Compressed Natural Gas Direct Injection (CNG-DI)

A Growth Opportunity

Harold Hochstadt

ORBITAL

Natural Gas Direct Injection

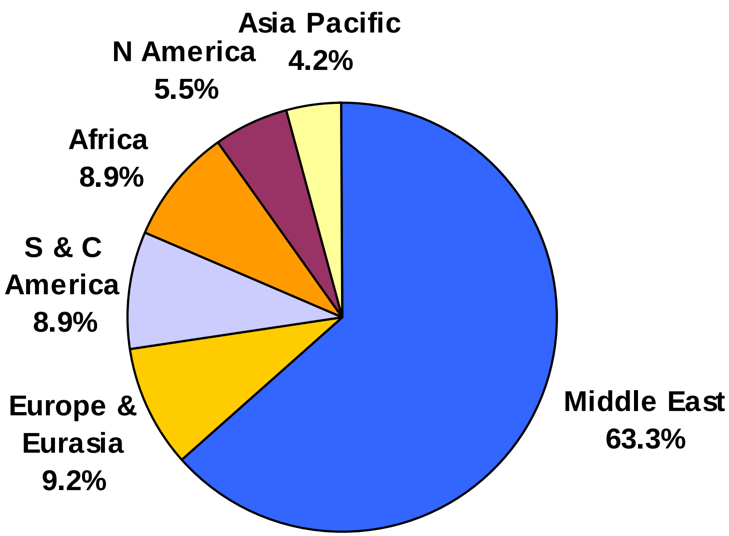
- Background and rationale
- Modified Strata-1 (air injector) Testing with CNG
  - Nominal Injector Specification
  - Bench Test Initial Prototype Injector
  - Strategies for Fuel Metering Range
  - Initial Engine Test Results
- Current Development Status

Rationale for Gaseous DI CNG

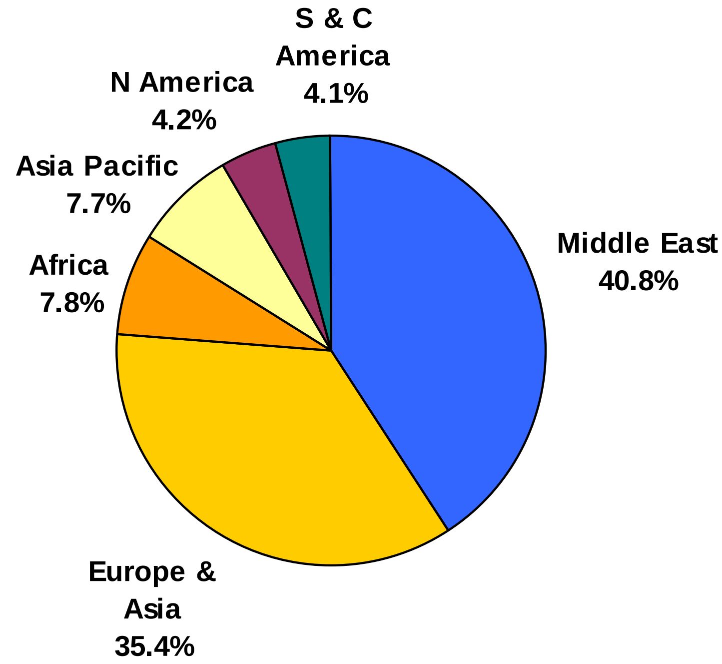
- Energy Security – distributed sources
- Natural gas reductions in greenhouse gas emissions (CO_2) and utilisation of additional energy reserves
  - Reductions in CO_2 of 20 to 25% over current gasoline SI engines possible due to fuel properties
  - Emissions reduction – Air Quality Improvement
- Cost of fuel for transport – 50% of gasoline
- Many Alternative Fuels Policy show significant introduction of CNG for transport fuel (eg. 10% by 2020 in Europe)

CNG as Alternate Fuel Resource
Fuel Proved Reserves, 2003

OIL



NATURAL GAS

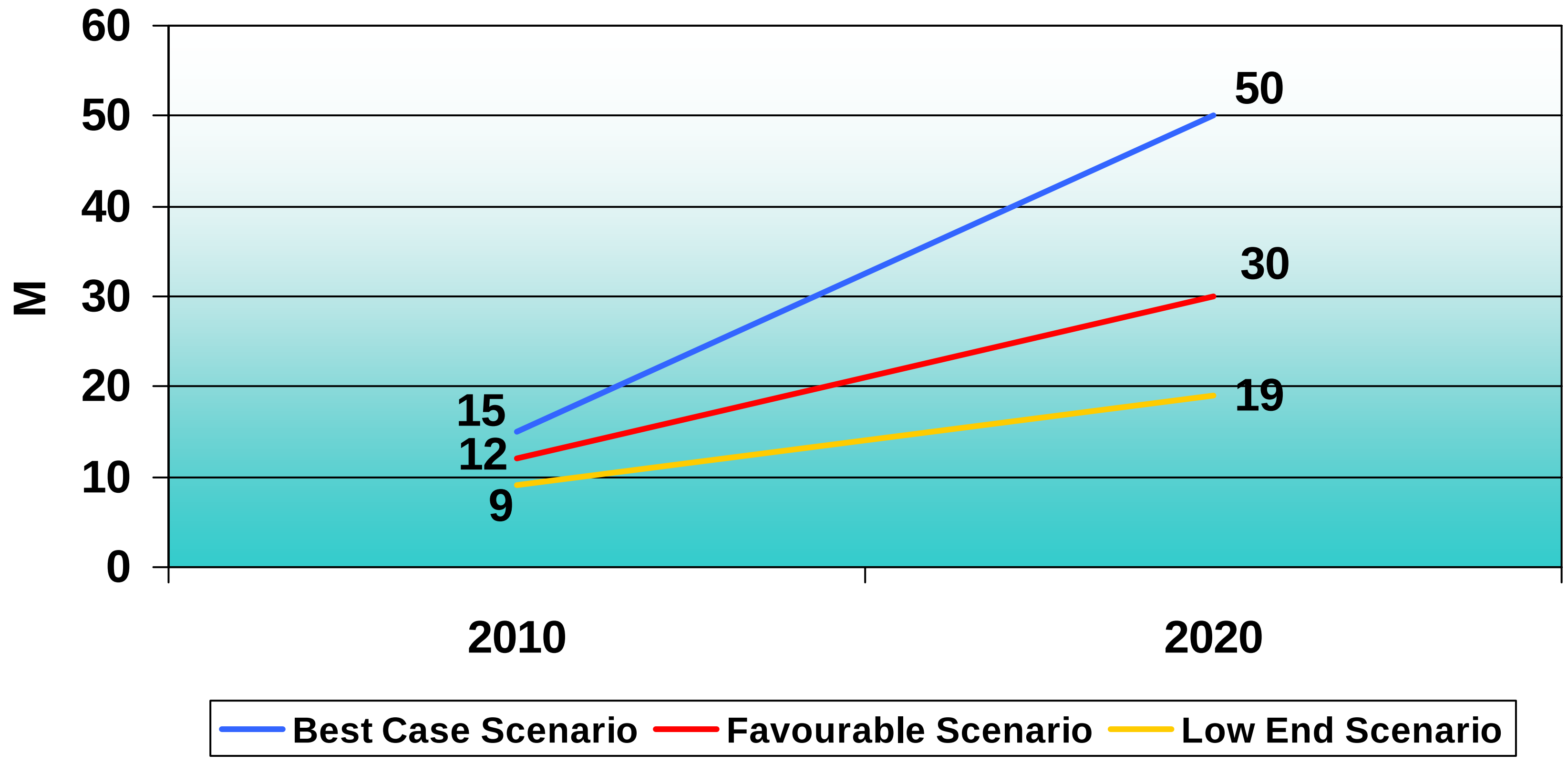


Source: BP Statistical Review of World Energy, June 2004 (Data 2003)

