Micro Power

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This lecture discusses the Micro Power Generation Program (MPG) at DARPA and examples of micro rocket technology.

MICRO POWER GENERATION PROGRAM (MPG)

The goal of MPG, which was initiated by Dr. Bill Tang, is to generate power on the micro scale and to enable standalone sensors and actuators with wireless communication. Five DARPA projects will be reviewed, covering micro fuel cells and micro engine.

Prof. Savinell, Case Western Reserve University, is developing a micro hydrogen-air fuel cell with integrated fuel storage for autonomous operation, capable of delivering 10 mW continuous and 100 mW pulse power. The potential application is a wireless sensor with power, sensor, radio, and electronics in one package. Major tasks are to fabricate and test the fuel cell, develop novel polymer electrolytes with higher conductivity at low relative humidity, and investigate both on-board storage of hydrogen (using metal hydrides) and generation of hydrogen (from NaBH4). To date, an integrated device with on-board hydrogen supply based on NaBH4 has been tested with over 67% H2 utilization. A steady-state power output of 2 mW/cm2 and pulse power output of 10 mW/cm2 have been demonstrated. Future goals are to increase power output by improving porosity of substrate and enhance capability to manufacture higher voltage stacks.

Dr. Evans Jones, Battelle, is developing an integrated micro fuel processor and fuel cell. The fuel reformer coverts fuel and water into H2 and CO2 gas using mature catalyst technology and readily available fuels; the fuel cell converts H2 gas into H2O and electricity. Various fuels are being considered, which have the potential to exceed battery performance even at low conversion efficiency. A catalytic reformer system with 10 to 500 mW was fabricated and tested. The reactor volume was less than 5 mm2.

Prof. Fernandez-Pello, University of California, Berkeley, is a developing a MEMS rotary internal combustion engine for miniature-scale power generation using hydrocarbon fuels, which have a fuel specific energy significantly higher than the battery specific energy. Several research issues are being addressed to allow fabrication of micro engines, including combustion, fluid flow, fabrication, and materials. Steady combustion at the micro-scale below the quenching distance was demonstrated. Two generations of mini-engines with

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78 mm3 and 348 mm3 displacement were tested on a dynamometer, and a maximum power of 3.7 W at 9300 rpm was generated. These investigations provide the background for future development of micro engines.

Prof. Ho, UCLA, is developing a high electret generator energized by a MEMS based chemical-thermal reactor. The jet exhaust from a pulsed combustor of 35 mm length is driving a turbine of 20 mm diameter integrated with an electric generator. For the integration a CFDRC developed MEMS software simulation code is used. The pulsed reactor is a multiplayer silicon/ceramic structure.

MIT is developing MEMS heat engines with applications to micro gas turbines, micro rocket engines, and micro blowers. Enabling technologies include MEMS turbo-machinery, micro combustion dynamics, high temperature materials and packaging, gas bearings, and micro electromechanics. The operation of silicon turbine system with 21 mm diameter, 2 grams engine weight, and 1 million rpm has been demonstrated using hydrogen.

MICRO ROCKET TECHNOLOGY

Several organizations are developing micro rocket technologies. One example is the work at Mechatronic, which has developed cold-gas (N2) micro thrusters capable of thrust delivery up to 500µN. They are equipped with micro valves, pressure sensors, and electronics.

An experimental setup for testing the micro propulsion system in space is under development. The experiments will be performed on-board the micro satellite UNISAT-2, in the framework of a cooperation between Università di Roma “La Sapienza”, Mechatronic and INFM. Two pairs of micro thrusters mounted with their thrust direction orthogonal to the spin-axis of the spacecraft will be used to perform spin-up/ spin-down maneuvers.

MICRO POWER

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MONTEREY, CA., USA, 3/4 MARCH 2003

MICRO POWER MEMS

- **MICRO POWER GENERATION PROGRAM AT DARPA**
- MICRO ROCKETS

Micro Power Generation Program at DARPA

William C. Tang, Ph.D.
Program Manager,
MEMS / MPG / NMASP / CSAC
Microsystems Technology Office
Defense Advanced Research Projects Agency

MPG Program Goals

- Generate power at the micro scale with superior energy density compared to batteries; and
- Enable standalone micro sensors and micro actuators with wireless communication function.

DARPA

MPG PROGRAM AT DARPA

- ROBERT SAVINELL, CASE WESTERN RESERVE UNIVERSITY, “A MICRO-HYDRGEN-AIR FUEL CELL”
- EVAN JONES, BATTELLE, “AN INTEGRATED FUEL CELL AND FUEL PROCESSOR FOR MICROSCALE POWER GENERATION FROM LIQUID FUELS”
- CARLOS FERNANDEZ-PELLO, UNIVERSITY OF CALIFORNIA AT BERKELEY, “MEMS ROTARY INTERNAL COMBUSTION ENGINE”
- ALAN EPSTEIN, MIT, “BUTTON-SIZED MICROMACHINED GAS TURBINE GENERATORS”
- CHIH-MING HO, UCLA, “HIGH VOLTAGE ELECTRET GENERATOR ENERGIZED BY A MEMS BASED CHEMICAL-THERMAL REACTOR”

A Micro Hydrogen-Air Fuel Cell

PI: Professor Robert F. Savinell

Co-I(s): Professors C. C. Liu, M. H. Litt, and J. S. Wainright

Case Western Reserve University

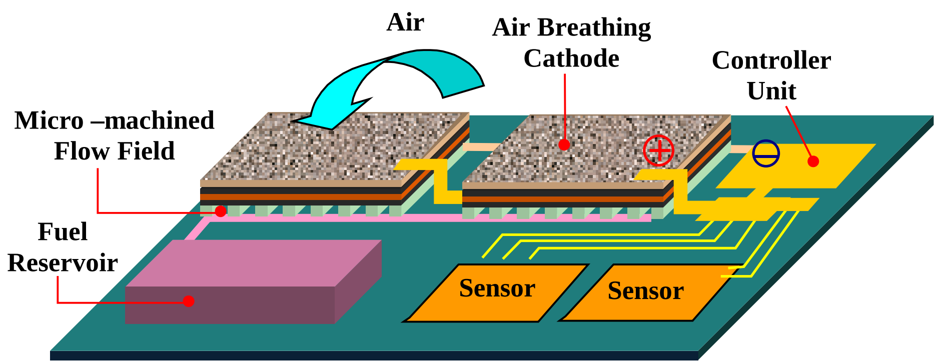
Ernest B. Yeager Center for Electrochemical Sciences

Cleveland, OH 44106-7217

Overview

- Background & Motivation
  - On-board power is required to enable wireless application of MEMS sensors and actuators. Polymer electrolyte fuel cell technology can provide both the steady-state and pulse power required by these devices, and can be integrated with the MEMS fabrication.
- Project Goal
  - Develop a microfabricated hydrogen-air fuel cell with integrated fuel storage for autonomous operation, capable of delivering 10 mW continuous and 100 mW (pulse) power.

Wireless Sensors – A Potential Application?



