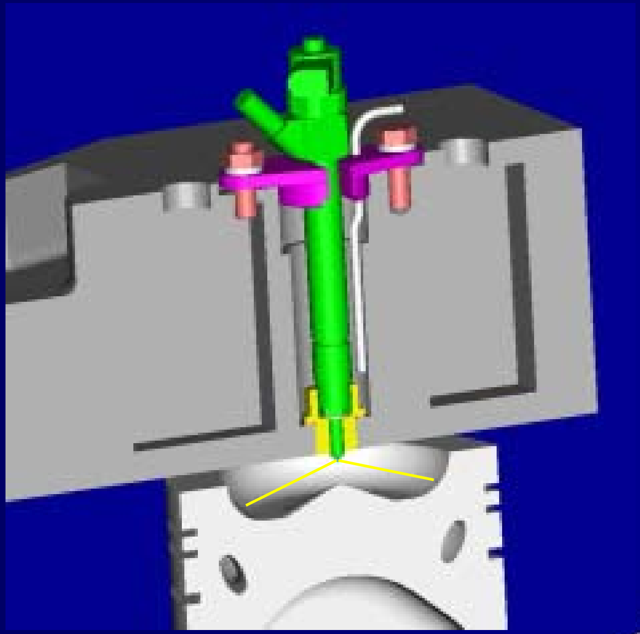


- Higher power density leads to a reduction in frictional losses

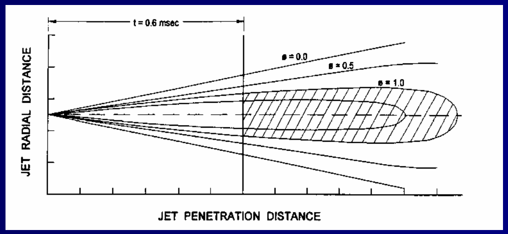
Multiple Site Spark Ignition

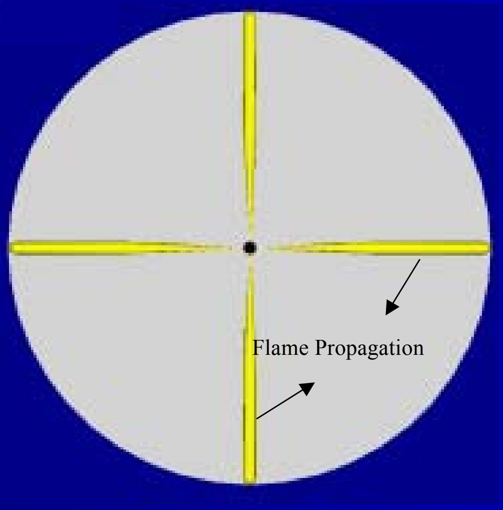
- Combustion, initiated at multiple sites, proceeds from outside toward center
- Faster combustion rates and elimination of end gas regions prone to knock
- Improved
  - lean misfire limit
  - shorter combustion duration
  - higher combustion efficiency
  - higher BTE