Rationale for Gaseous DI CNG

- An issue associated with gaseous fuels is the reduced engine full load performance due to displaced air. In a natural gas engine this is typically 9%
- Direct injection of the fuel after inlet valve closure can eliminate loss in airflow due to air displacement in order to improve the full load performance of natural gas engines
- Direct injection of CNG can also further reduce CO_2 emissions through lean, stratified operation

World CNG Vehicle Volume Projections



•NGV GLOBAL View JUAN C. FRACCHIA NGV 2004 – IV ExpoGNC

Natural Gas CO_2 Emissions

- Today:
  - Clear advantage over PFI gasoline engines (20-25% reduction in CO2 emissions) but on par with diesel (tank-to-wheel only)
- Future (2010+ technology):
  - Well to wheel analysis shows 16% reduction compared to gasoline and 13% reduction compared to diesel possible
- Further advantages possible:
  - Advanced engine technology (including DI CNG)
  - Highly boosted engines to take advantage of high Octane characteristics

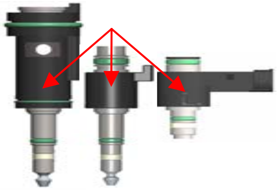
European Natural Gas Vehicle Association

Gaseous Direct Injection

- Gaseous Direct Injection presents a number of challenges including:
  - Start of injection after inlet valve closure resulting in a high flow rate requirement of the injection system.
  - Achieving the fuel metering turn-down ratio required for idle fuelling.
  - Fuel injector durability when operating with dry gas.

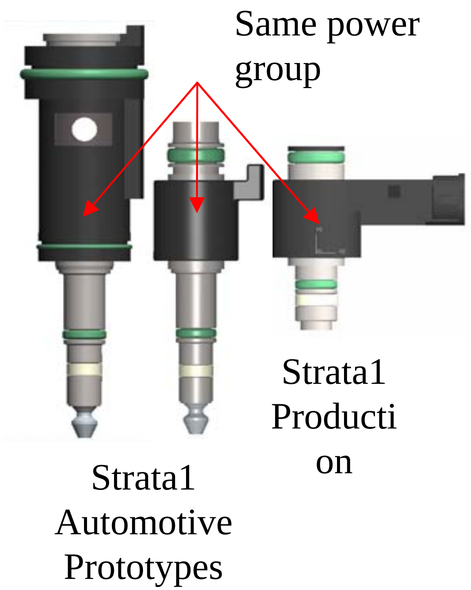
Gaseous Direct Injection

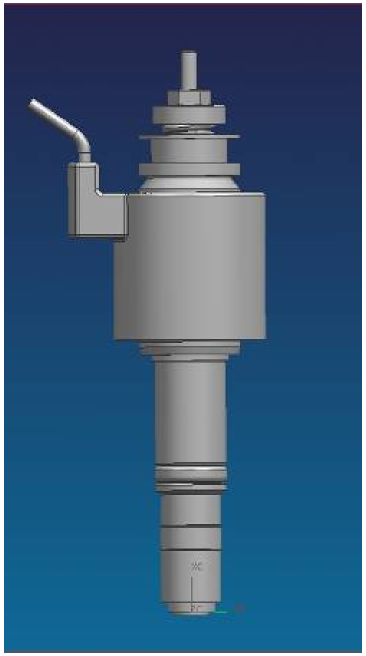
- There are many synergies between the Orbital developed air-assist DI system and the requirements for gaseous fuel direct injection
  - Air Injector Nozzle has larger flow cross-section than typical liquid only injectors
  - Designed for application within the combustion chamber
  - Package envelope has been designed to compactly fit into modern multi-valve cylinder heads
  - Could share power-group with production injector



Gaseous Direct Injection

- Orbital have begun development of a gaseous fuel direct injection system based on extensive experience with the air-assist direct injection system