Wireless Sensor

Power, Sensor, Radio and Electronics in one package

Operational life	**2-3 wks**
Continuous power	**100 μW**
Xmit power	**50 mW**
10 ms pulse every hour	
total energy	**$\approx$50 mWh**

- **These targets have been exceeded with a single cell of 1 cm^2 area.**
- **The weight of fuel required is <0.2g of 30% $NaBH_4$ solution.**

Project Description

- Task 1 Fuel Cell Fabrication and Testing
  - Designs and materials are being developed for the thick-film fabrication of each component in the fuel cell. Testing provides feedback to the fabrication effort as performance limiting factors are identified.
- Task 2 Novel Polymer Electrolyte Development
  - Advanced electrolytes are being developed that provide higher conductivity at low relative humidities and that are fabrication compatible.
- Task 3 Hydrogen Storage/Generation
  - Both on-board storage of hydrogen (using metal hydrides) and on-board generation of hydrogen (from $NaBH_4$) are being investigated. Fabrication compatibility and controlled H_2 pressures and release rates are key issues.

Project Status

- Significant Accomplishments:
  - Steady-state power output of 2 mW/cm^2 has been achieved on H_2 and air (50%RH)
  - Pulse power output of >50 mW/cm^2 has been demonstrated for 10 msec pulses.
  - An integrated device with an on-board hydrogen supply based on $NaBH_4$ has been tested with over 67% H_2 utilization.

Future Plans

- Improve porosity of substrate/current collectors – increase power density

  Goal: 10-20 mW/cm^2

- Develop improved methods for depositing electrolyte layer

  Goal: Enhance capability to manufacture higher voltage stacks

- Develop improved metal hydride storage using higher pressure hydride materials

  Goal: Increase energy density to 500 mWh/cm^3

mWatt-Scale Power Generation

Integrated fuel processor and fuel cell

or

"Turning power plants into batteries – scaling from MW to mW"

Evan Jones, Jamie Holladay, Max Phelps, Bob Rozmiarek, Cathy Chin
Battelle
Robert Savinell, Jesse Wainright, Morton Litt
Case Western Reserve University

Contact: Evan Jones
evan.o.jones@pnl.gov
tel: 509-376-4610 fax: 509-376-5106

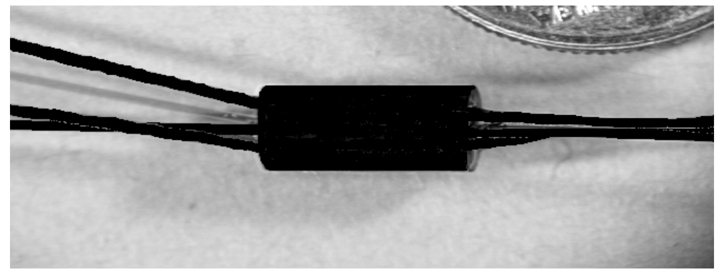
Overall System

Fuel Reformer:

Converts fuel and water into H_2 and CO_2 gas.

Fuel Cell:

Converts H_2 gas into H_2O and electricity.



Description and Key Features

- Fuel reformer
  - High energy density
  - High efficiency
  - Low temperature
  - Fabricated using conventional manufacturing technology
  - Compact
  - Mature fundamental catalyst technology
  - Readily available fuel
- Fuel cell
  - High efficiency
  - CO tolerant – reduce system complexity
  - Clean emissions

Significant Accomplishments

- Liquid fuel to electricity - initial testing of integrated fuel processor and fuel cell complete
- Current reactor meets requirements that exceed battery power density
- Demonstrated fuel reforming system with efficiency of over 9% and estimated overall efficiency of over 4%
- Worlds smallest catalytic reactor system - assembled, fabricated and tested a 10- to 500-mW_e fuel reformer system with a reactor volume of less than 5 mm^3.
- Achieved near maximum theoretical conversion for methanol with approximately 1% CO in product H_2 gas and nearly 100% conversion to H_2
- Meso sized fuel cell built and tested

Required Fuel Efficiency to exceed battery performance

Fuel	LHV (kJ/mol)	Energy Density (kWh/kg)	Efficiency Required to Meet Battery (100% fuel)
Methanol 1:1 water:fuel	**639**	**5.6** 3.3	5.5%
***n*-Octane** 2:1 water:fuel	**5100**	**12.3** 3.0	2.4%
***n*-butane** 2:1 water:fuel	**780**	**12.6** 3.1	2.4%
H_2 storage	**242**	**0.5-1.0**	30-60%
$NaBH_4$ solution 1kg $NaBH_4$ + 950g H_2O	**495**	**3.6**	6.0%
Lithium polymer battery		0.3 (projected)	

MEMS Rotary Internal Combustion Engine

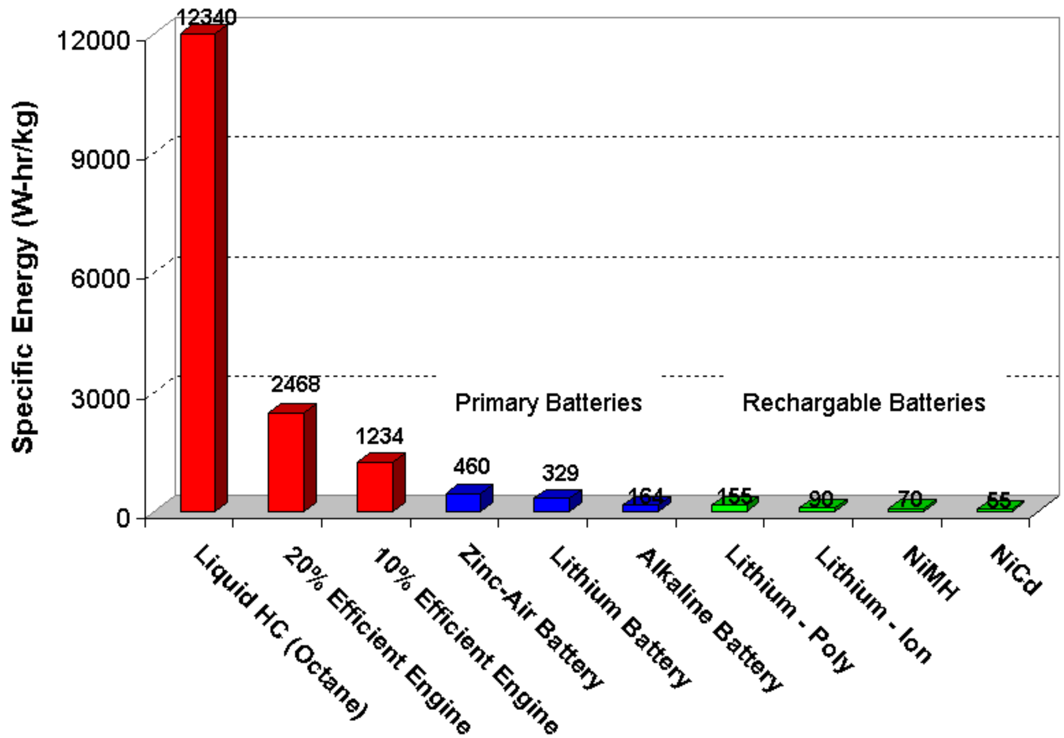
Carlos Fernandez-Pello

DARPA Grant # DABT63-98-1-0016

University of California, Berkeley
Department of Mechanical Engineering
Micro-Rotary Combustion Lab
Berkeley Sensor and Actuator Center
Berkeley, CA 94720-1740
http://euler.me.berkeley.edu/mrcl/

