Commercialization of Environmental and Fuel Efficiency Technology Spinoffs of Fusion Research

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Presentation to Fusion Energy Scientific Advisory Committee (FESAC) meeting Feb. 27-28, 2002

Commercialization of Environmental and Fuel Efficiency Technology Spinoffs of Fusion Research

- Waste treatment and energy recovery systems
  - Improved protection of the environment
  - Commercial units being sold and installed by Integrated Environmental Technologies (spinoff company from research at Battelle PNNL and MIT)
  - Renewable hydrogen energy production from waste
  - Initial R&D support from DOE Environmental Management

- Onboard hydrogen generation technology for improved internal combustion engine vehicles
  - Clean, high efficiency gasoline engine
  - Diesel engine pollution reduction by exhaust aftertreatment
  - Support from DOE office of Transportation Technologies
  - Commercial development of MIT plasmatron fuel converter technology by Arvin Meritor ($7 billion/yr vehicle components and systems manufacturer). Licensing of intellectual property and support of research at MIT

Integrated Environmental Technologies, LLC

Waste Transformation Using Plasma Enhanced Melter™ Technology

Company Background

- IET, a Richland, WA company, is commercializing Plasma Enhanced Melter™ (PEM™) technology for waste treatment and clean energy production in a range of markets
- PEM™ technology uses optimized combination of plasma heating and joule-heated glass melter technology
- PEM™ process builds on development of joule-heated glass melter technology at Battelle Pacific Northwest National Laboratory (PNNL) and plasma technology at MIT

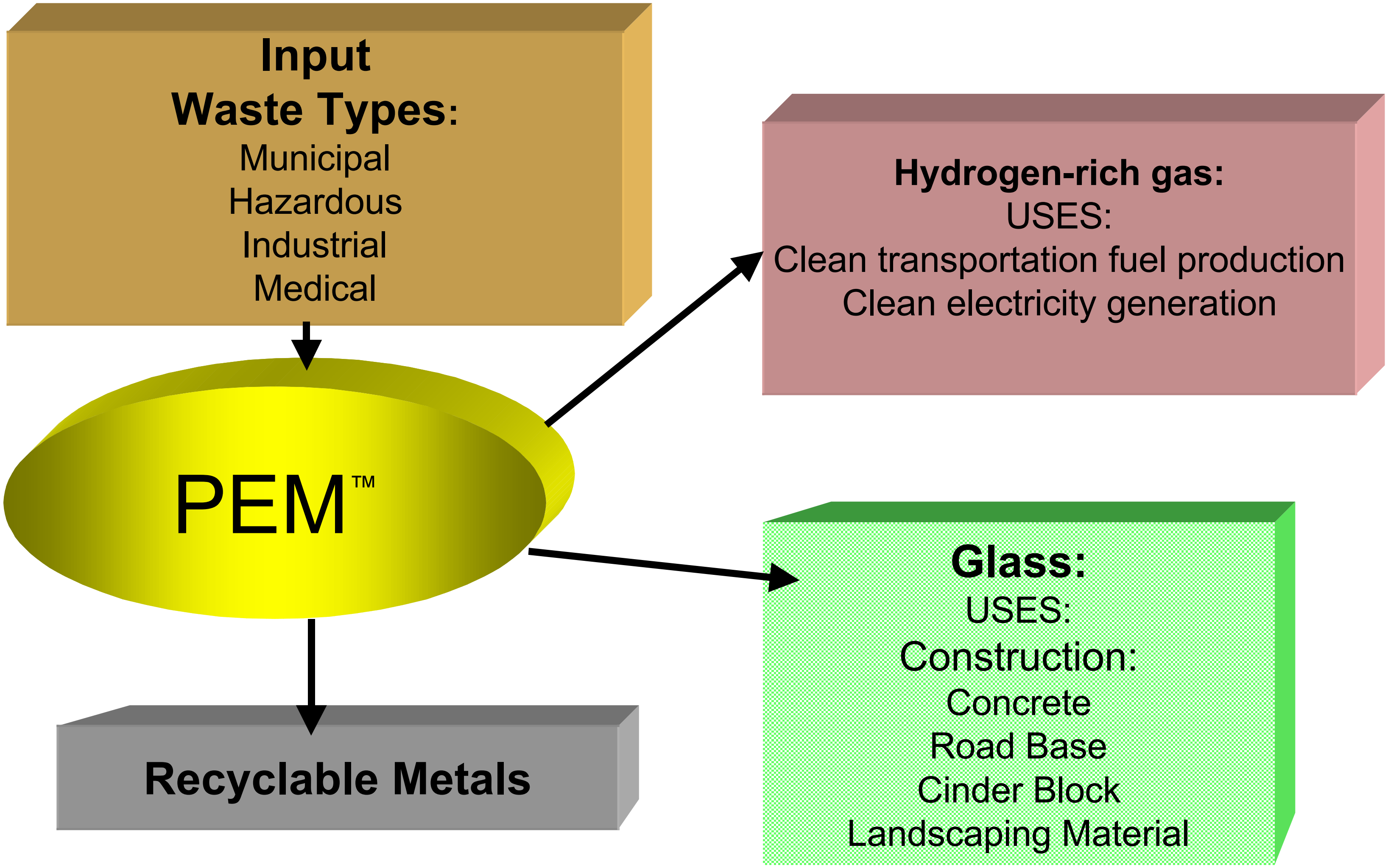
Company Background con’t

- IET staff includes engineers who formerly occupied key positions in the DOE waste vitrification program at Pacific Northwest National Laboratory

- IET has installed its first commercial units for mixed radioactive/hazardous waste treatment at Richland, WA, and medical waste at Honolulu, Hawaii (1-10 ton per day size units)

- IET has sold units for installation in other parts of United States, Japan, Taiwan and Malaysia