Pilot Ignition also a Multi-Site Ignition Concept

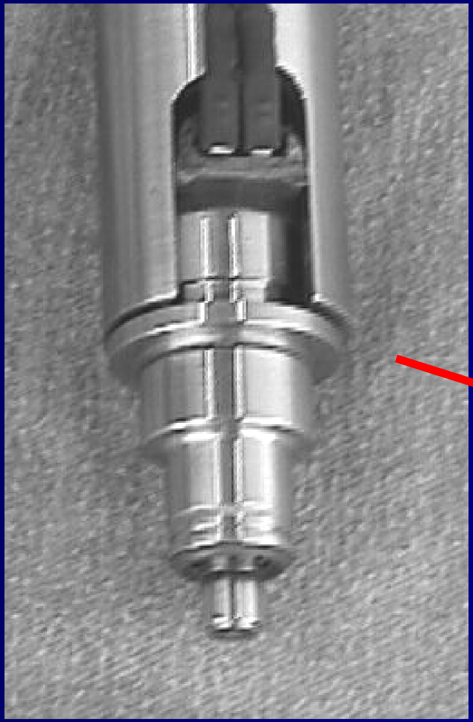


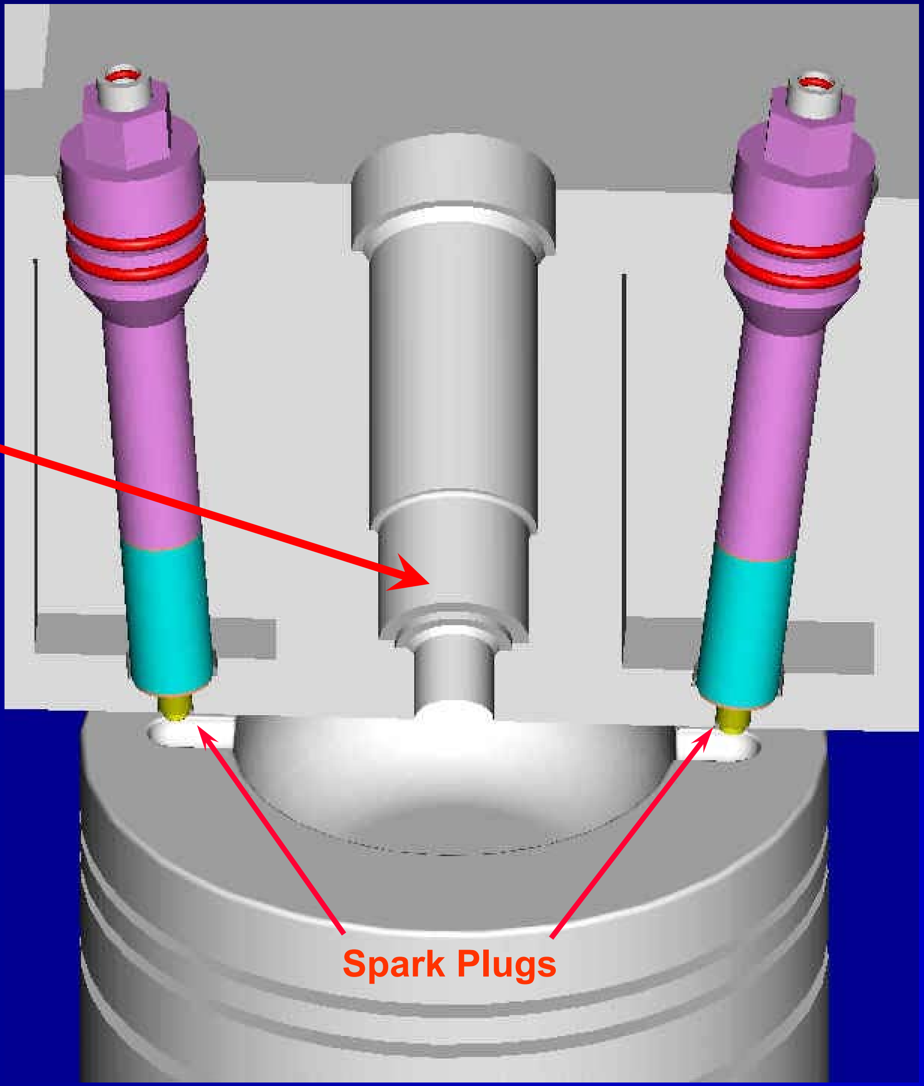
- Diesel fuel penetrates the combustion chamber prior to ignition
- High pressure enable good penetration
- Injection pressures of diesel injection systems now approaching 30 ksi





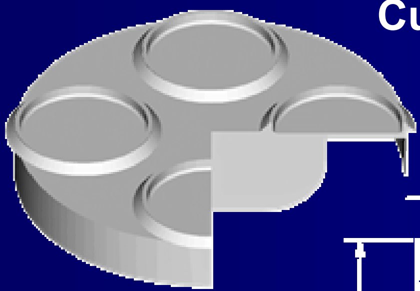
Simultaneous Knock and NO_x Mitigation: Direct In-cylinder Water Injection



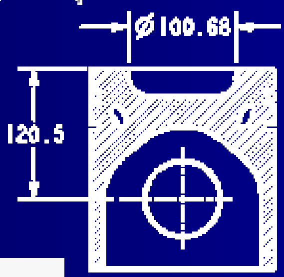


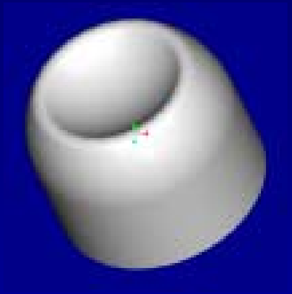
Water injection used to lower in-cylinder temperatures reducing potential for knock and NOx formation