Motivation

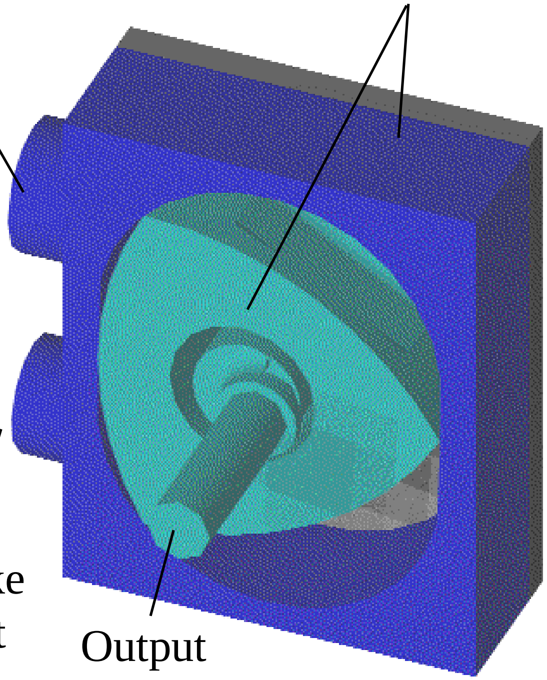
- Miniature-scale power generation using hydrocarbon fuels
- Liquid HC fuel specific energy >> Battery specific energy
- Potential Applications
  - Portable electrical power supply (battery replacement)
  - mechanical power supply



Project Accomplishments

- Investigated Micro-combustion
  - Demonstrated steady combustion at the micro-scale (below quenching distance)
  - Investigated various thermal management techniques
- Manufactured and Tested Mini-Rotary Engine
  - Developed mini-rotary engine test stand
  - Investigated combustion, fluid, sealing issues at smaller engine sizes
  - Validated design
- Investigated development of micro-rotary engine

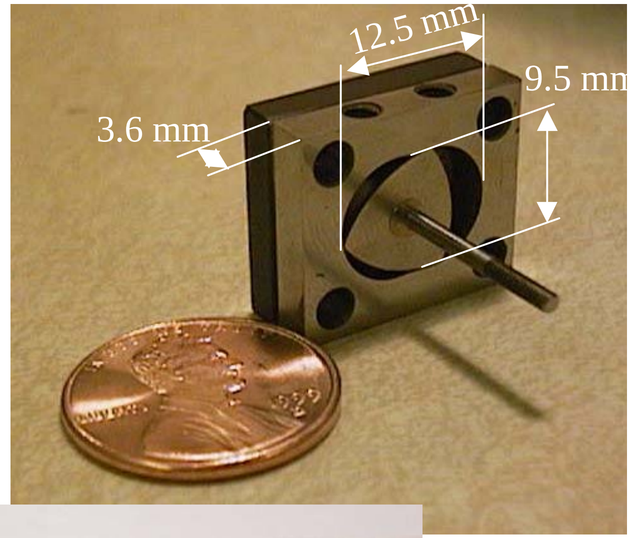
Research Issues



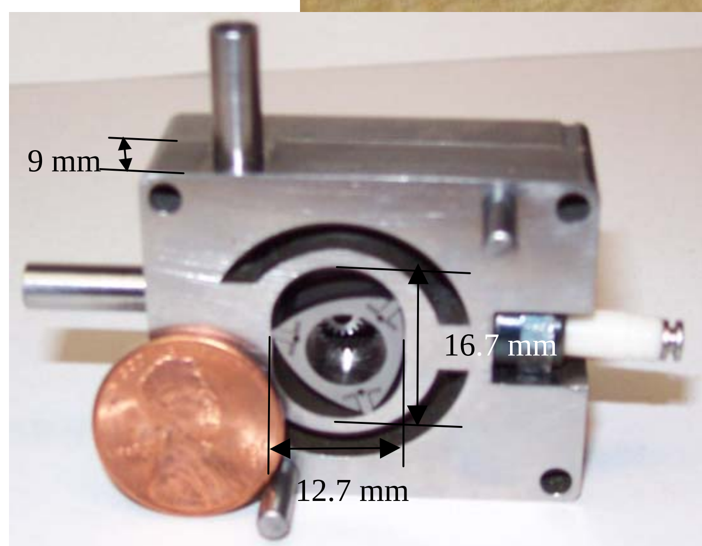
- Combustion
  - Quenching / heat losses due to high surface / volume ratio
  - Need to control heat loss to heat generation ratio
- Fluid Flow
  - Increased viscous forces, laminar flow
  - Need to reduce pumping losses and enhance atomization and mixing
- Fabrication
  - Mini-rotary engine at the limit of traditional machining (EDM)
- Materials
  - High temperature, oxidizing environment
  - Need high temperature material

Mini-Rotary IC Engine

- Rotary engine selected as power source for portable power system
- Major features of the rotary engine include:
  - Planar geometry
  - High specific power vs. other IC engine designs
  - Minimum number of moving parts
  - Self-valving operation (i.e. naturally aspirated)
  - Power output flexibility (mechanical or electrical)

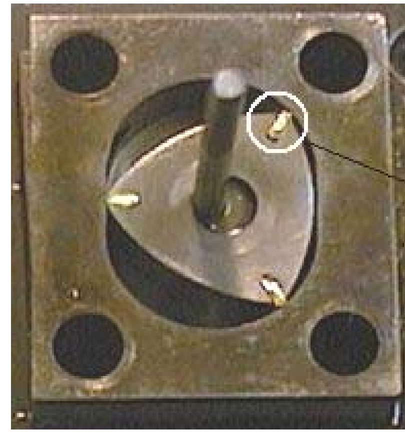


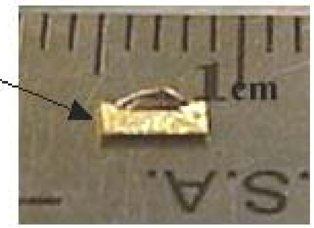
- 1st generation mini-engine
  - Displacement: 77.8 mm^3
  - Max. RPM (est.): 30,000
  - Power Output (est): 29 W
- 2nd generation mini-engine
  - Displacement: 348 mm^3
  - Max. RPM (est.): 30,000
  - Power Output (est): 148 W