Wastes are Converted to Useful Products



Input
Waste Types:
Municipal
Hazardous
Industrial
Medical

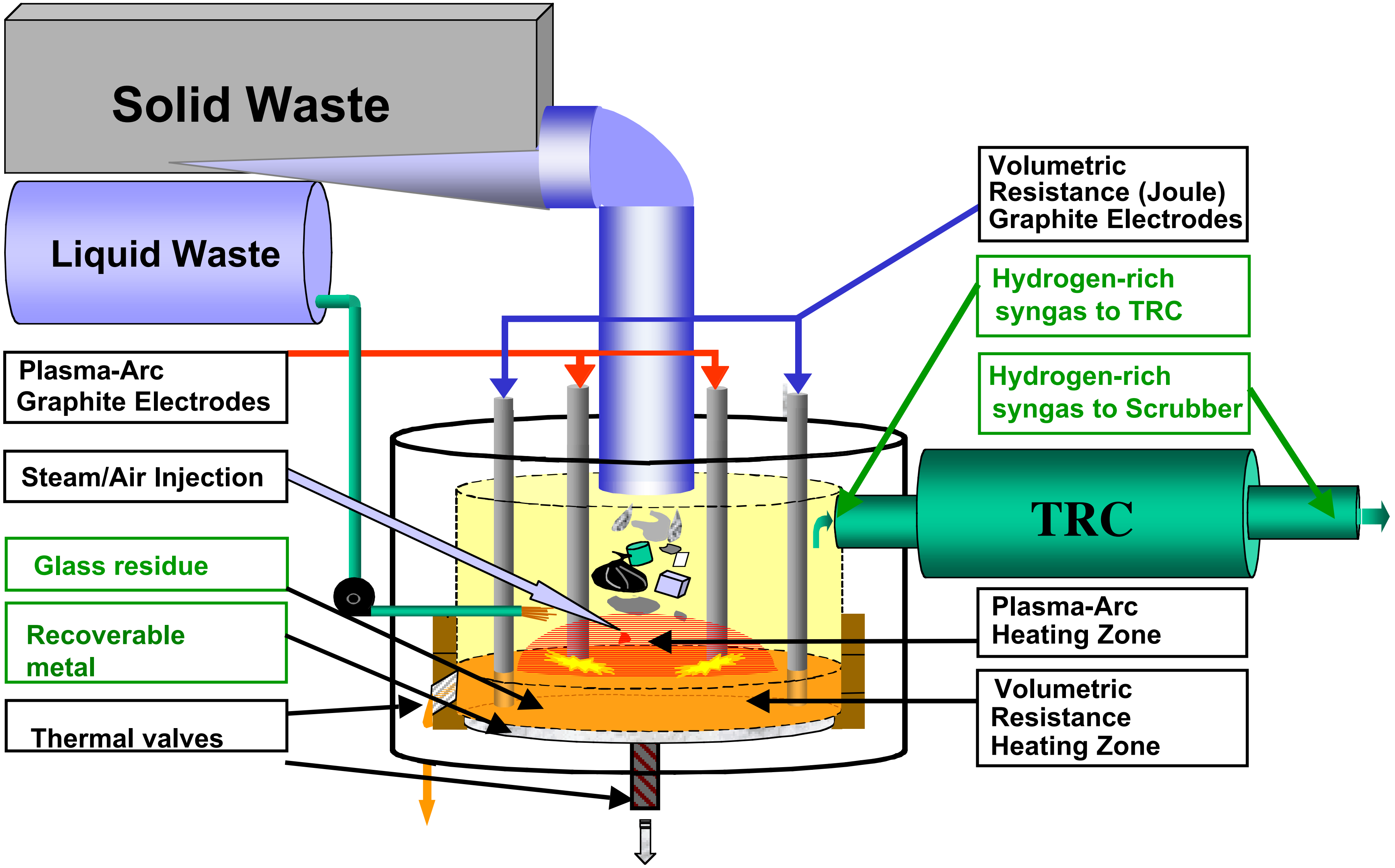
PEM™

Hydrogen-rich gas:
USES:
Clean transportation fuel production
Clean electricity generation

Glass:
USES:
Construction:
Concrete
Road Base
Cinder Block
Landscaping Material

Recyclable Metals

PEM™ System Operational Diagram



Operational Features of PEM^{TM} Waste Transformation System

- Non incineration technology
- Reducing environment inhibits the production of pollutants (dioxin, NO_x)
- Virtually no air pollution emissions Stable non-leachable vitrified product from inorganic material
- Converts waste into hydrogen-rich gas, hydrogen, methanol or other products

Operational Features of PEM™ Waste Transformation System (cont.)

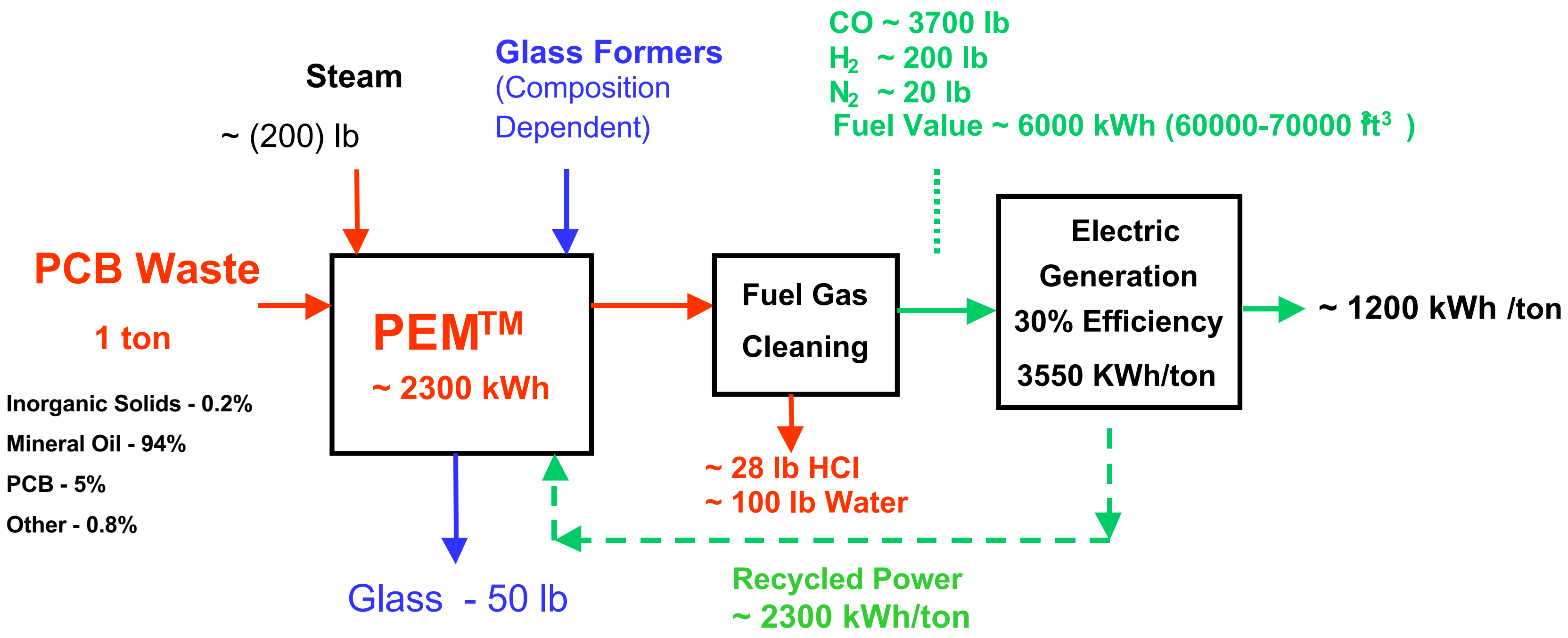
- Ease of intermittent and variable waste processing operation
- High quality synthesis gas (hydrogen-rich gas) production
- Lower processing costs
- Suitable for clean conversion of waste into valuable products at site of waste generation
- Maximizes recycling and minimizes waste transportation

