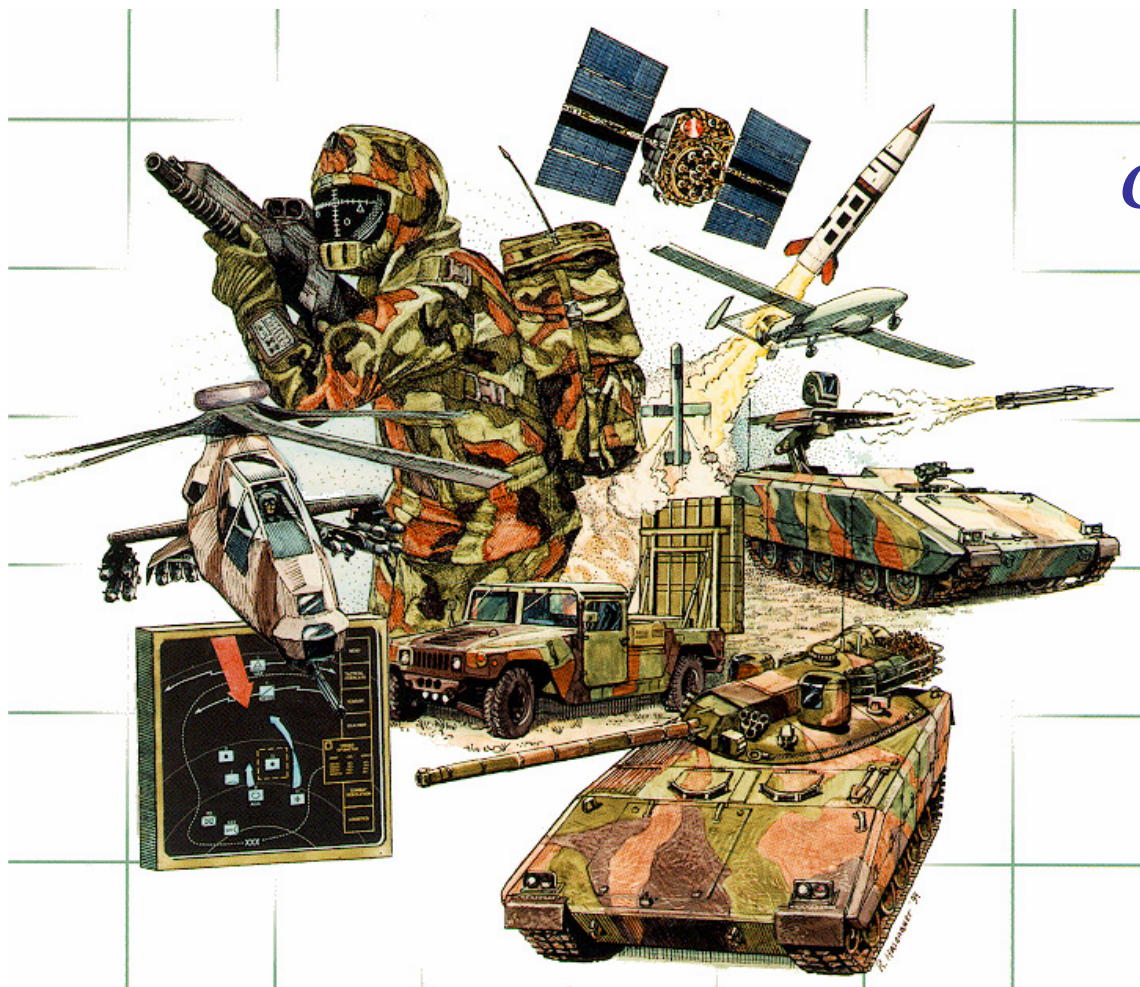




Fundamentals and Innovations Of Army Energy Conversion Systems



*Symposium on Energy
Conversion Fundamentals*

Istanbul, Turkey
June 21-25, 2004

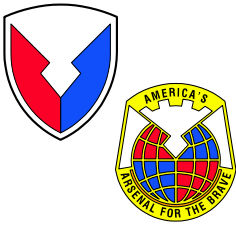
Dr. C. I. Chang
Director
US Army Research Office