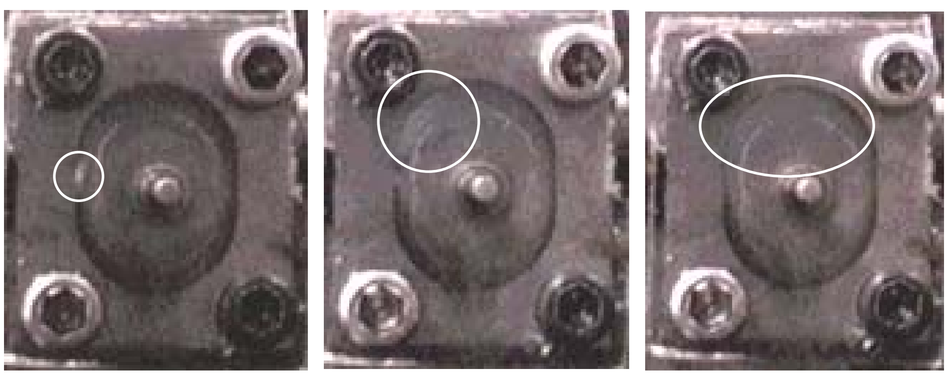


1st Gen Mini-Engine Testing

- Base Rotor Testing
  - Design tolerances not met
  - Obtained combustion but not power
  - Identified leakage sources
- Apex Seal Testing
  - Brass seals backed with leaf springs
  - Improvement observed in compression

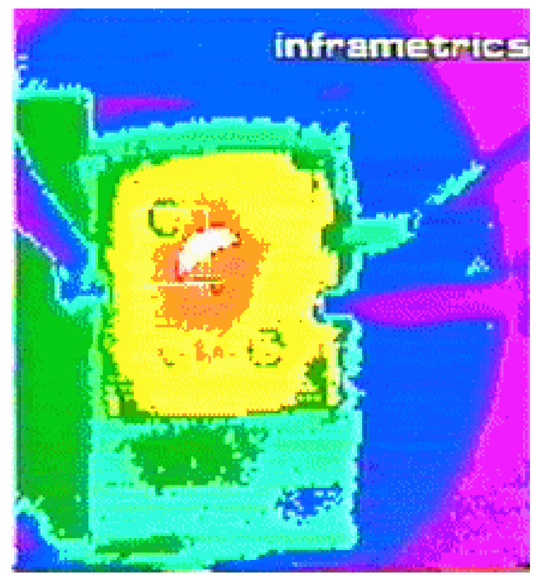






Exhaust

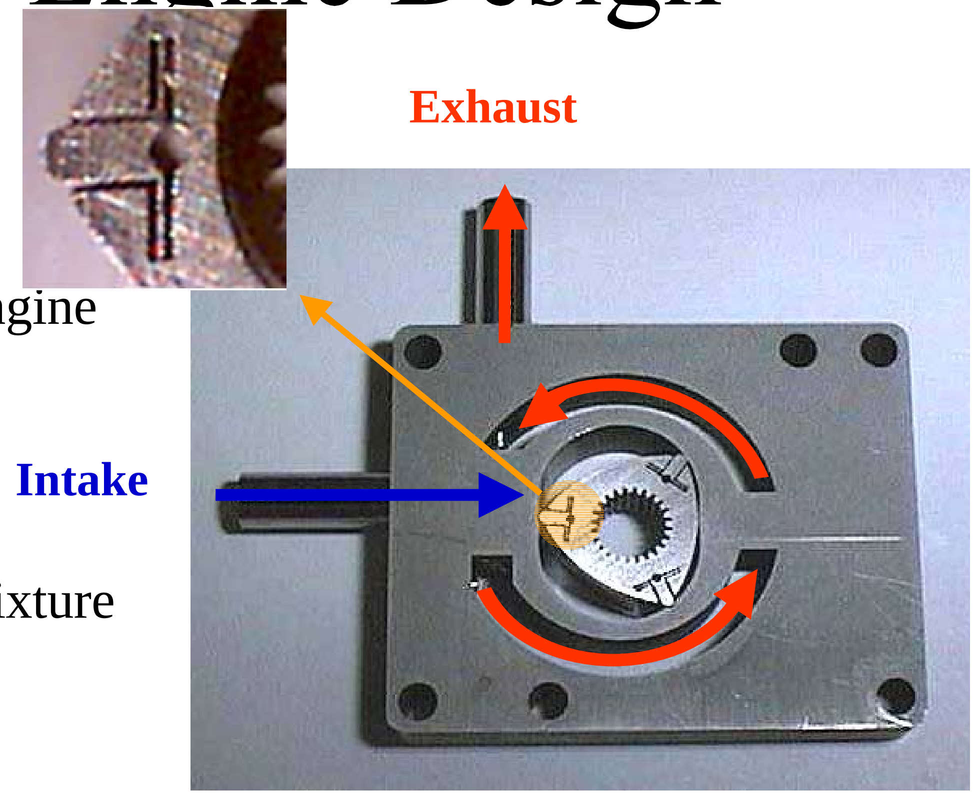
Inlet



Above: Sequence of images of mini-rotary engine during H_2-C_3H_8-air combustion

2nd Gen Mini-Engine Design

- Integrated Apex Seals
  - Simplifies assembly and manufacturing
  - Applicable for micro-rotary engine
- Exhaust Gas Recirculation
  - Exhaust gases channeled around combustion chamber
  - Pre-heat incoming fuel / air mixture
- Assembly / Manufacture
  - Improved alignment
  - Higher fabrication tolerance (< 20 micron)



Conclusions

- Combustion at small-scale investigated
  - No fundamental combustion impediments found
  - Thermal management sufficient to achieve sub-quenching diameter steady combustion.
  - Technological rather than fundamental impediments
- Miniaturized rotary engines designed and fabricated
  - Small-scale engine test stand developed
  - Net power outputs have been achieved (smallest operational rotary engine)
  - Maximum power generated: 3.7 W at 9300 RPM
- Background for the development of micro-engines

High Voltage Electret Generator Energized by a MEMS Based Chemical-Thermal Reactor