PEM^{TM} DRE and Dioxin Measurements

- PEMTM system was demonstrated to have suppressed Dioxin and Furan production to amounts far below current acceptable levels. (Tests on incinerator fly ash and PCB waste as reported by US EPA in EvTec Evaluation Test Program)

- PEMTM system was demonstrated to have ≥ 99.9999% DRE for many organics including:
    - Naphthalene
    - Chlorobenzene
    - Benzene
    - Tetrachlorobenzene
    - Toluene
    - PCBs

Illustrative
Hazardous Waste
Mass and Energy Balance



Steam

~ (200) lb

Glass Formers

(Composition Dependent)

CO ~ 3700 lb

H_2 ~ 200 lb

N_2 ~ 20 lb

Fuel Value ~ 6000 kWh (60000-70000 ft^3)

PCB Waste

1 ton

Inorganic Solids - 0.2%
Mineral Oil - 94%
PCB - 5%
Other - 0.8%

PEM^{TM}

~ 2300 kWh

Fuel Gas Cleaning

Electric Generation

30% Efficiency

3550 KWh/ton

~ 1200 kWh /ton

~ 28 lb HCl

~ 100 lb Water

Glass - 50 lb

Recycled Power

~ 2300 kWh/ton

Radioactive Waste Treatment

- Organic materials are destroyed and waste volume is reduced
- Inorganic material is vitrified into a stable, nonleachable glass
- Radioactive materials are immobilized in the glass
- Plasma heating increases waste processing throughput of joule heated melter and facilitates processing of waste that contains organic material
- Capability for treatment or low level, mixed (radioactive and chemical hazardous) and high level waste

Current Installations of PEM™ Systems

❖ Operational Units

- 1/2 tpd Process Test Facility (engineering scale)
  - Operational, Richland, WA, IET Technology Center
- 2 tpd Commercial System
  - Operated in Richland, WA during 1999
  - Currently awaiting delivery to customer
- 1/4 tpd Mobile Needle Treatment System
  - Operational, Richland, WA, IET Technology Center
- 10 tpd Commercial System for RCRA, TSCA, and Radioactive Waste
  - Located at customer site in Richland, WA
- 1tpd Commercial System for Medical Waste
  - Located at customer site in Honolulu, HI

PEM^{TM} Waste Transformation System
0.5 tpd Process Test Facility

0.5 tpd Process Test Facility
at Richland Technology Center

- Process Capacity = 0.5 tons per day
- Feed - Continuous, Batch or Lance via a 6" Port
- Operational Since 3/97 (over 20,000 hrs)
- Available for Treat ability Studies

PEM^{TM} Waste Transformation System
Model 10 Commercial Prototype

Ten Ton Per Day PEM™ Unit at IET

- Process Capacity = 6 to 14 tons per day
- Feed - Continuous, Batch or Lance via a 12” Port
- Operational Since 6/99 (over 4,000 hrs)
- Available for Treat Ability Studies

PEM^{TM} Waste Transformation System
Model 10 Off Gas System

- Skid Mounted Off Gas System
- >99.5% Acid Gas Removal
- >99% H_2S Removal
- >92% Particulate Removal (65% $\leq$ 1μm)

Model 10 PEM^{TM} System
Installed at Customer Facility

- Permitted under RCRA,TSCA, and mixed radioactive waste
- Operational September 2000
- First plasma based technology to receive RCRA and TCSA permits for mixed waste processing
- Notification received for BDAT* equivalency to incineration

*Best Demonstrated Available Technology

Hawaii Medical Waste System

Renewable Energy Generation from Plasma Enhanced Melter Systems

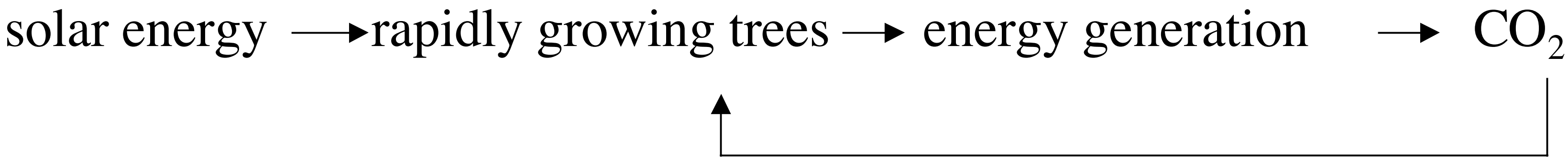
- Larger PEM systems (50-1000 tons /day) will be commercialized to process municipal solid waste (MSW)

- A high fraction of MSW is renewable energy biomass

- MSW is converted into hydrogen-rich gas which can be used for
  - Clean electricity generation (fuel cell, gas turbine, reciprocating engine)
  - Hydrogen for industrial or transportation use
  - clean liquid transportation fuels (methanol or super low sulfur diesel fuel)

Renewable Energy Generation from Plasma Enhanced Melter Conversion of Municipal Solid Waste (MSW)

Conventional biomass energy generation:



solar energy → rapidly growing trees → energy generation → CO_2

MSW renewable biomass energy generation:

solar energy → rapidly growing trees → paper products → MSW →

energy generation → CO_2

Conclusions

- IET's Plasma Enhanced Melter^{TM} technology is well suited to convert a wide range waste streams into hydrogen-rich gas and glass products
- Important operational advantages of PEM^{TM} technology have been demonstrated under the EvTEC Program in the Process Test Facility
- IET is delivering systems to customers in the U.S., and the Pacific Rim for treatment of hazardous, radioactive and medical waste
- PEM^{TM} capital & operating costs are competitive with the costs of other treatment technologies and PEM^{TM} systems provide many environmental advantages
- Larger PEM systems are planned for economically attractive hydrogen energy generation from municipal solid waste (a renewable energy source)