Report Documentation Page

Form Approved
OMB No. 0704-0188

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Outline

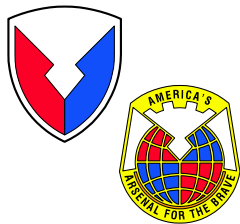
Overview of Army Basic Research

Challenges for Army Energy Conversion

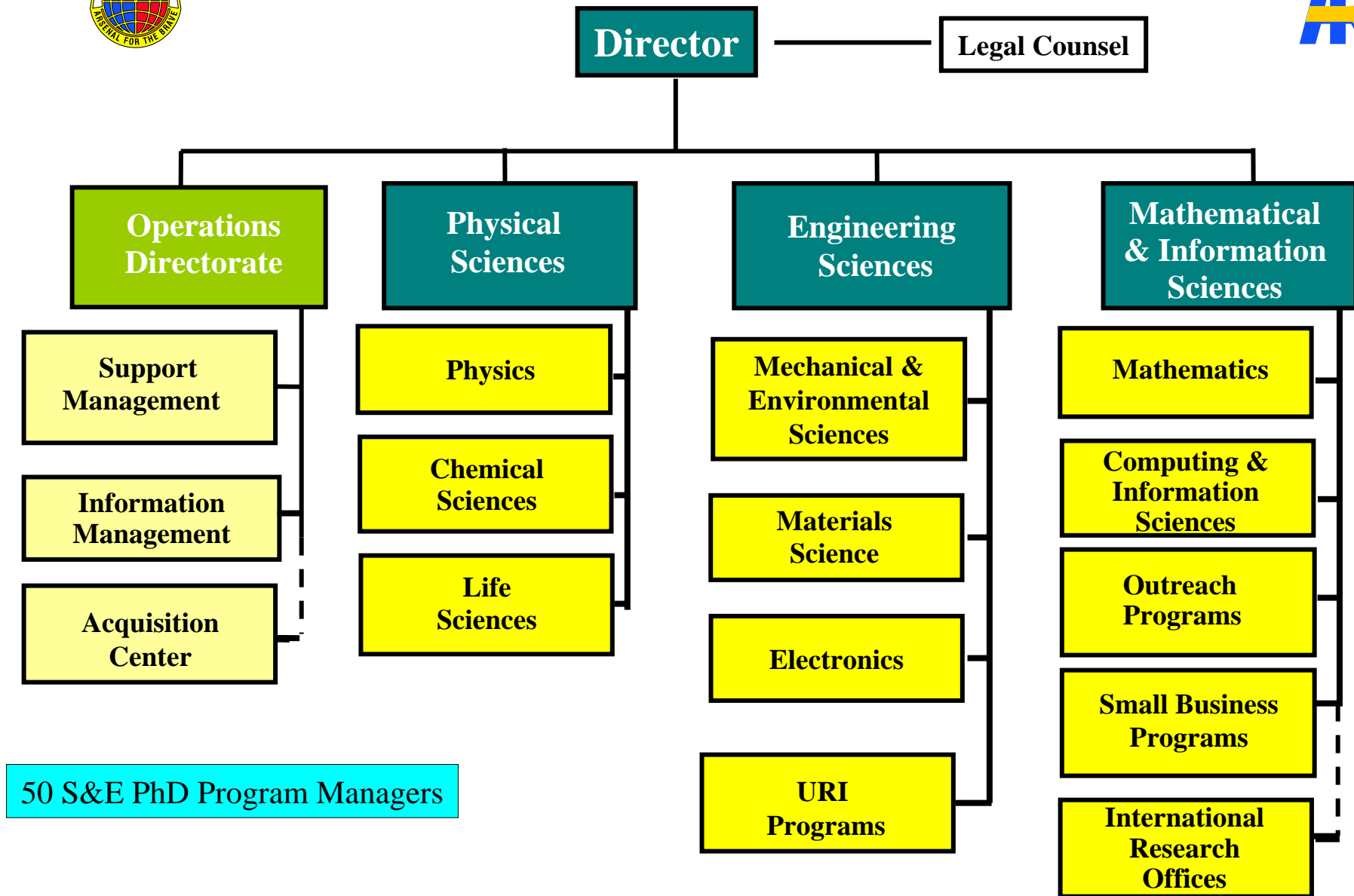
Initiatives in Energy Conversion

- Compact Power
- Vehicle Propulsion
- Weapons Propulsion

Summary



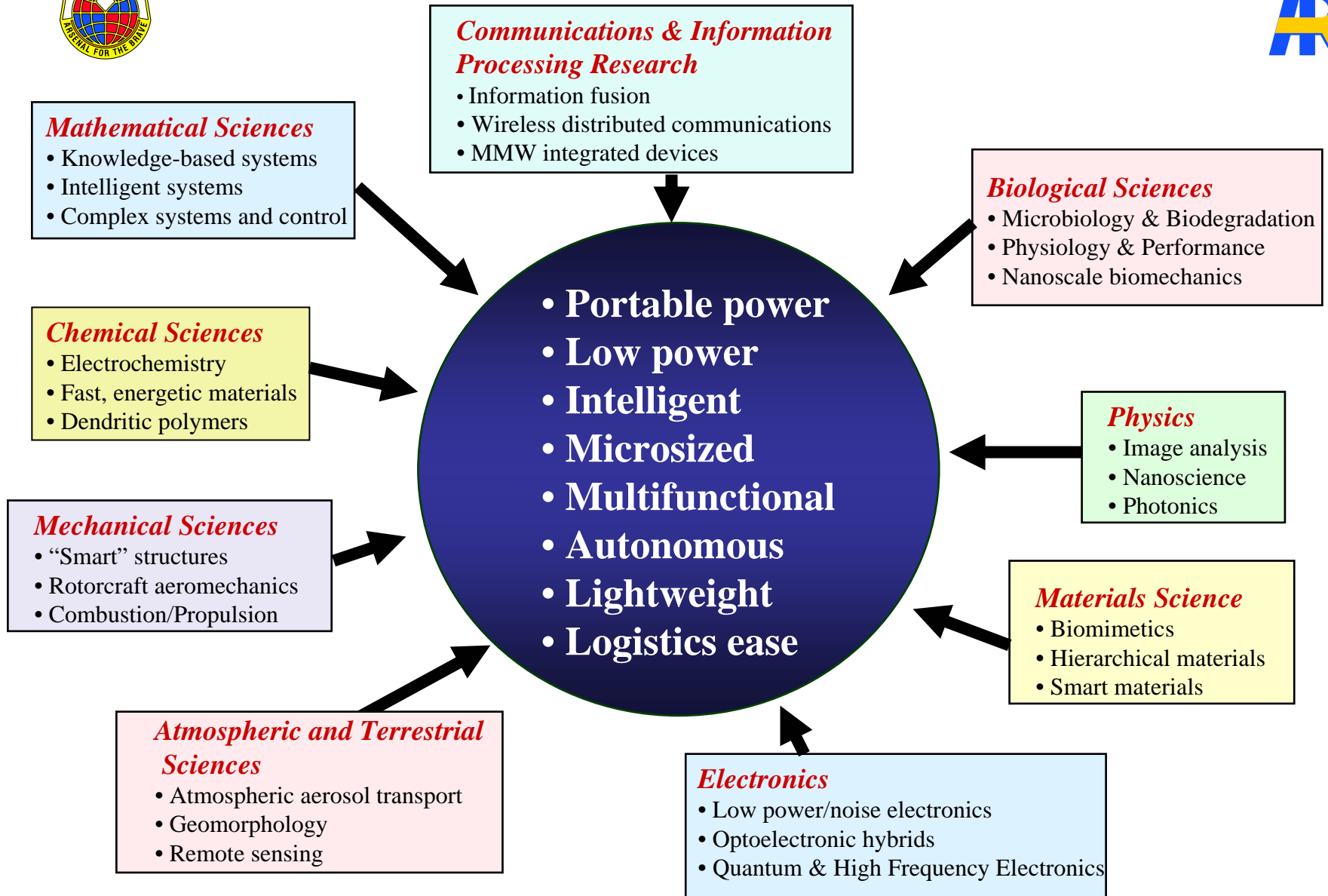
Army Research Office



Provisional Organization Structure



Army Basic Research Pursuits