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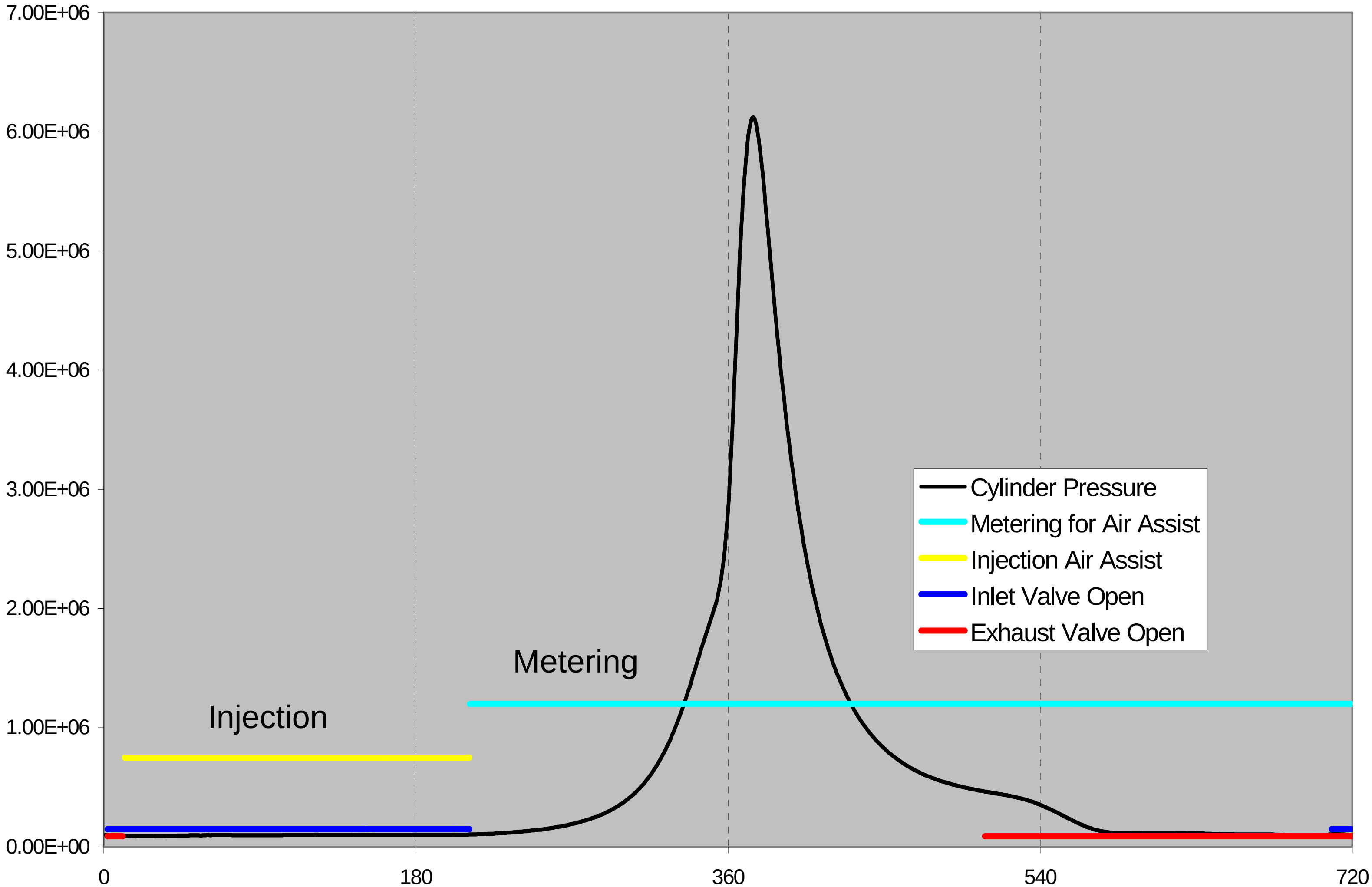
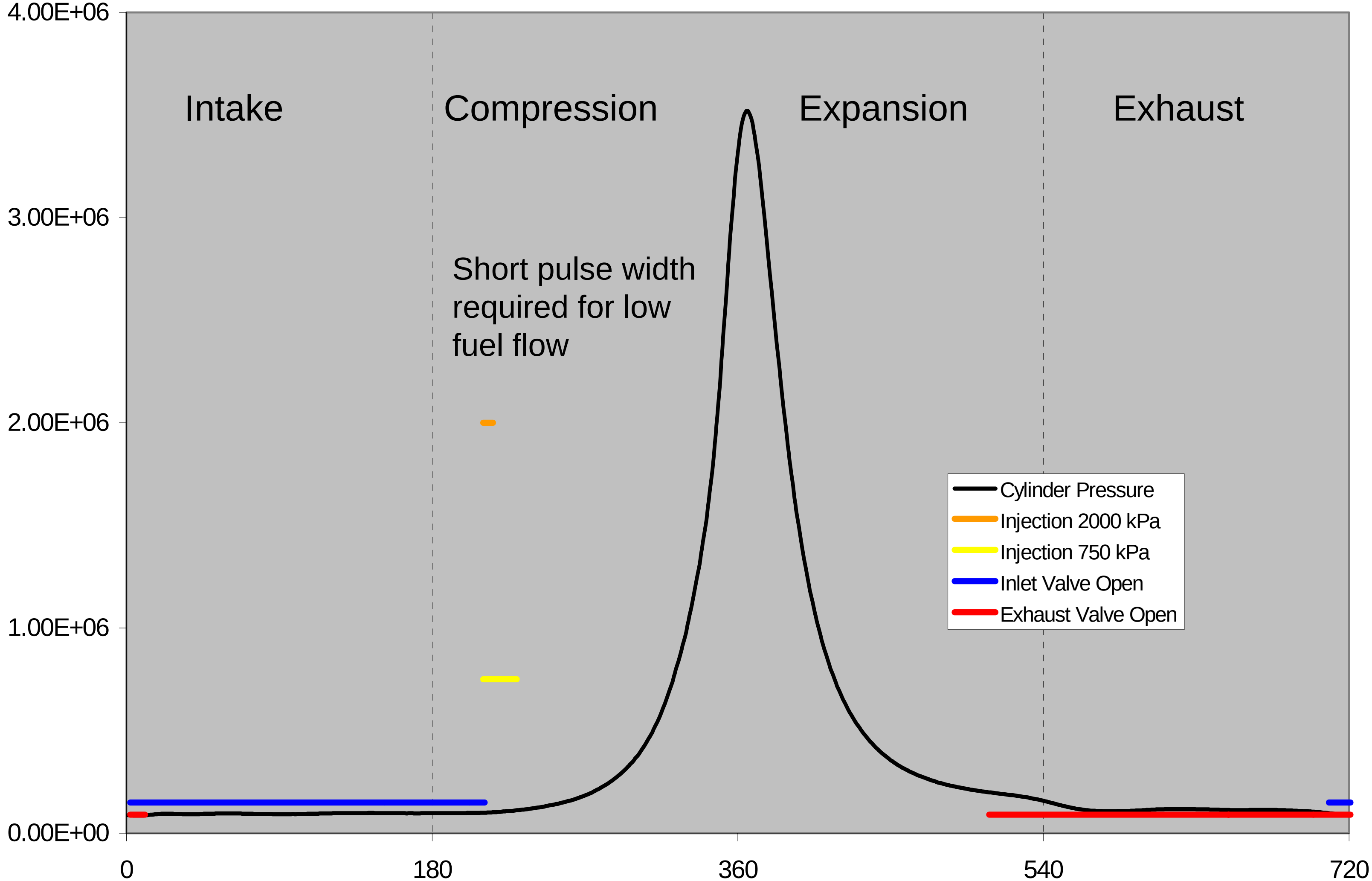
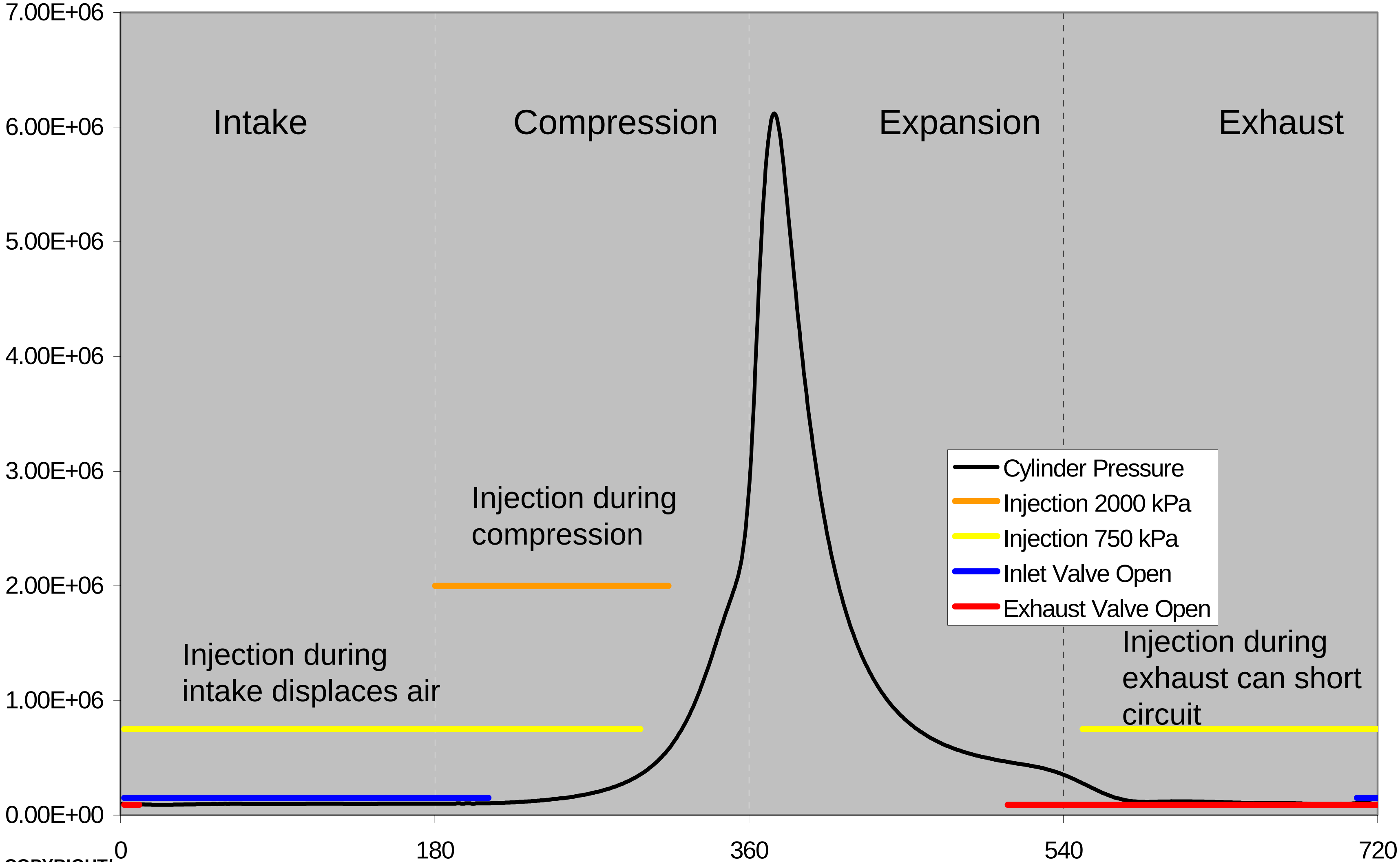
Injection Timing – Air-Assist DI