PI
Chih-Ming Ho
UCLA

Co-PIs

Yu-Chong Tai
Caltech

Siegfried Janson
Henry Helvajian
Aerospace Corporation

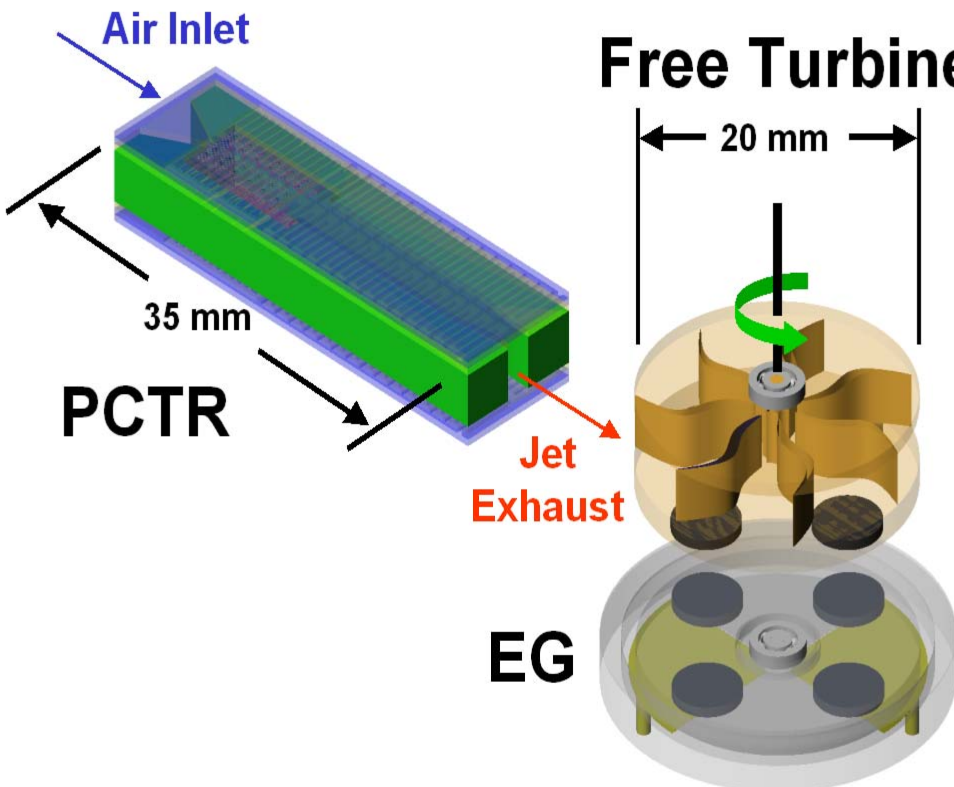
H.Q. Yang
Andrzej J. Przekwasa
CFDRC

MPG Kick-off Meeting
January 8, 2002

UCLA Caltech THE AEROSPACE CORPORATION CFDRC

MTO DARPA

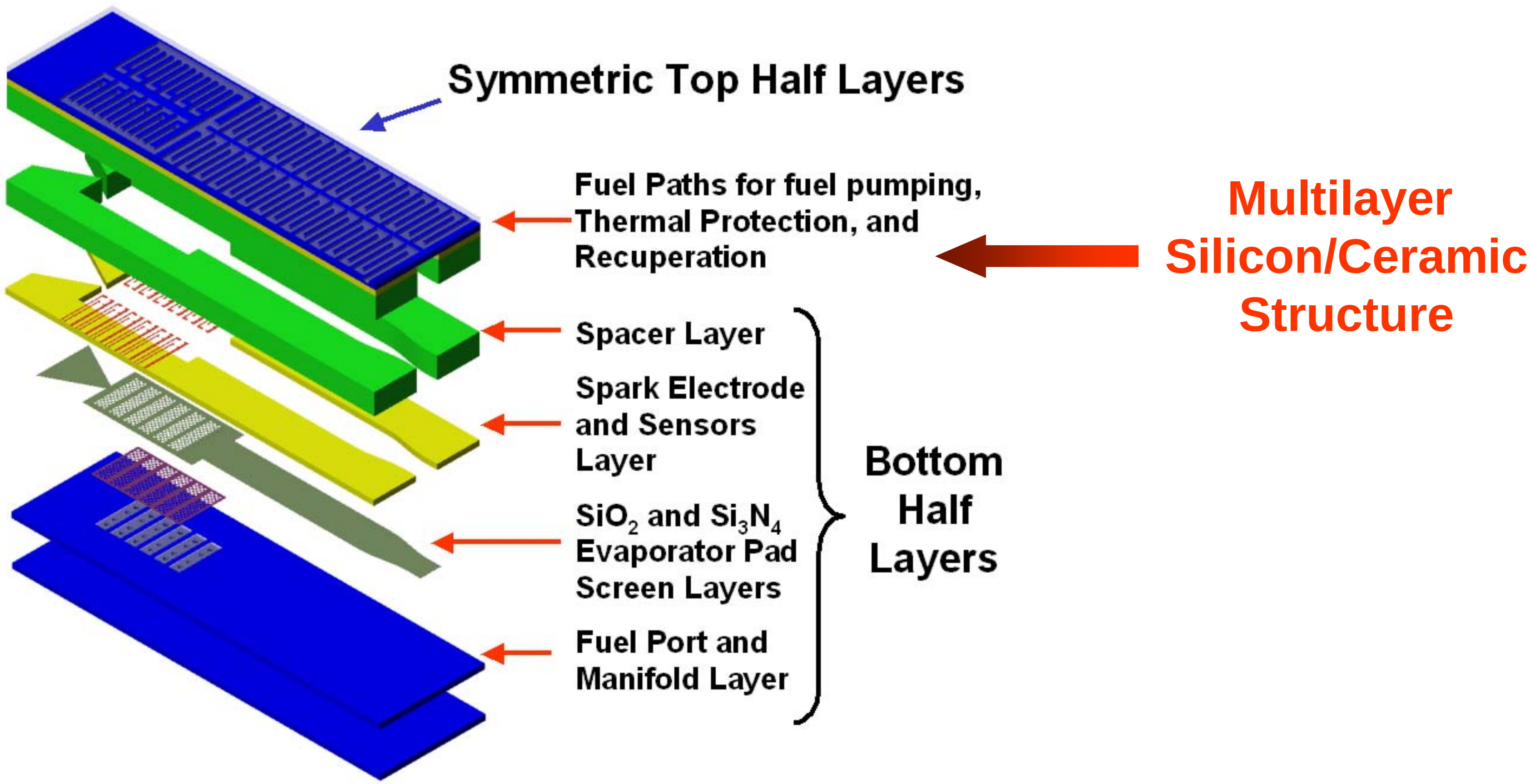
Pulsed Chemical Electret Generator System (PCEG System)



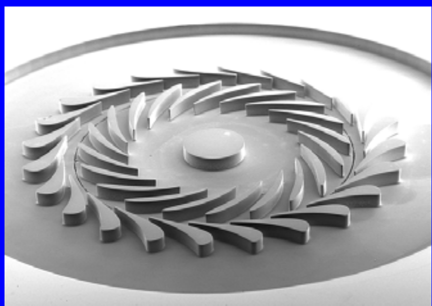
Integration:
Using CFDRC developed MEMS software simulation codes for component development and system integration.