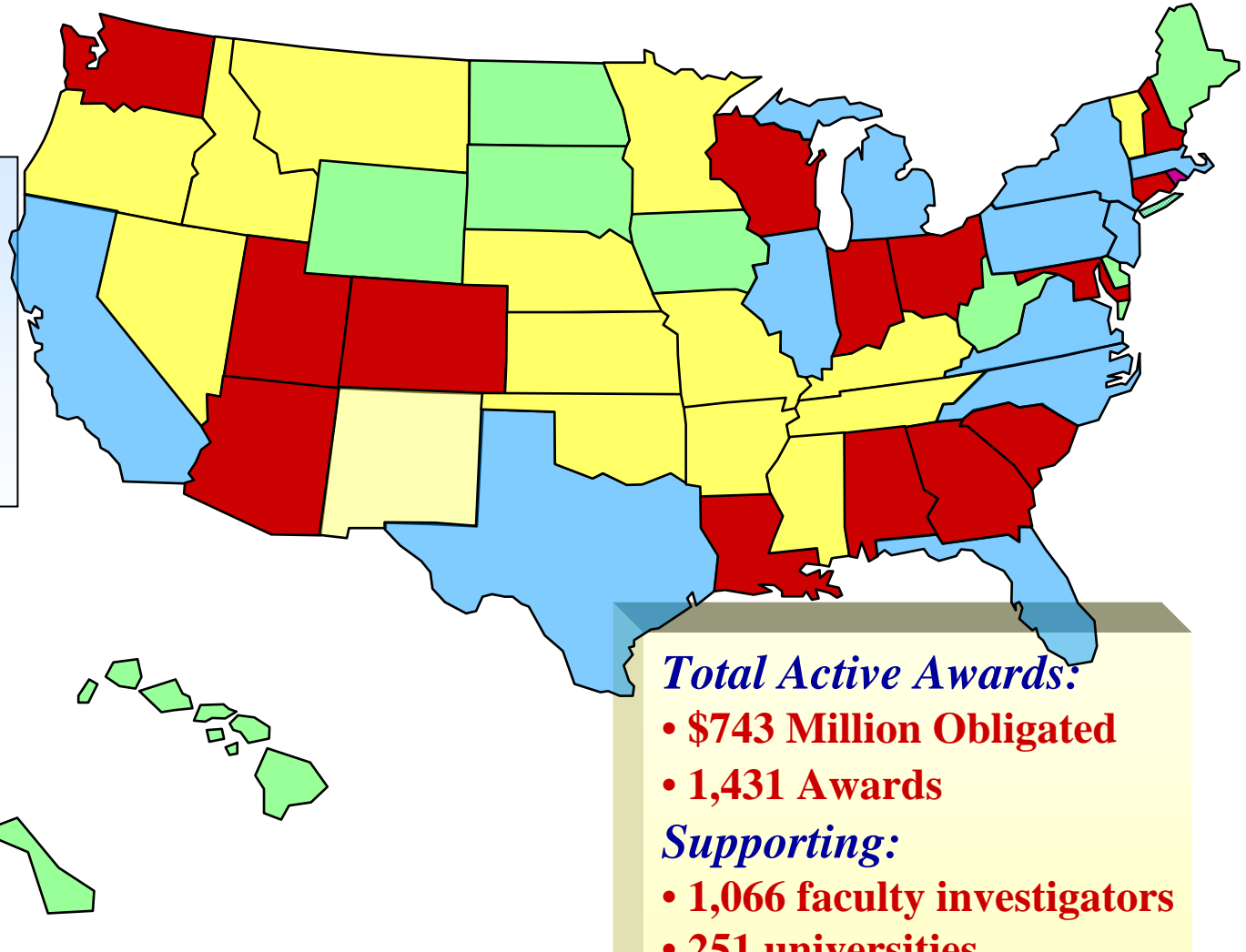


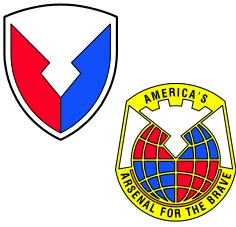


Distribution of Research Funds Managed by ARO



Total Award Amount to the State





Challenges for Army Energy Conversion:

Mission Complexity

Force Transformation



Objective Force for Full Spectrum of Missions

Environmental Complexity

Urban

High



Open rolling terrain

Low



Stability and Support Operations

Small Scale Contingencies

Major Theater War

Spectrum of Conflict

Increased strategic responsiveness