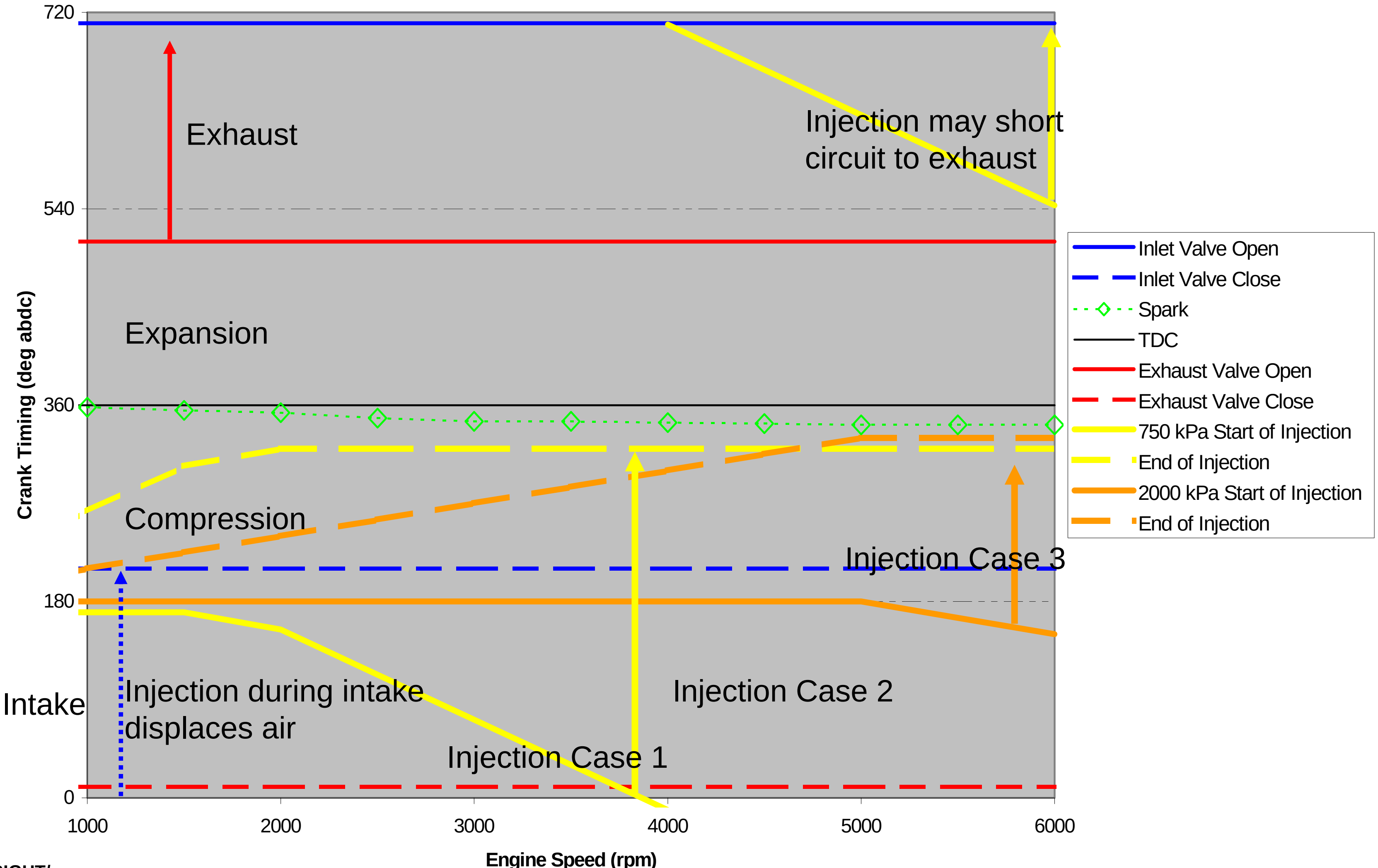
Injection Timing – Gaseous DI @ Part Load



Injection Timing – Gaseous DI @ Full Load



Gaseous Injection Timing – Speed Effect



Initial DI CNG Test

- Initial testing on modified automotive “air” injector to help determine new injector specification targets
- Initial DI CNG injectors with modifications to allow testing up to 1.2MPa injection pressure
- (demonstrated on Lotus Elise prototype)
  - – Insufficient flow rate
  - – Insufficient turn-down

Gaseous Direct Injection Development

- Desirable system characteristics:
  - Simple (14V) solenoid for low cost / complexity
  - Low operating pressure – maximise tank usage (mileage) without additional pump
  - Small injector size suitable for installation into existing gasoline DI engines (enables potential of PFI for gasoline + existing DI cylinder head for CNG for multi-fuel vehicle).
  - Flexibility of injected plume characteristics for optimising part load and full load combustion
  - Maintain sonic flow through injector for metering accuracy