Onboard Hydrogen Generation for Improved Internal Combustion Engine Vehicles

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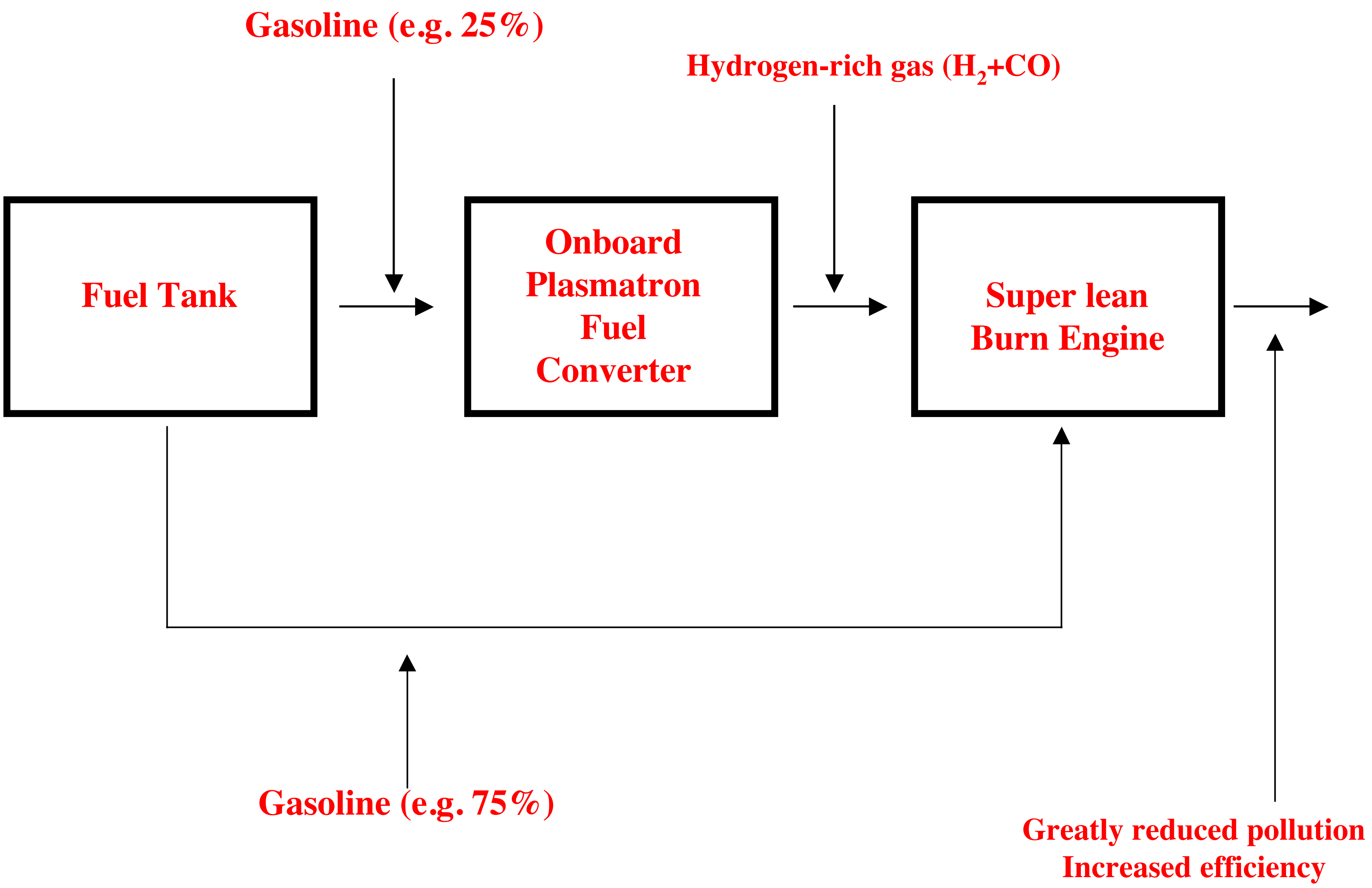
Plasmatron Enhanced Gasoline Engine



Gasoline (e.g. 25%)

Hydrogen-rich gas (H_2+CO)

Fuel Tank

Onboard Plasmatron Fuel Converter

Super lean Burn Engine

Gasoline (e.g. 75%)

Greatly reduced pollution
Increased efficiency

Potential Applications of Plasmatron Fuel Converters

- Large reduction in NO_x (up to 90% reduction) from gasoline engine vehicles (spark ignition engines)
- Large reduction in hydrocarbons from gasoline engine vehicles engines (up to70% reduction)
- Higher efficiency spark ignition engines (up to 25% relative increase in efficiency)
- Diesel engine exhaust aftertreatment (90% reduction in NO_x; particulate emissions reduction)
- Lower pollution and higher efficiency in hybrid vehicles
- Increased use of biomass derived fuels

Plasmatron Fuel Converters

- Electric discharge (plasma) continuously applied to flowing gas
- plasma boosts partial oxidation reaction that converts hydrocarbon fuels into hydrogen-rich gas

partial oxidation (at oxygen/carbon ratio=1):

$$C_nH_m + \frac{n}{2}O_2 = nCO + \frac{m}{2}H_2$$

Exothermic reaction

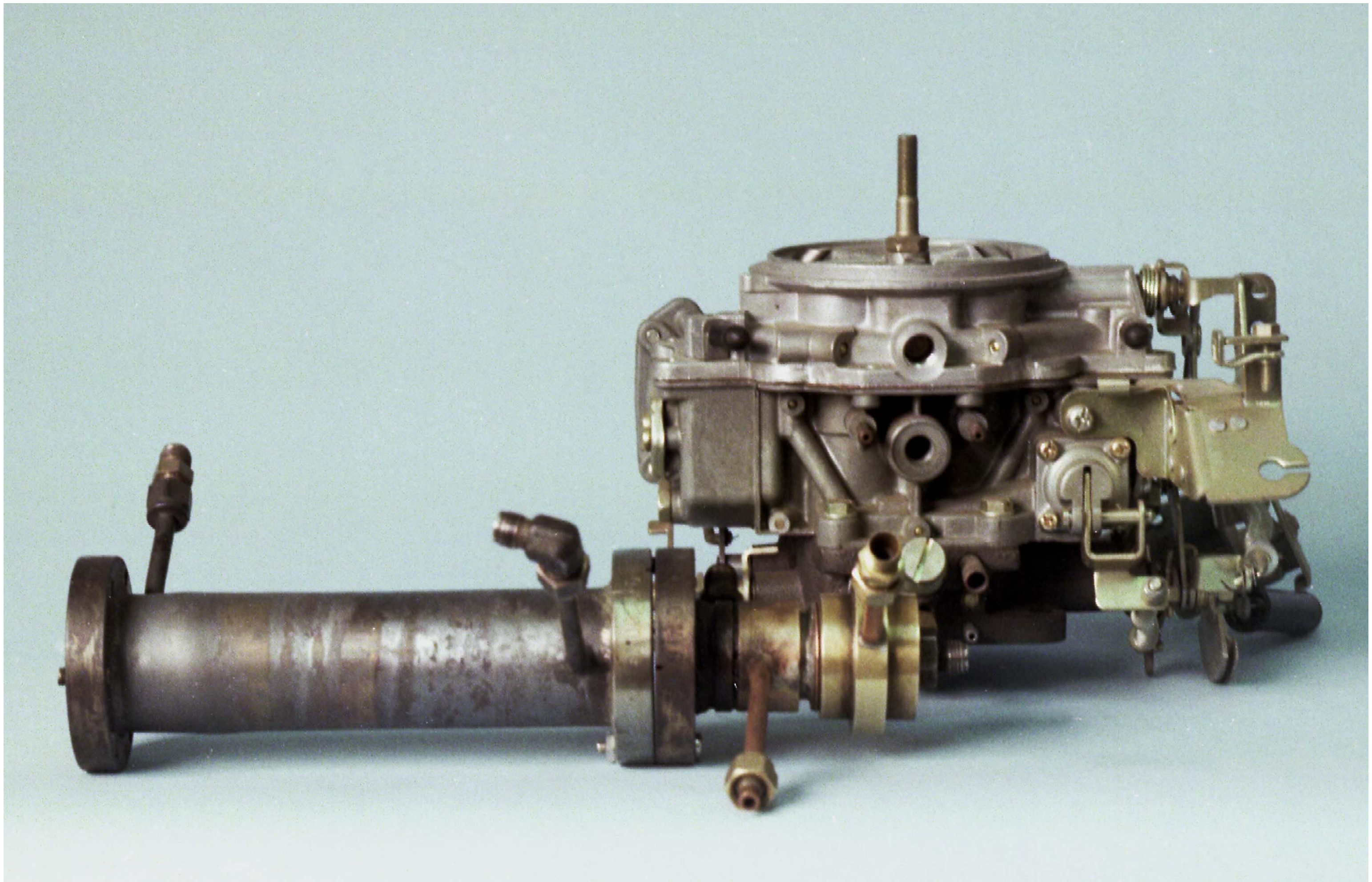
For octane:

$$C_8H_{18} + 4O_2 = 8CO + 9H_2$$

~15% of energy released

- Plasmatron can boost reaction by
  - Production of reactive species throughout incoming fuel mixture
  - Mixing of reactants
  - Significantly increasing temperature

Plasmatron fuel converter (foreground) and conventional carburetor (background)



Plasmatron Fuel Converters

- Provides wide area continuous ignition
- Provides additional enthalpy (startup, transients)
- Ensures reaction over whole reactor volume (high conversion efficiency)
- Decreases soot

Benefits of Plasmatron Operation

- Rapid startup of hydrogen production
- Reliable hydrogen production under changing conditions
- Compact design
- Greater flexibility in fuel converter operating regime
- Relaxed catalyst requirements
- Operation with difficult to convert fuels (diesel, biofuels)

Compact Plasmatron Fuel Converters

DC Arc plasmatrons

- Near equilibrium plasmas ($T_e \approx T_i \approx T_n$)
- Substantial plasma heating (e.g. equal to heating power provided by partial oxidation)
- Relatively high current (~20 amps)
- Relatively high power (≥ 1kW)
- Water cooled
- Electrode life issues

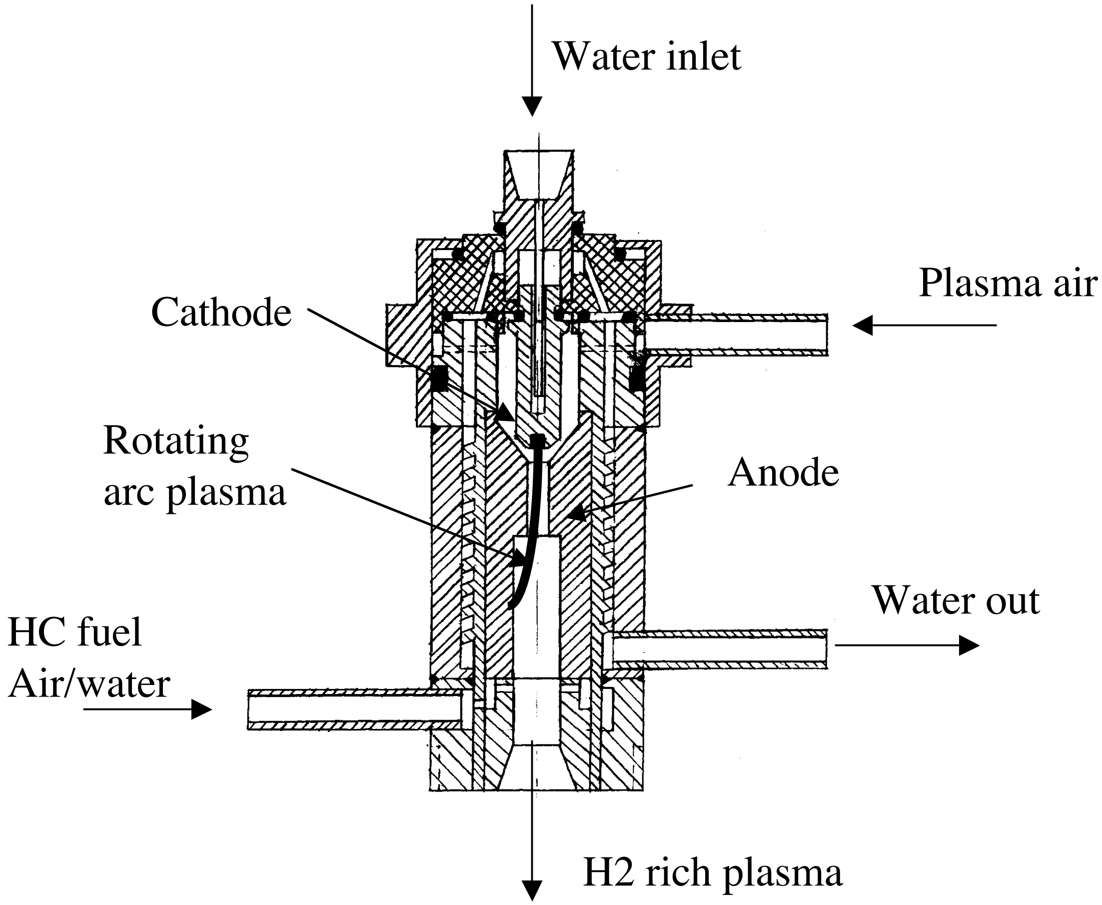
Low current plasmatrons

- Non equilibrium plasmas ($T_e > T_i > T_n$)
- Low level of plasma heating (e.g. 10% of heating provided by partial oxidation)
- Electrical power levels of 50–2000W
- Relatively low current (~0.1 amps)
- Long electrode life

DC Arc Plasmatron Fuel Converter

V ~ 120 V DC
I ~ 20 A
P ~ 2.4 kW

O/C ~ 1
(stoichiometric
partial oxidation)



DC Arc Plasmatron Fuel Converter Tests
(Oxygen/Carbon≈1)

Plasmatron Parameters	Iso-octane	Diesel
Current, Amp	18	18
Voltage, V	140	130
Power, W	2530	2340
Fuel Power, kW	13	13
Product Gas Composition		
H_2, vol%	22	23.5
O_2, vol%	0	0.3
CH_4, vol%	3	0.03
CO, vol%	13	23
CO_2, vol%	2	0.1
Hydrogen yield, H_2	78%	95%