- ✓ Brigade in 96 hrs; Division in 120 hrs; Five Divisions in 30 days
- ✓ Fight immediately upon arrival
- ✓ Simultaneous air and sea lift
- ✓ Anti-terrorism

Capabilities for an Uncertain Future:

Current and future armies have a wider range of problems to solve



A Revolution in Capabilities

... Smaller, Lighter & Faster

Objective Force

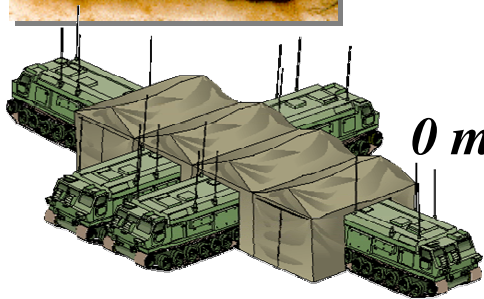
Today



~100 lb.
load

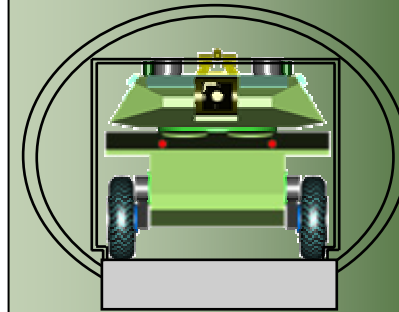


70+
tons



0 mph

Fit the C-130
"Crucible"