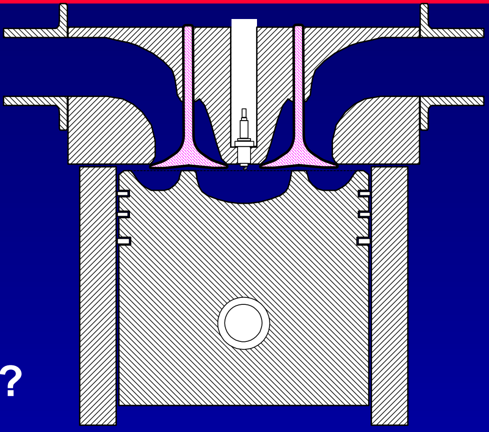
Combustion Chamber Evolution



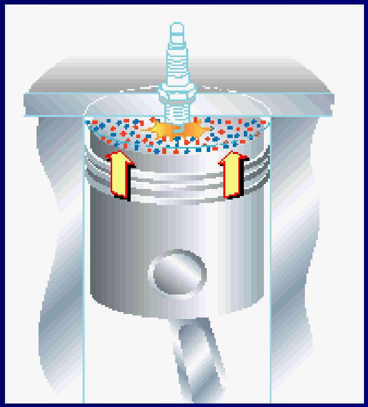
Current technology

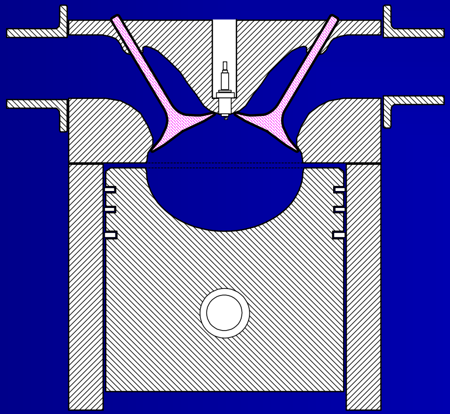






Future ?





- **Appropriate design of combustion chamber required for**
  - **Complete combustion of dilute mixtures**
  - **Knock tolerance**

Aftertreatment Options

- Lean NO_x catalyst (LNC) - currently not a viable technology
- Selective catalytic reduction (SCR)
  - Viable, requires reductant
  - Potential for ammonia slip, control issue
  - 90-95% efficiency
- 3-way catalyst if stoichiometric combustion
  - Proven in light duty, shorter life applications
  - 95-99% efficiency

Engine Development Decisions

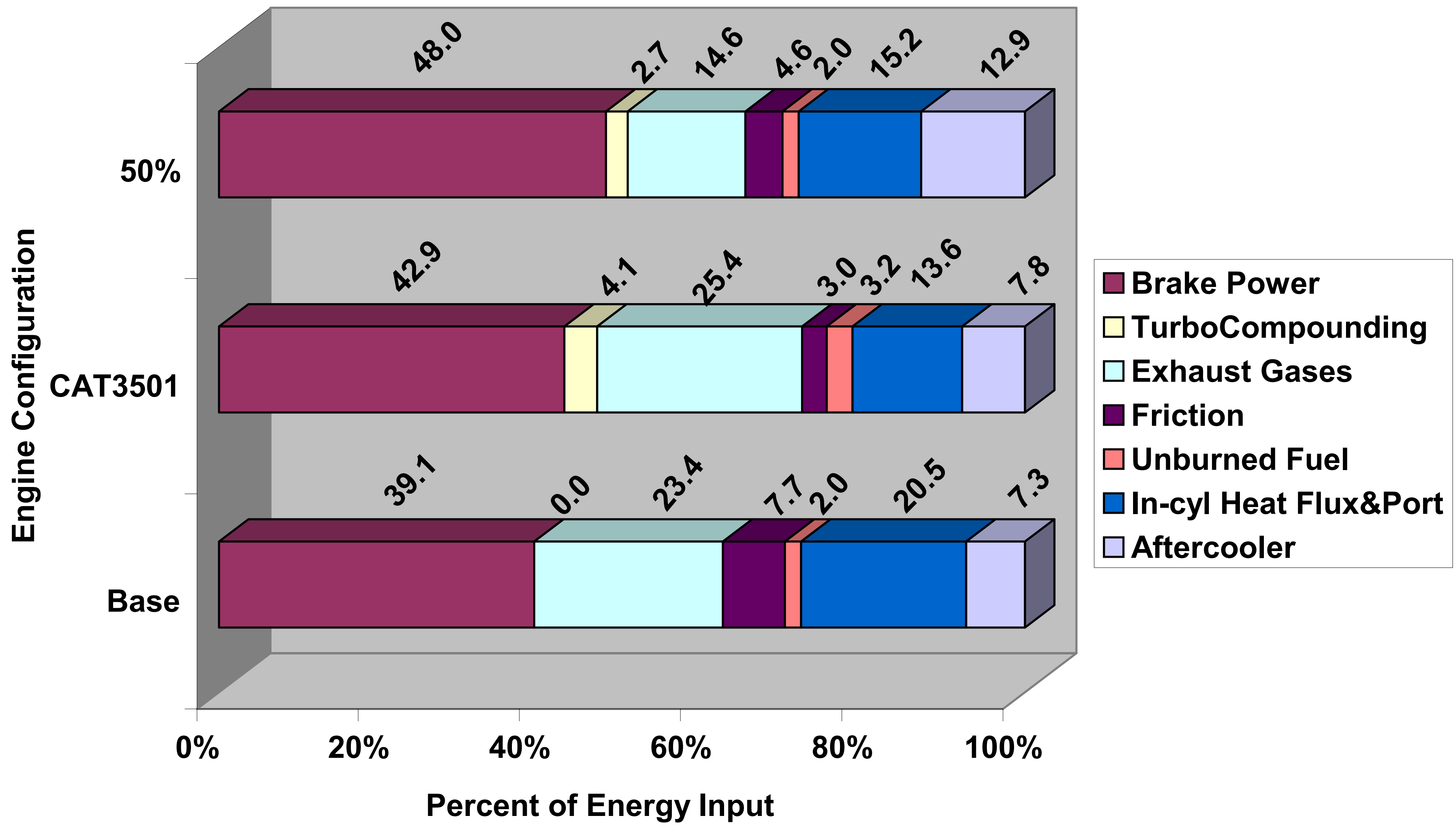
- Lean burn vs stoichiometric
  - Dictates exhaust aftertreatment options
    - 3-way catalyst
    - Selective catalytic reduction
- Turbulent combustion chamber vs non-turbulent
- Multiple-site ignition vs single source