Pulsed Chemical Thermal Reactor (PCTR) System

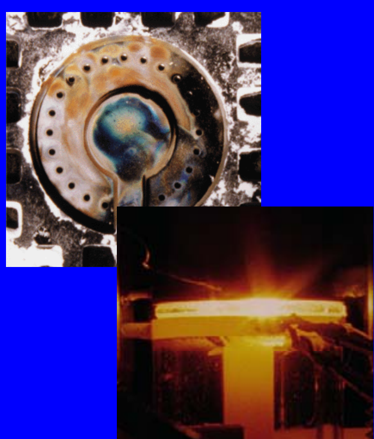
no moving part



MEMS HEAT ENGINES AT MIT
– Common Technology, Diverse Applications –

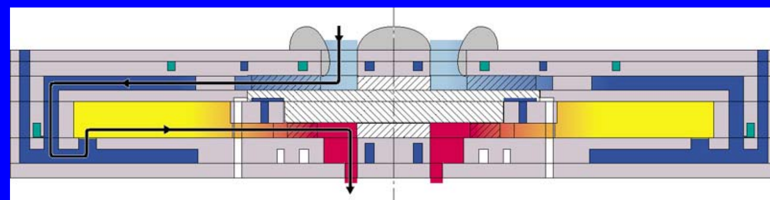


Turbomachinery

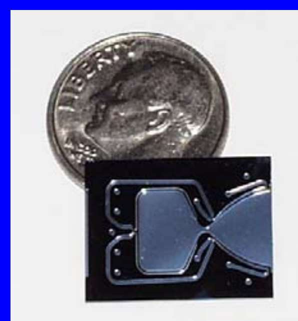


Combustion

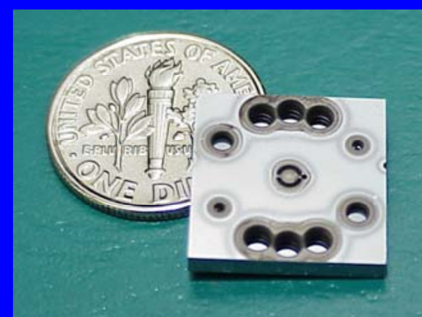
APPLICATIONS



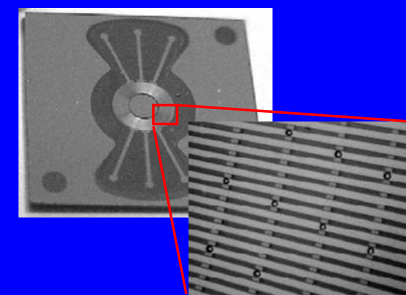
Micro-Gas Turbine (TTO, ARO)



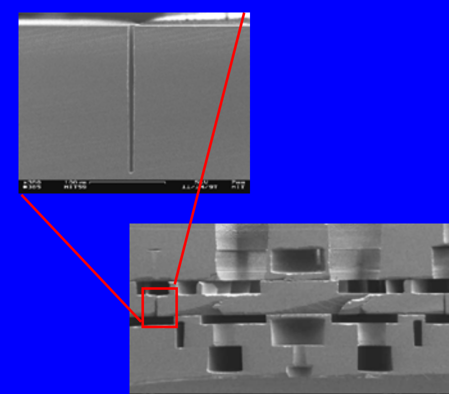
μ-Rocket Engine
(TTO, ARO, NASA)



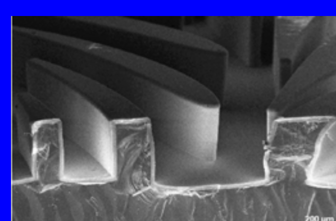
μ-Blower
(DSO)



Electromechanics
(Motor/Generator)



Gas Bearings



High Temp Materials & Packaging

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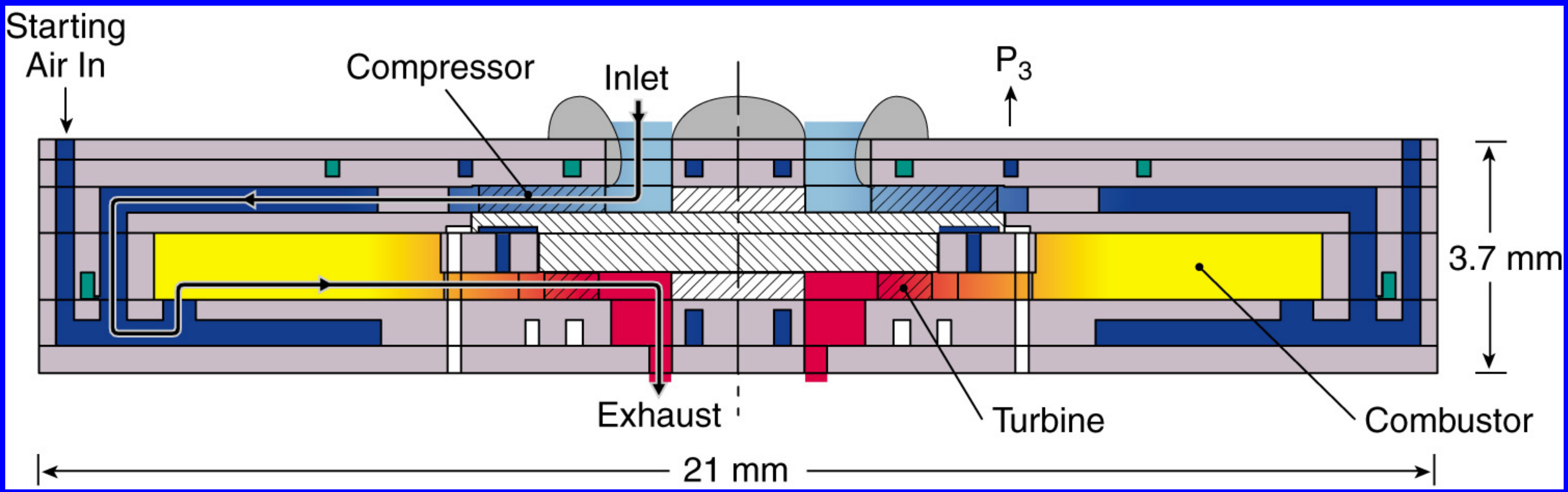
MIT H_2 DEMO ENGINE
– Silicon, Cooled Turbine –



Thrust = 11 g

Fuel burn = 16 g/hr

Engine weight = 2 grams

Turbine inlet temp = 1600°K (2421°F)