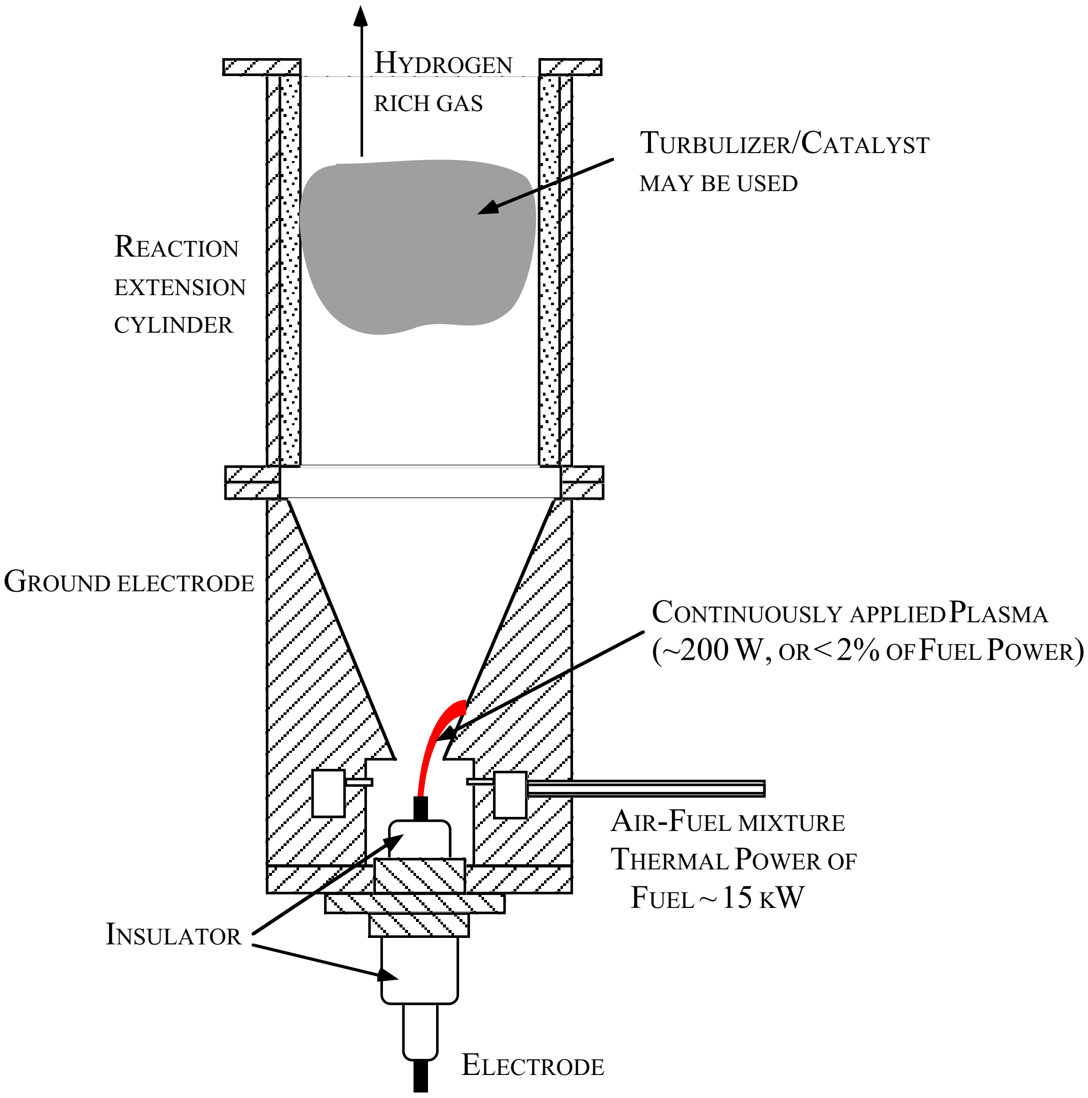
Hydrogen Yield=Hydrogen in H_2/Hydrogen in Fuel

DC Arc Plasmatron Fuel Converter Tests
(Oxygen/Carbon≈1)

	Canola	Corn Oil
Fuel rate (g/s)	0.3	0.47
Hydrogen % vol	25.6	23
methane % vol	1.7	7.6
Carbon Monoxide % vol	26	18.6
Carbon Dioxide % vol	0.3	2.1
Hydrogen yield	92%	84%

Hydrogen Yield=Hydrogen in product gas/Hydrogen in Fuel

First Generation Nonthermal Low Current Plasmatron Fuel Converter



First Generation Low Current Plasmatron Fuel Converter

Power	50–300 W
Current	15–120 mA
H_2 flow rate	30–50 liters/min
Height	25 cm
Volume	2 liter
Weight	3 kg

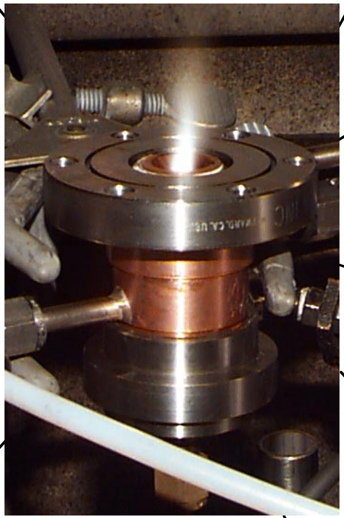
- Additional heating by combustion is provided by operation with oxygen/carbon ratio >1
- Combustion heating especially useful during cold start
- Additional heating by combustion results in reduced hydrogen yield (Hydrogen in reformate/hydrogen in fuel)

Second Generation Plasmatron Fuel Converter

- **Goals**:
  - Higher plasma power capability than present low current plasmatron fuel converter
  - Improved thermal design
  - Improved fuel injection and soot suppression
  - Hydrogen yield >50% after 10 sec (Hydrogen in H2/Hydrogen in Fuel)
- **Status**:
  - Higher Power capability (500 – 1500 W)
  - Large area cathode and anode
  - Large volume coverage with high power nonthermal plasma
  - Robust operation over a wide range of conditions

Gasoline Conversion Tests Second Generation Low Current Plasmatron Fuel Converter

- Plasmatron fuel converter power: 0.6 kW
- O/C > 1
- Gasoline power to converter: 8.5–20 kW
- Product gas composition
  (Hydrogen yield = H_2 in product gas/H in fuel)
- t = 10 sec: 11% H_2, 13% CO, 5% $CO_{2;}$ hydrogen yield: 45%
  t = 90 sec: 20% H_2, 22% CO, 3% $CO_{2;}$ hydrogen yield: 80%
- Power conversion efficiency (power in product gas/fuel power)
  t =30 sec: 60%
  t =90 sec: 90%
- Comparable performance achieved with diesel fuel



Plasmatron Fuel Converter

High efficiency gasoline engines with reduced emissions

Compression ignition engines: emissions reduction (catalyst performance improvement)