< 30 lb.
effective
load



< 20
tons



> 40 mph



Innovation -- Accelerating the Pace of Army Transformation

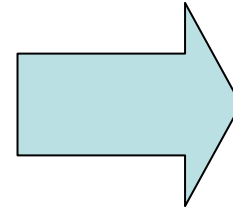


Compact Power for the Dismounted Soldier Enabling the Future



Present

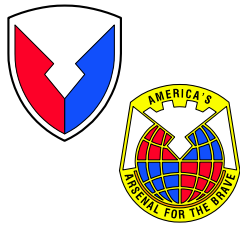
- heavy, single-purpose,
non-integrated equipment



Future

- integrated, multi-functional
protective suite

The Key is Lightweight, Compact Power



Specific Energy (Wh/kg)



SOURCE	SPECIFIC ENERGY (Theoretical)	SPECIFIC ENERGY (Practical)
Springs (watch) Rechargeable Batteries	0.25	0.15
Primary Li/SO₂	<1200	35-200
Primary Li/SOCl₂	1,400	175
Zinc/air	1,400	300
TNT	1,400	300-400
Methanol	6,200	N/A (M61 HG~260Wh)
Ammonia	8,900	1,500-3,100
Carbon	9,100	1,000-4,000
Diesel (JP-8 similar)	13,200	2,000-4,000
Hydrogen	33,000	1,320-5,000
Nuclear	33,000	1,000-17,000
	2,800,000	190,000

**Energy
of
Combustion**

ENERGY FROM COMBUSTION >> BATTERIES

Heat Engine vs Electrochemistry



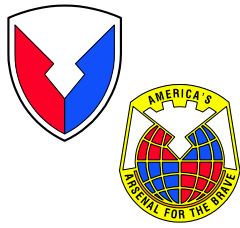
Liquid Fuels
High Energy Density

Higher Temperature
Lower Efficiency
Minimal Fuel Processing
Can burn impurities
Good infrastructure
...

Combustion/Heat Engines
About 30-35% efficient (full power)

Lower Temperature
Higher Efficiency ?
Large Fuel Processor
for many fuels (JP-8)
Sensitive to impurities
Little infrastructure
...

Electrochem/Fuel Cells
About 70% (reformer) X
50% (Fuel Cell) = 30-35% eff



Examples in H₂/Air fuel cell evolution



- 1992 - Analytic Power - SBIR:
- 15 W (on a good day)
- No fuel included
- 5 pounds
- Short life
- Analytic Power now produces much better stacks



- 1996 - H-Power -DARPA/ARO:
- 40 W sustained
- 90 Wh of stored hydrogen
- 3.5 pounds
- Starts/runs reliably after 6+ yrs
- Stack is used in commercial products
- **H-Power doesn't exist anymore**



- 2001?- Ball Aerospace -
- PM Soldier? / DARPA / CECOM / ARO:
- Concept based on available technology
- 15 W sustained, 25 W peak
- 400 Wh of generated hydrogen in 1 pound fuel canister
- 2.2 pounds

Relative Energy Density

The big challenge is the hydrogen fuel supply



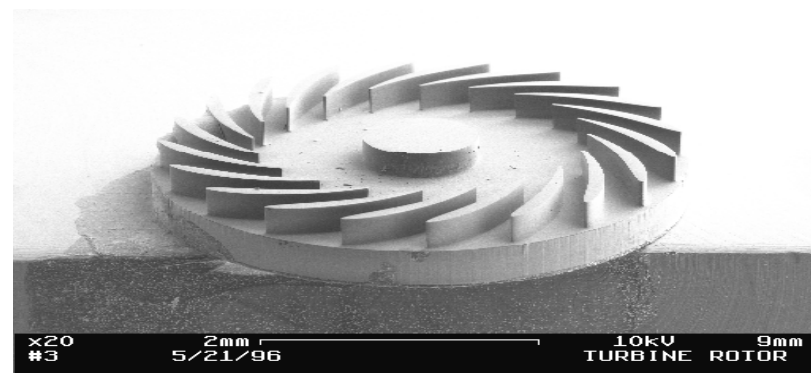
Microturbines



**DoD funded Multidisciplinary University Research Initiative
Massachusetts Institute of Technology, Prof Alan Epstein and team of 45**

Concept:

- μ Fab of refractory ceramics enables μ heat engines (includes cooling units)
- Power densities approach those of full-sized engines
- Cost very low given sufficient demand
- μ Engines enabling technology for

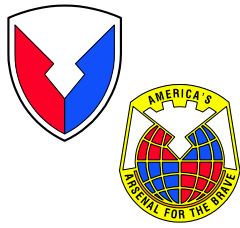


Payoff

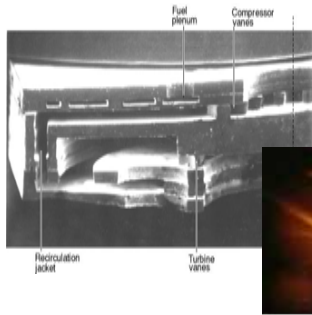
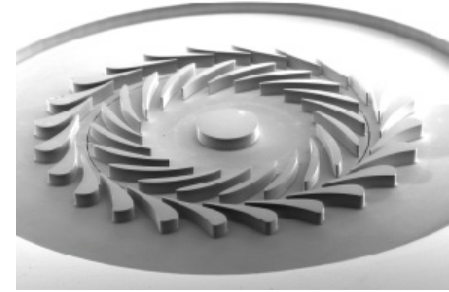
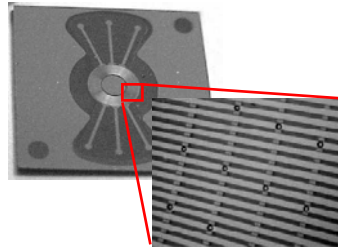
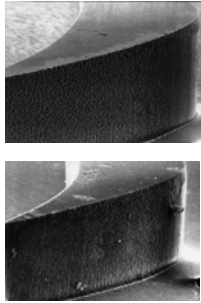
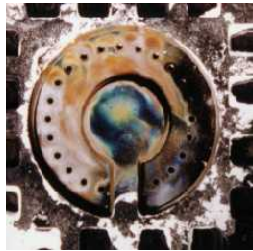
	<u>uturbogen+fuel</u>	<u>BA5590</u>
• Power	50 W	50 W
• Energy	175 W-hr	175 W-hr
• Weight	50 g	1000 g
• Size	50 cc	880 cc

Accomplishments:

- Wafer scale fabrication demonstrated
- Cooled Si - high temp structural material
- Studies plus experiment suggests HC fuels can be burned in microcombustor
- Microbearings spun at 1.4M RPM
- 6-layer hot structures fabricated and tested