Expected Gains for 50% BTE Come From Application of Multiple Technologies

	Description	Contribution (BTE points)
Miller Cycle	1.5 Expansion Factor	~ 1.7 points
Turbo-Compounding	80% turbine efficiency 95% gear train efficiency	~ 1.5 points
Low Heat Rejection Exhaust System	60 % heat loss reduction	~ 1.9 points
Low Friction/High BMEP	87% to 91% mechanical efficiency	~ 2.3 points
Burn Rate	20 degree to 18 degree 10 to 90% burn duration	~ 0.7 points
Flow Improvement	20% Improvement	~ 1.2 points
Two-Stage Compression w/ Intercooling	80% compressor efficiency per stage, 313 K intercooling	~ 0.4 points

Combination of above technologies improves brake thermal efficiency from 40 to 50 percent

Energy Balance for Base Engine, CAT3501 Test Engine, and 50 Percent ARES Engine



Improvements Required for ARES Engine

Parameter	Current Technology	ARES Technology
Power Density (BMEP)	170-200 psi	350 psi
Peak Cylinder Pressure	1500-1800 psi	3200 psi
Turbocharger Efficiency	56 %	65+ %
Mechanical Efficiency	87-89 %	91 %
Combustion Rate	25-30 Crank Angle Degrees	15-18 Crank Angle Degrees
Turbocompounding	No	Likely

Accomplishments

- Modeling efforts led to vision of ARES technology
- Bench scale testing and literature review of technology resulted in revision of technical path
- Single cylinder engine testing verified modeling assumptions
- Evaluation of potential combustion systems
  - Miller Cycle, micro-pilot open chamber, direct water injection, multiple-source ignition, lean burn, and stoichiometric with EGR

Conclusions

- Good near term potential to utilize stoichiometric combustion technology with 3-way catalyst for control of NO_x in advanced reciprocating engine systems for power generation
- Exhaust gas recirculation will be used as diluent for mitigating NO_x formation and knock
- Lean NO_x catalyst technology must be developed to enable lean burn combustion systems
- Potential ultra lean burn exception is implementation of homogenous charge compression ignition (HCCI)

Project Benefits and Impacts

- Identified and demonstrated various approaches to achieve the program goals
- Provided the competitive teams with direction for future development
- Provided DOE with direction for evaluation of the various proposals

Next Steps

- Competitive programs in progress
- Precompetitive areas identified for targeted research
- Continue ARES consortium providing guidance for university and commercial programs
  - Keep existing frame work of manufactures and suppliers intact as program advisory committee
  - Investigation of combustion concepts with high technical risk not pursued under ARES program
  - Evaluation of stoichiometric-high EGR operation with 3-way catalyst as a promising near term technology
  - Integration of lean-burn combustion engine with various aftertreatment options to achieve ultra-low NOx emissions

A Word About Funding...

- ARES - a multi-year program
- Funded incrementally by government and industry
- Equal cost share
  - Industry / Government

ARES

Advanced
Reciprocating
Engine
Systems