Natural gas vehicles: emissions reductions

Gasoline engine hybrids: emissions reduction, efficiency improvement

Turbine engines: emissions reduction

Biofuels:
greenhouse gas reduction;
reduced dependence on foreign oil

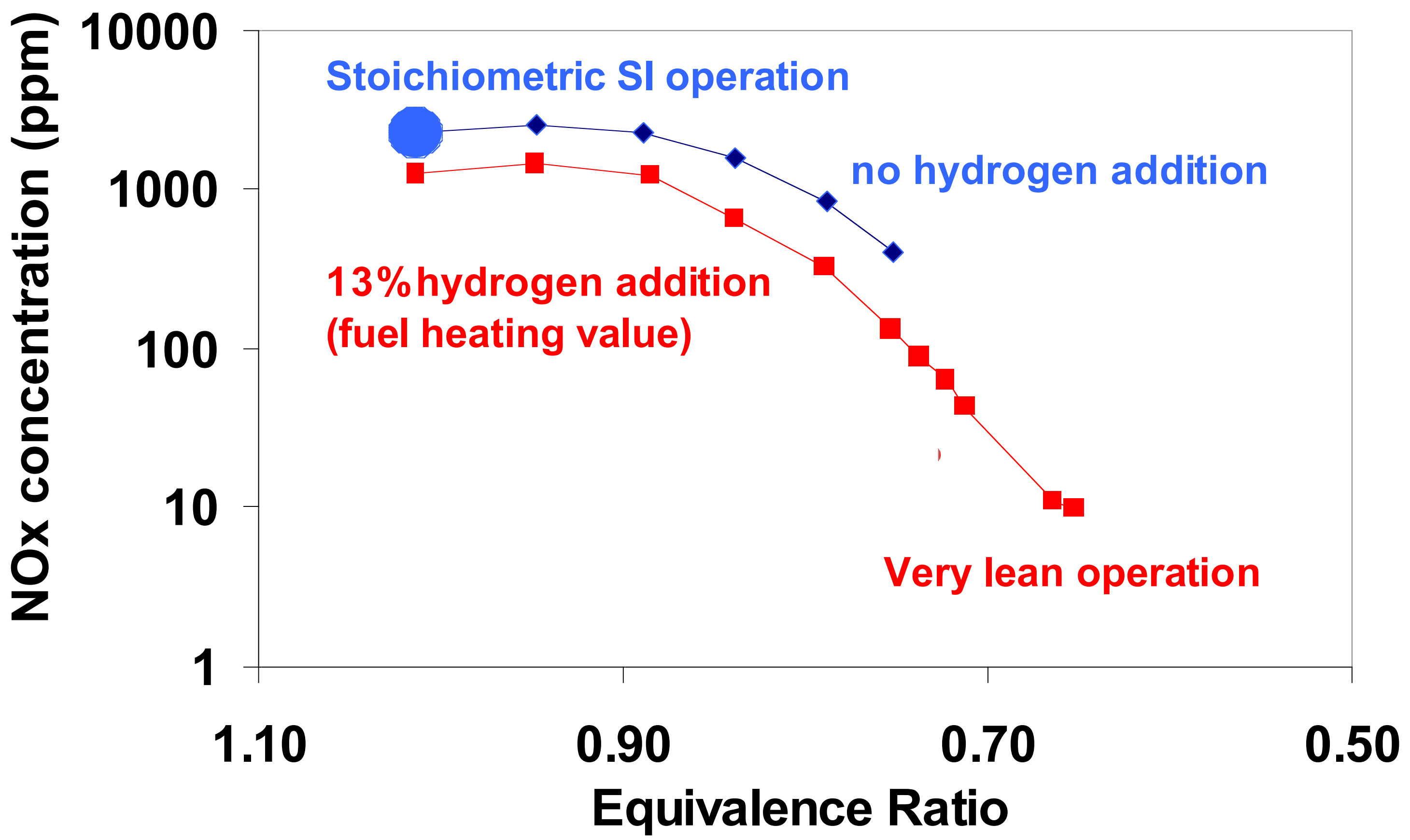
Fuel Cell applications: rapid response; small size reformers; fuel flexibility

MIT-ORNL Plasmatron Fuel Converter-Engine Tests (1999) (2.3L GM Quad 4 Engine at ORNL)

- Total fuel power to engine: 28 kW
- Fuel power to plasmatron 10 kW
  (fraction of fuel of processed: 35%)
- Fuel power of H_2-rich gas: 7 kW
- Fuel power of H_2: 2.8 kW

Engine Tests with Hydrogen Rich Gas from Microplasmatron Fuel Converter

Quad-4 engine, 1500 rpm, 2.6 bar IMEP
(medium load conditions)



In collaboration with ORNL
Advanced Propulsion Technology Center

$$\text{Equivalence ratio} = \frac{\text{(fuel/air) actual}}{\text{(fuel/air) stoichiometric}}$$

High Efficiency Hydrogen Enhanced Gasoline Engines

- Modest amount of gasoline (e.g. 25%) is converted onboard into hydrogen-rich gas which facilitates lean operation
- Hydrogen enhanced lean operation, increases gross spark ignition gasoline engine efficiency by up to 30%
- Net engine efficiency is projected to be up to 25% higher than that of conventional gasoline engine (taking all fuel conversion losses into account)

Clean, High Efficiency Hydrogen Enhanced Gasoline Engines for Cars and Light Duty Vehicles

- Increase efficiency by up to 25%
- Reduce NO_x emissions by 90% relative to present vehicles
- Very cost effective way to increase efficiency and reduce emissions
- Potential for attractive payback time Potential use for higher efficiency gasoline engine hybrid vehicle with extremely low emissions
  - 40% lower fuel consumption than gasoline powered fuel cell vehicle
  - Lower cost than gasoline powered fuel cell vehicle

Clean, High Efficiency Hydrogen Enhanced Gasoline Engines for Trucks and Buses

- Particularly attractive for urban trucks and buses
- Extremely low emissions
  - Potential reduction of 97% relative to present diesel engine emissions
  - Remove particulate emission problems of diesel engines
- Close to diesel engine efficiency
  - Efficiency up to 95% of diesel engine efficiency (possibly higher than 95% when compared with projections for future diesel vehicles with exhaust aftertreatment systems)
- Vehicle cost relatively close to that of diesel vehicle
- Ultra low sulfur fuel not required
- Hydrogen enhanced gasoline engines also attractive for heavy vehicle hybrid
- Potential applications for natural gas vehicles

Feasibility Issues

- Onboard fuel converter with suitable response, size, cost, reliability and lifetime
- Achievement of ultralean engine operation with only a modest amount of hydrogen