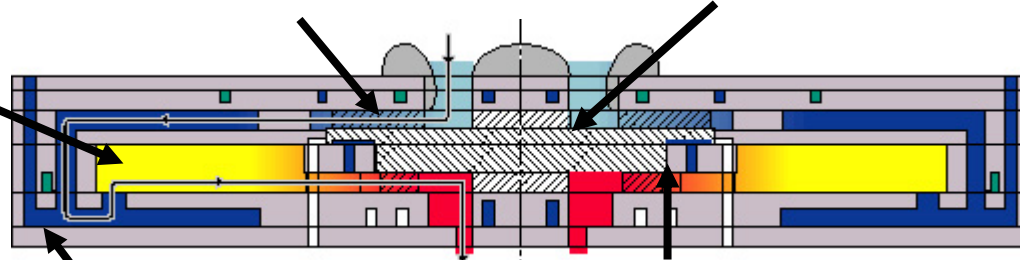


MIT/ARO Demo Microturbine



Motor/Generator

Turbomachinery

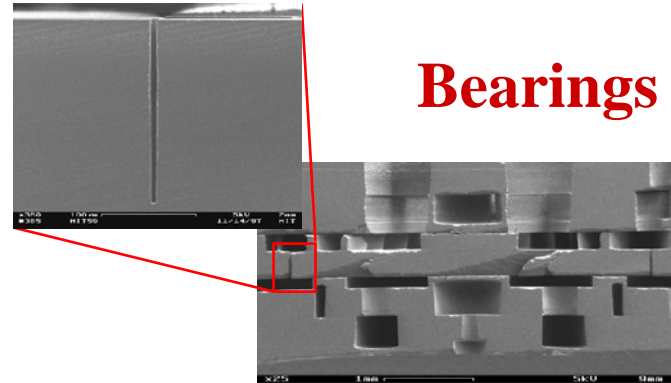


Combustion



Electrical & Fluidic Interconnects

Bearings





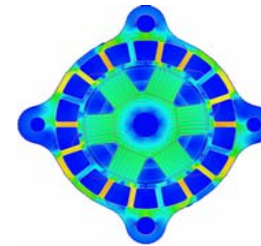
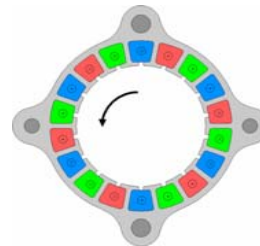
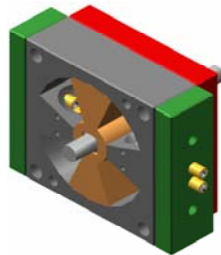
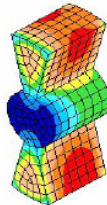
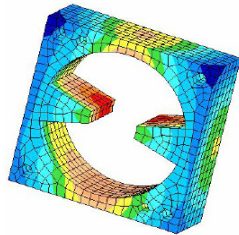
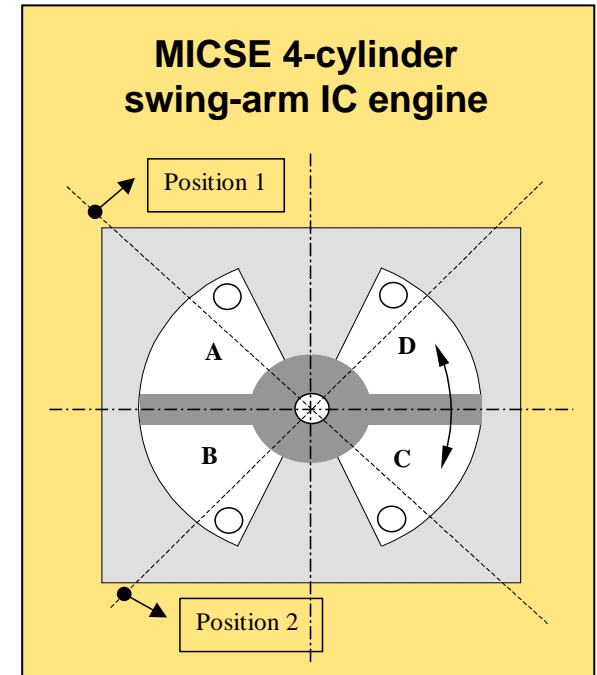
“Micro” Combustion Swing Engine

(Werner Dahm, wdahm@umich.edu)



Micro Internal Combustion Swing Engine (MICSE)

- Power generation systems based on small internal combustion engines with integrated generators:
 - Comparatively low fixed mass (high specific power)
 - Moderate thermal efficiencies (**currently 8%; expected by end of program >17%**)
 - Fuel flexible operation (butane/propane, JP-8, etc.)