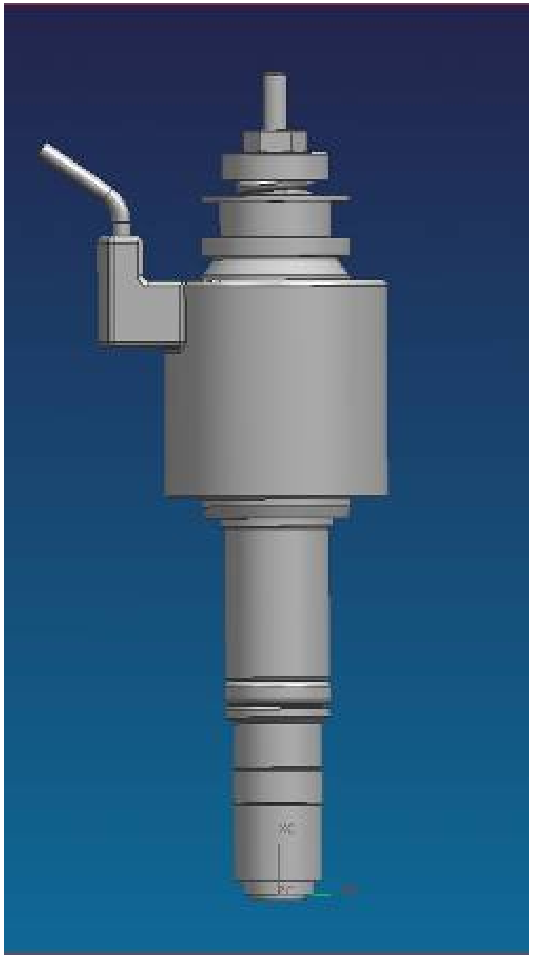
Nominal Specification for Prototype Injection System

1) CNG Fuelling capability for a 400cc naturally aspirated cylinder.
2) Nominal injection window of 130 c.a. deg from 200 deg BTDC to 70 deg BTDC at 5500 rpm.
3) Sonic flow throughout injection event. Latest end of injection 40 deg BTDC. (Cyl pressure ~710 kPa)
4) Match stated characteristic for Production PI CNG injector.
5) Nominal 14 volt system.

Nominal Injector Specification / Targets

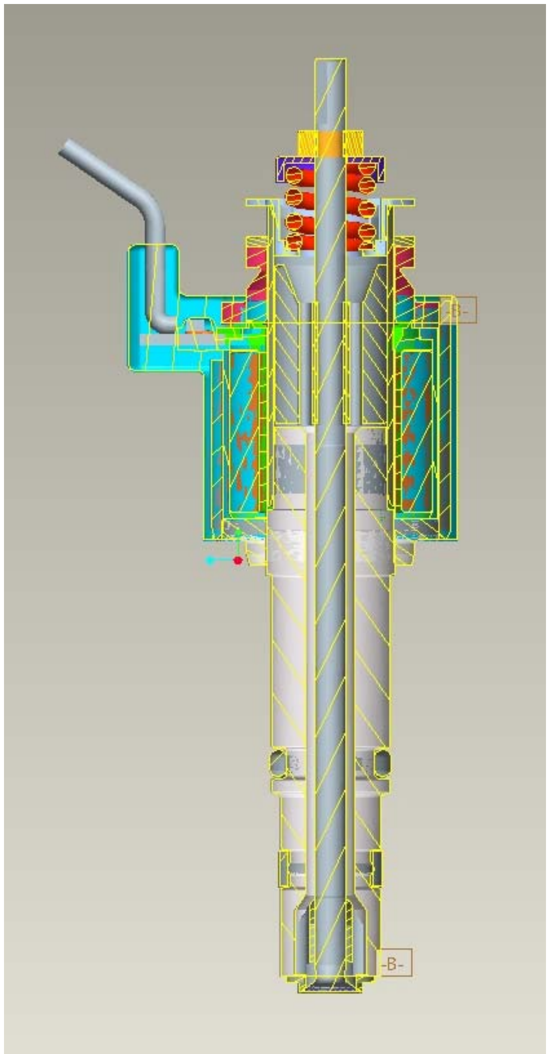
Item	Specification
Minimum Fuel	3.5 mg/pulse
Maximum Fuel	36 mg/pulse
Maximum Fuel Duration	4.0 msec
Nominal fuel flow	9 mg/msec (9 g/s)
Minimum Fuel Pressure	1300 kPa absolute
Nozzle Leakage	< 0.5 cc/min.
Durability	290,000,000 cycles
Mounting	~Ø8 mm injector leg.
Temperature Range	-30 to 120 °C
Voltage Range	6 to16 Volts

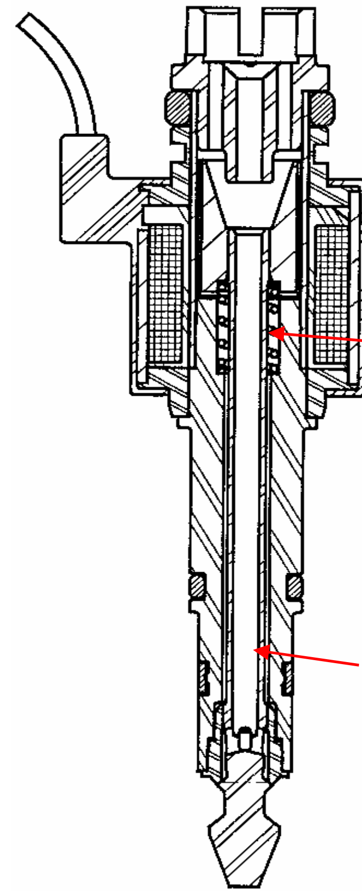
Orbital Prototype Gaseous Direct Injector



- Outward Opening Valve
  - Based on experience with air assist direct injector.
  - Reduces spring load and solenoid requirement to resist combustion pressure.
  - Simple, low cost 12V solenoid design
- Low maximum injection pressure of 1200 to 2500 kPa
  - Allows substantial utilisation of pressurized fuel tank without requiring an on-board fuel pump.
- Increased gauge-line flow
  - High flow rate with reduced stroke improves turn-down ratio

Orbital Prototype Gaseous Direct Injector





"STRATA 1 AUTO"

Strategies for Achieving Turn-down Ratio

1. Turn down ratio by injection duration
   - Maximum duration of 4msec = minimum duration of approx 0.4msec
   - Requires rapid opening and closing to achieve small opening times
   - Difficult to achieve with conventional (solenoid) actuation, especially for high lifts (approx 0.26mm to achieve flow rate at 2.5MPa)

2. Variable flow area
   - Variable aperture (orifice size)
   - Variable lift (stroke)
   - Needs to be simple, low cost for high volume production

Strategies for Achieving Turn-down Ratio (cont'd)

3. Variable injection pressure
   - Gaseous flow rate proportional to pressure
   - Dynamic control of rail pressure difficult (lag from high pressure to low pressure)