Rotor speed = 1.2 x 10^6 RPM

Exhaust gas temp = 970°C

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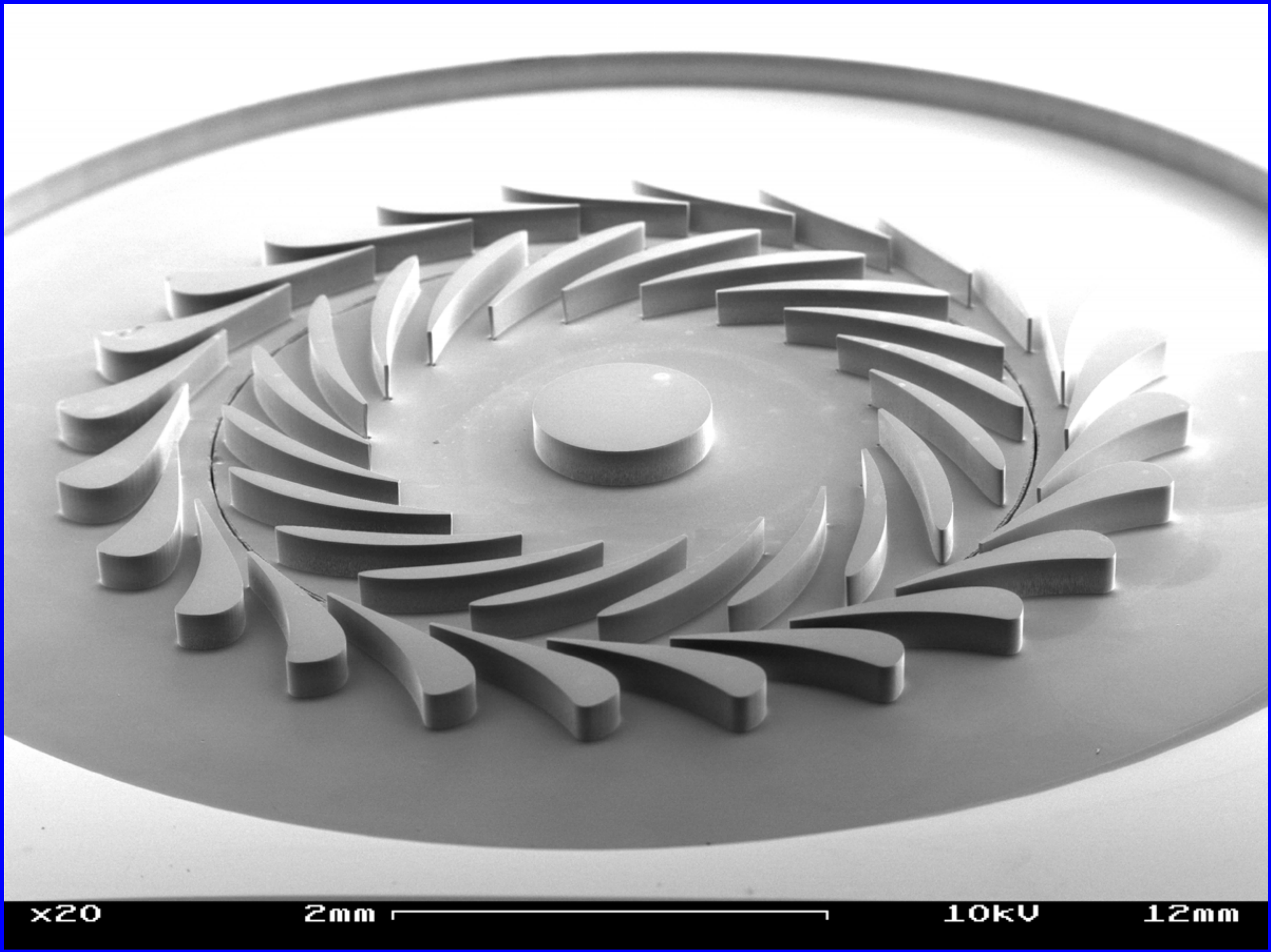
MIT-ARO MICROTURBINE



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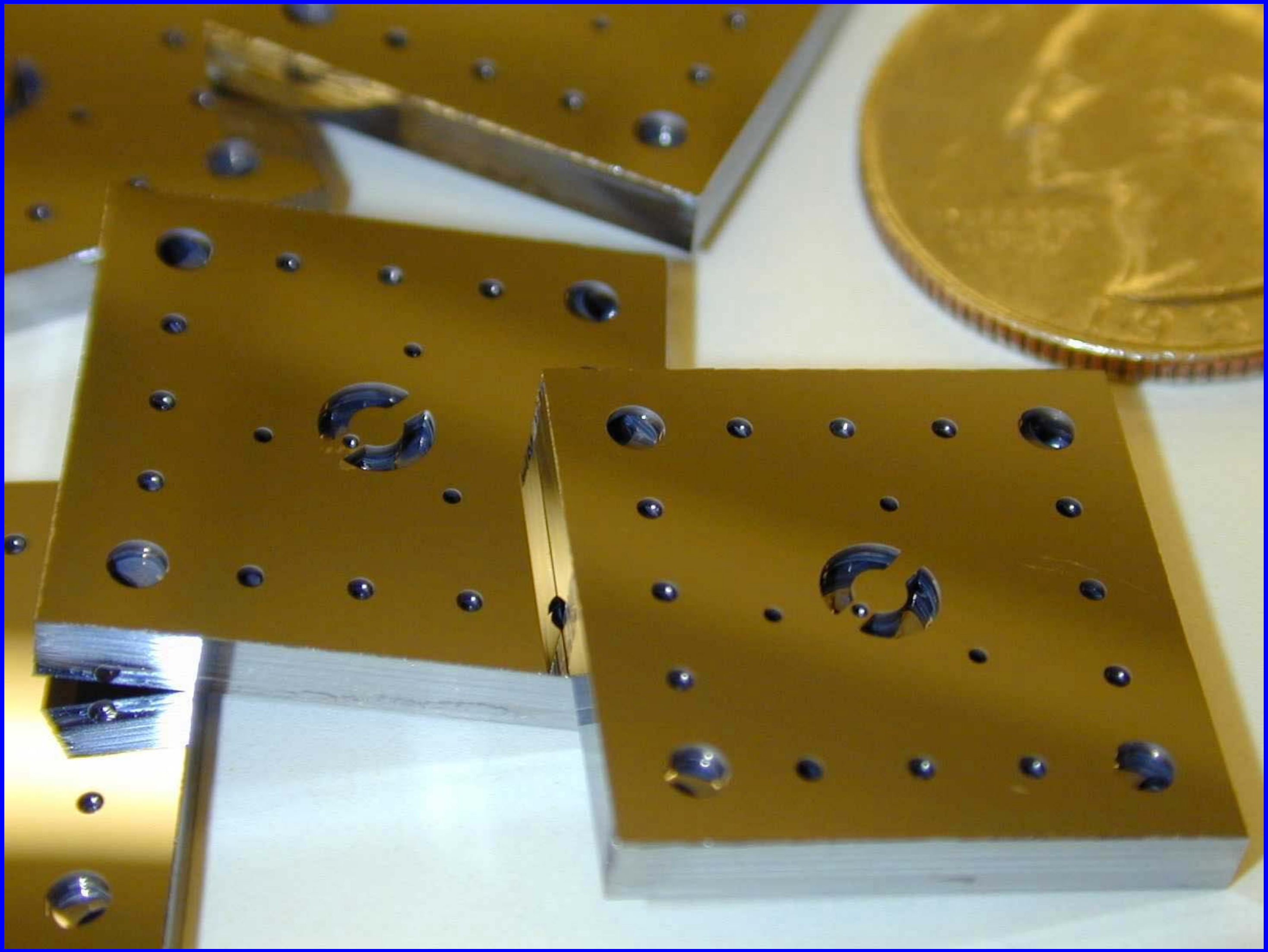
MIT MICRO-GAS TURBINE ENGINES