Potential Impact of Plasmatron Enhanced Gasoline Engines

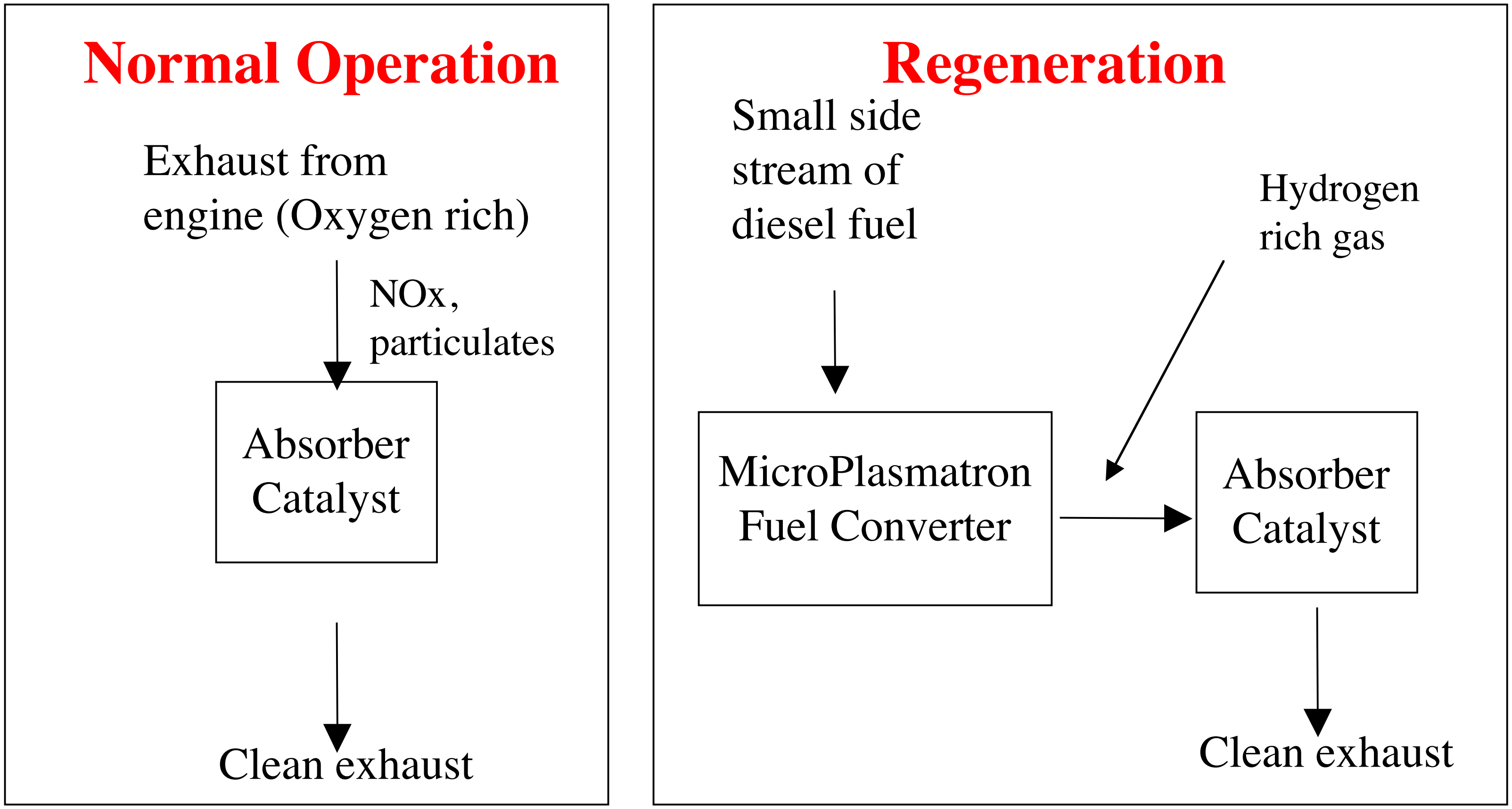
- Widespread use is possible due to economic attractiveness of substantial efficiency and increase pollution reduction at modest cost (short payback time)

- Could reduce US demand for petroleum by up to 1.5 million barrels/day (approximately 60% of oil imported from Middle East)

- Could provide best technological opportunity to increase US vehicle fleet efficiency averaged over the next 30 years

- Greater reduction possible in hybrid vehicles using plasmatron enhanced gasoline engines

Diesel Engine Emissions Aftertreatment Concept



Normal Operation

Exhaust from
engine (Oxygen rich)

NOx,
particulates

Absorber
Catalyst

Clean exhaust

Regeneration

Small side
stream of
diesel fuel

Hydrogen
rich gas

MicroPlasmatron
Fuel Converter

Absorber
Catalyst

Clean exhaust

Advantages of regeneration with H_2-rich gas:

- Greater operating range
- Greater regeneration effectiveness
- Reduced adverse effects on catalyst (e.g. sulfur)

NOx trap regeneration
using Plasmatron Fuel Converter

NOx generation (g/hp hr)	2g/hp hr		
H2 required (H2/NOx, per volume)	2.2(H2/NOx)		
Fraction of fuel to plasmatron	1.3%		
Engine power (hp)	100	200	300
Plasmatron electrical power (W)	56	112	168
Hydrogen generation (l/min)	5	11	16
Fuel flow rate to plasmatron (g/s)	0.070	0.140	0.210

Commercial Development

- Arvin Meritor, a tier 1 vehicle components and systems supplier ($7 billion/yr. sales) has signed agreement to commercialize plasmatron fuel converter technology for exhaust aftertreatment and other applications through technology license from MIT

- Technology will be developed by Arvin Meritor at Columbus, Indiana facility with supporting R&D at MIT

Plasmatron Fuel Converter Technology

- Onboard production of hydrogen using plasmatron fuel converter technology could be employed to substantially increase efficiency and reduce pollution from gasoline engine vehicles

- There is also potential to greatly reduce diesel engine vehicle exhaust emissions through plasmatron enhanced exhaust aftertreatment

- This approach could be an especially cost effective means to increase efficiency and improve environmental quality in the transportation area

Summary
Environmental and Fuel Efficiency Spinoff Technology from Fusion Research

- Waste treatment equipment for improved environmental protection and energy recovery is presently being sold and installed in the United States and Asia

- Technology is being developed to exploit the use of municipal solid waste (MSW) as a renewable biomass energy resource for production of hydrogen and clean liquid transportation of fuels

- Onboard hydrogen generation technology is being developed by a major automotive components manufacturers (Arvin Meritor) for reduced vehicle pollution and increased efficiency

Summary
Environmental and Fuel Efficiency Spinoff Technology from Fusion Research

(continued) .

- Plasmatron enhanced gasoline engines are one of a small number of potential technological solutions for significantly reducing US fleet use of petroleum averaged over the next 30 years

- Environmental and fuel efficiency technology spinoffs from Fusion research are contributing to Department of Energy goals for environmental management, renewable energy and energy efficiency