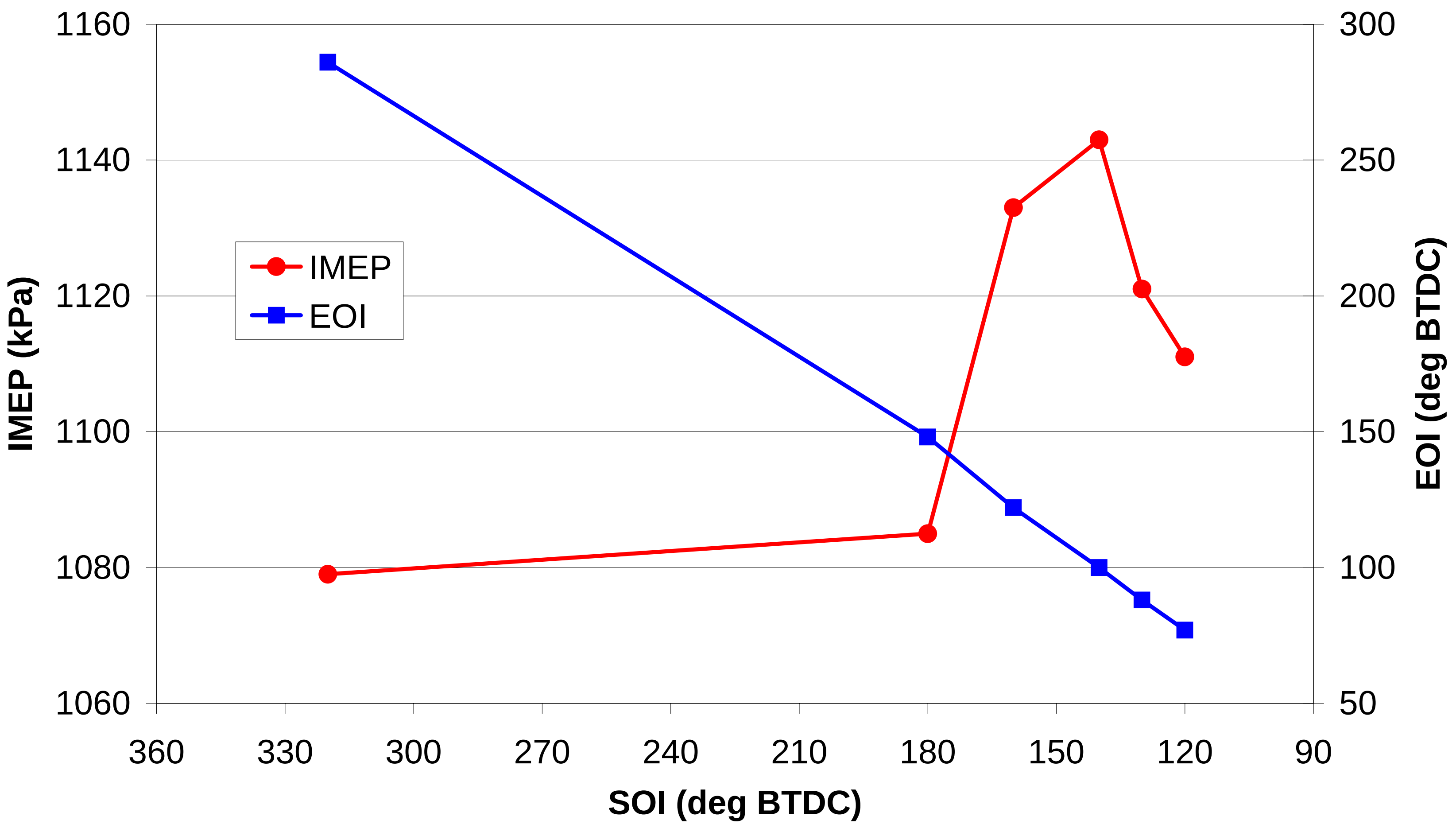
4. Multiple injectors
   - Two direct injectors (difficult for packaging)
   - Use PI for part load and DI for full load
   - Added expense of two fuel systems for gas only

Initial Prototype Injector Engine Test Results

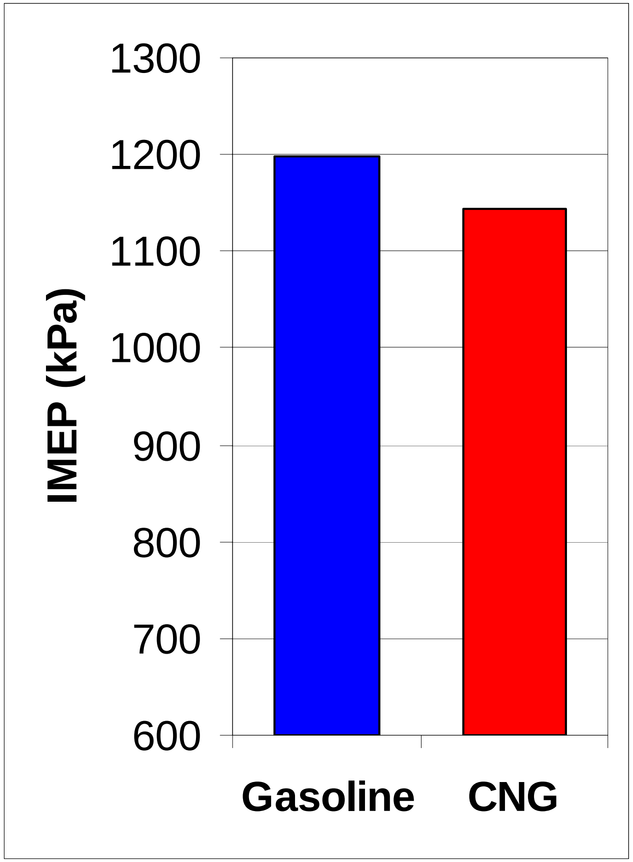
- Engine Testing on SCRE:
  - 400cc DOHC 4-stroke engine
  - C/R = 11.8:1
  - Central Injection Combustion Chamber Design
  - 2000rpm, full load presented
  - Full load engine testing completed

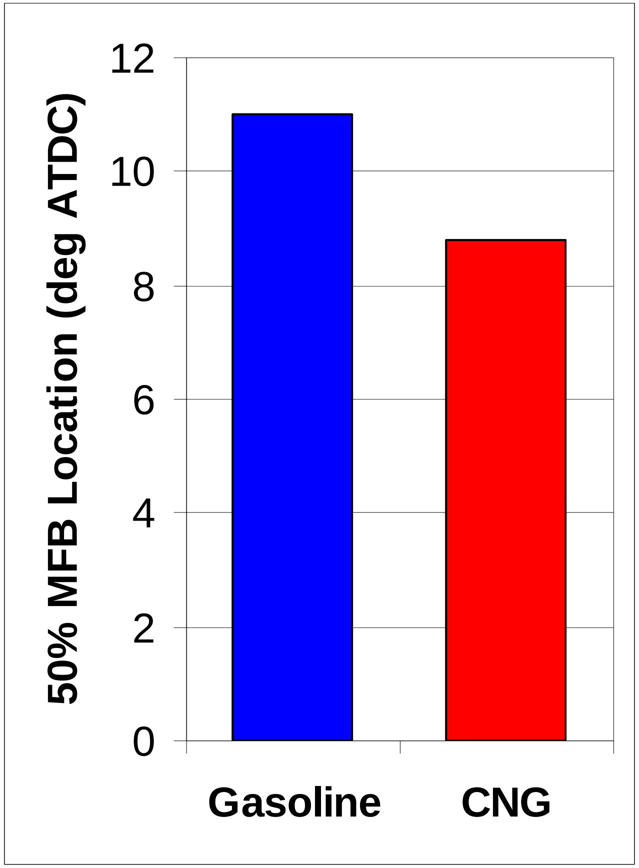
Initial DI CNG Full Load Operation at 2000rpm