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MIT DEMO ENGINE

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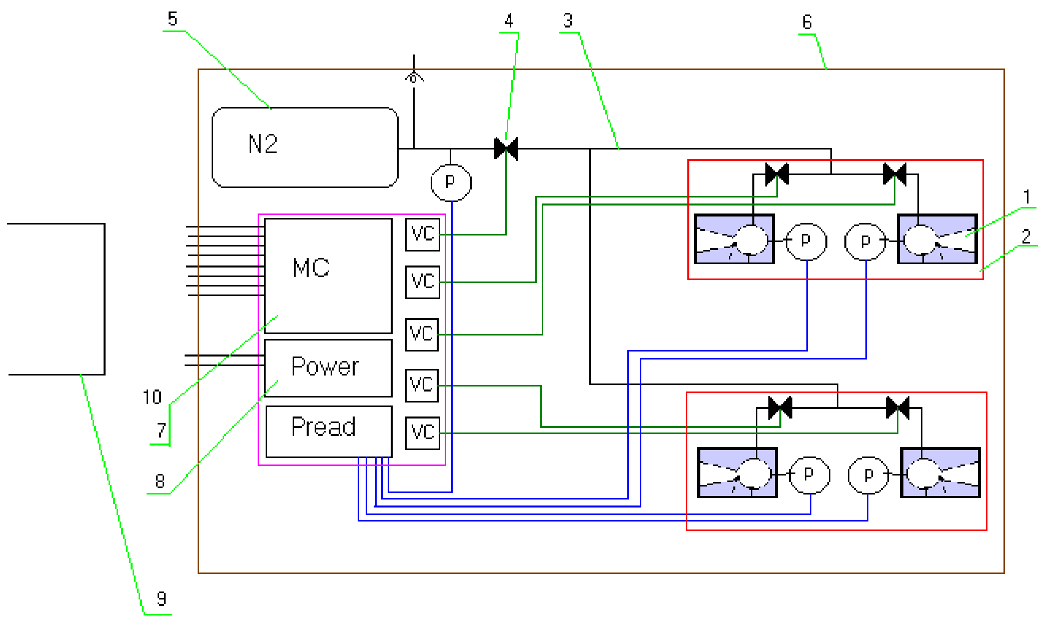
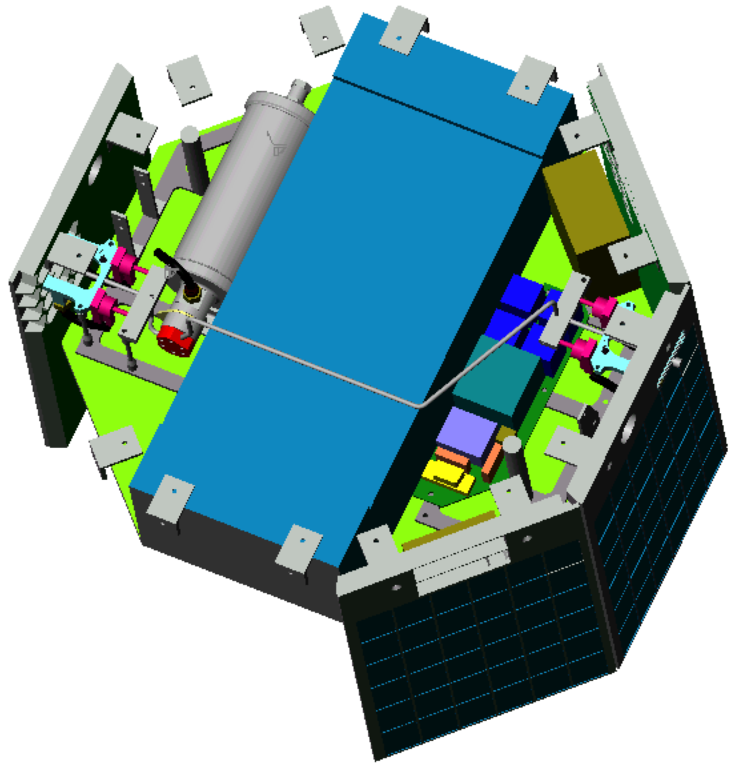
MICRO POWER MEMS

- **MICRO POWER GENERATION PROGRAM AT DARPA**
- **MICRO ROCKETS**

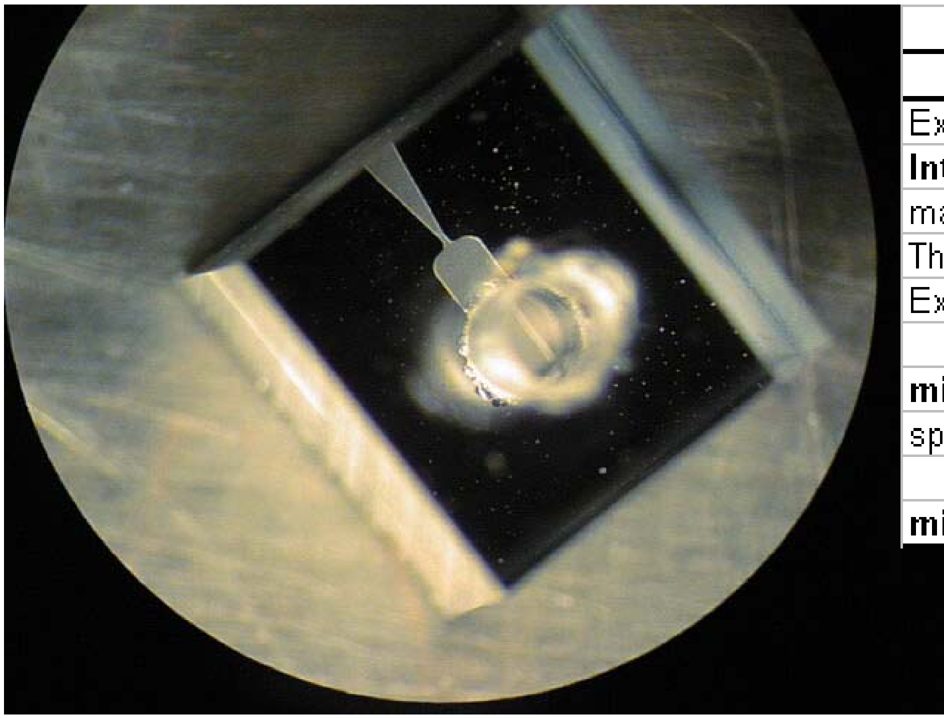
UNISAT2 - System configuration





- Microthruster
- thrusters group
- fluidic connections
- Safety valve
- gas tank
- Mechanical interface
- Control unit
- Power
- Unisat-2
- Control Software

Microthruster



Microthruster Performances				
External pressure	Pe	Bar	1	0
Internal pressure	**Pi**	**Bar**	**6**	
mass flow rate	dm/dt	mg/s	0,96	
Theoretical thrust	Ft	µN	246	656
Experimental thrust	Fe	µN	210	*560*
error	+/-	µN	15	40
minimum thrust	**Fmin**	**µN**	**195**	**520**
specific impulse	Is	s	21	57
estimated error	+/-	s	1	3
minimum specific impulse	**Is min**	**s**	**20**	**54**

UNISAT2 - Assembly