400cc SCRE, central injection 11.8:1 C/R



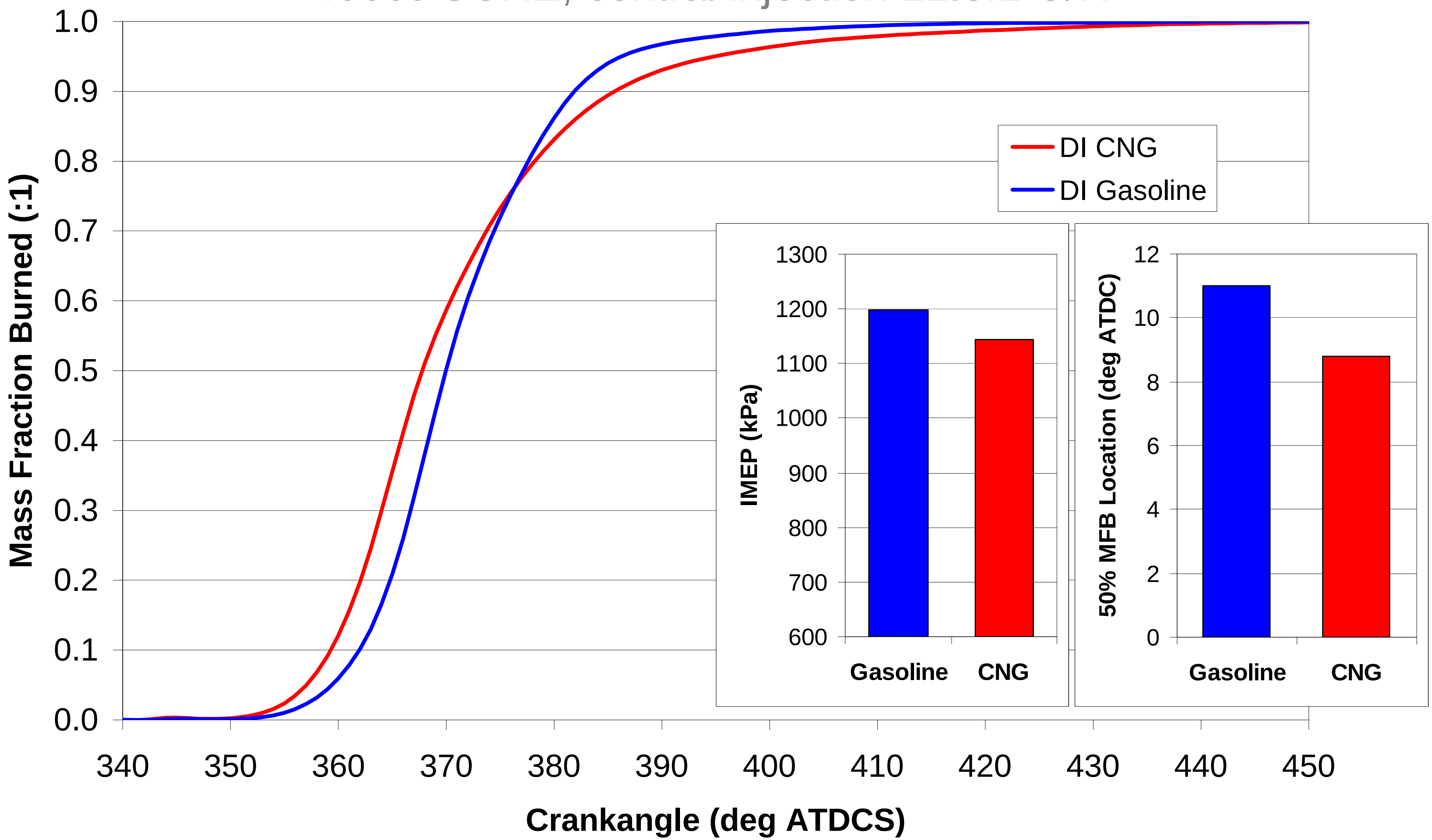
DI CNG Full Load Operation at 2000rpm



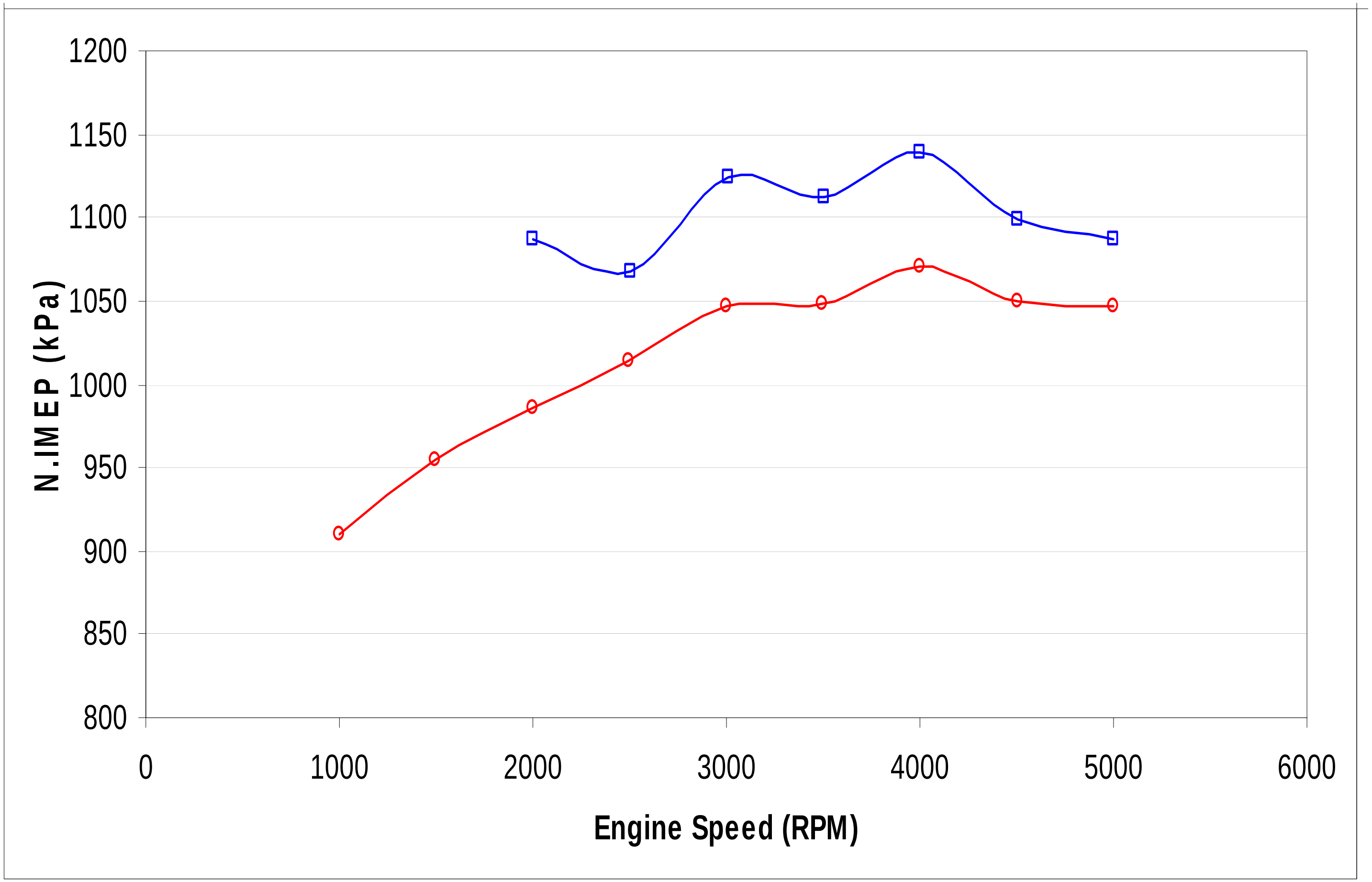


Initial DI CNG Full Load Operation at 2000rpm

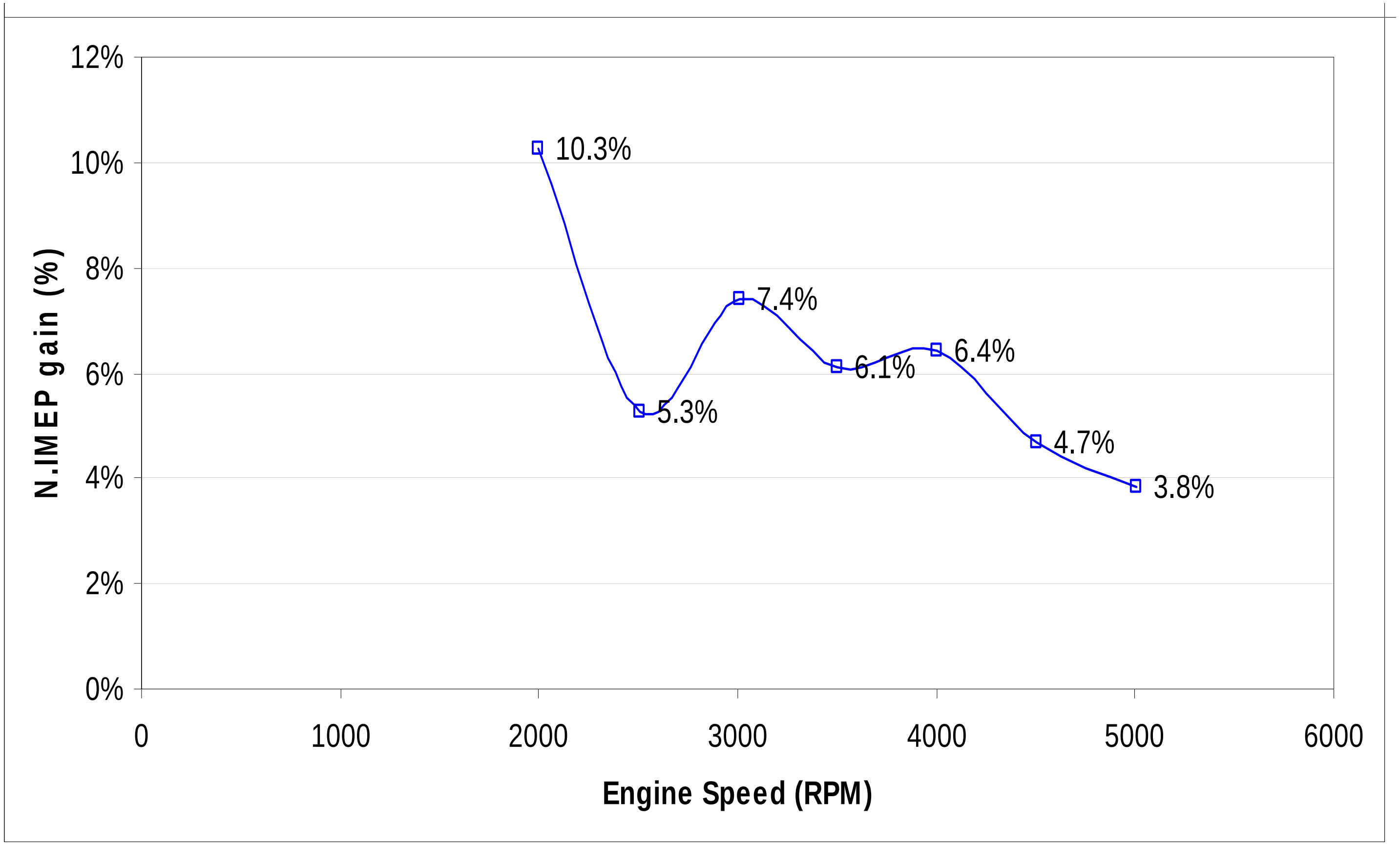
400cc SCRE, central injection 11.8:1 C/R



DI CNG versus Manifold Injected CNG



DI CNG versus Manifold Injected CNG

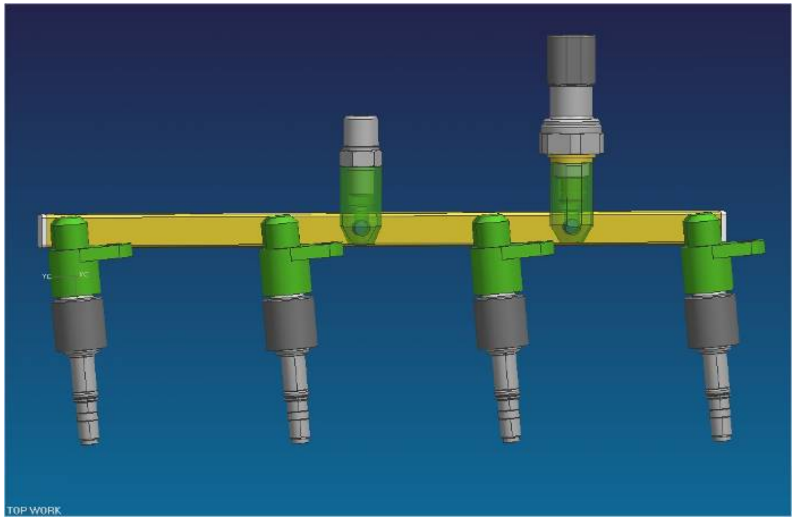


Durability Status

- Bench Durability Test Modified Strata Injectors
  - Tests conducted with dry air
  - Stroke is observed to increase (armature wear)
  - Some wear of bearing surface and spring

CNG-DI Injector Status

- Prototype Injectors
  - Initial samples produced for bench testing
  - Material / coating options for increased durability under investigation
  - Low impact armature design & modified driver waveform progressing for reduced wear



CNG-DI Injector Status

- Prototype Development
  - CNG test facility installed at Orbital including bench test & engine dynamometer testing
  - Single cylinder and multi cylinder development in parallel
  - System development, including specific EMS strategies under development
  - Engine testing of new prototypes for injector development
  - ***Combustion system development commencing as injector design at sufficient maturity***