S.M. Wu
Manufacturing
Research Center

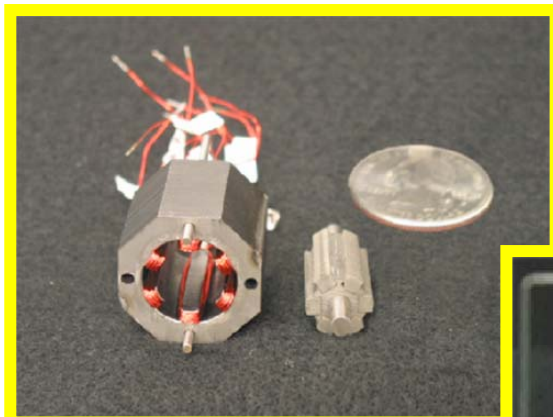




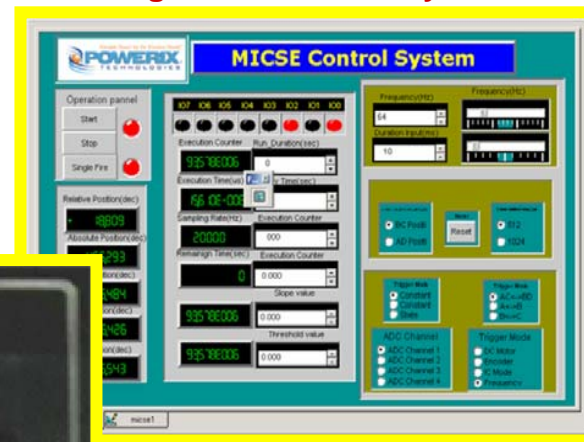
Major Progress Areas



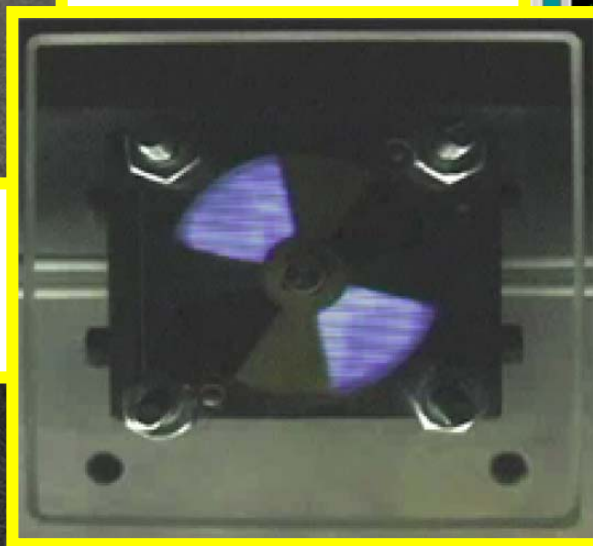
MICSE Generator Subsystem



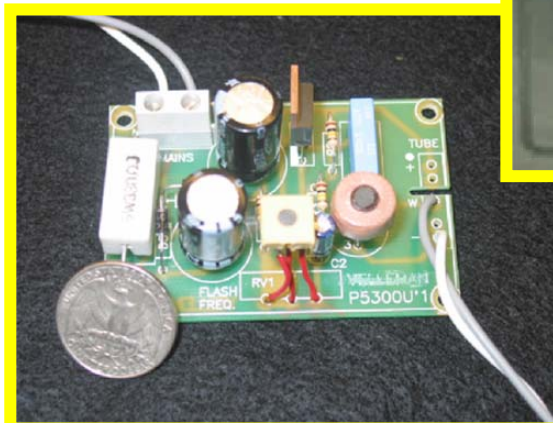
Engine Control Subsystem



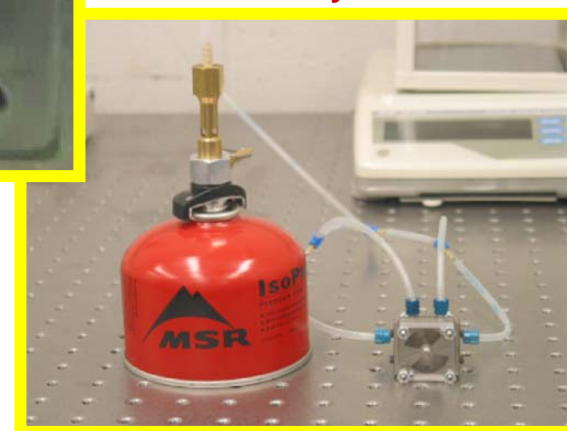
MICSE Engine Core



Ignition Subsystem



Fuel Subsystem



S.M. Wu
Manufacturing
Research Center



Mesosopic
Devices



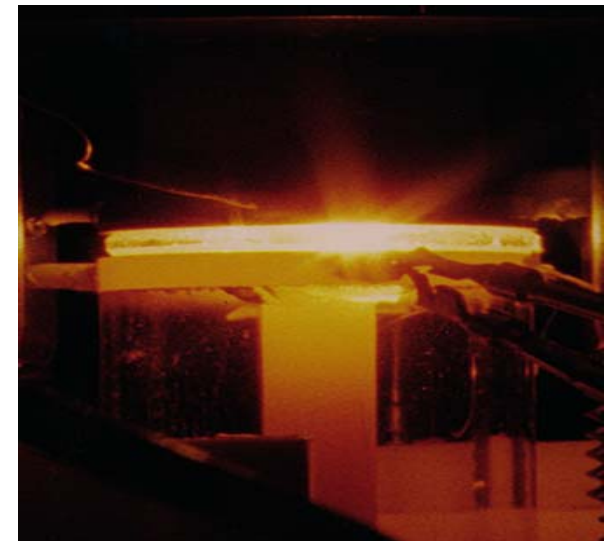
Technical Challenges/Opportunities



High-Temperature Materials

Refractory material microfabrication (SiC , Si_3N_4 , Al_2O_3 , ???)
High temperature electrical properties for electromechanical components

- **Electromechanics:** decoupling of electrical and fluid performance
- **MEMS tribology:** very high speed bearings and drive trains, stiction
- **Fluid mechanics**
Diffusion at low Reynolds numbers
Flow turning with micro-fab constraints
- **Combustion:** Catalytic combustion of liquid fuels
- **Diagnostic tool development**
- **Wafer-Scale Precision Microfabrication**
- **Packaging of small high temperature systems**



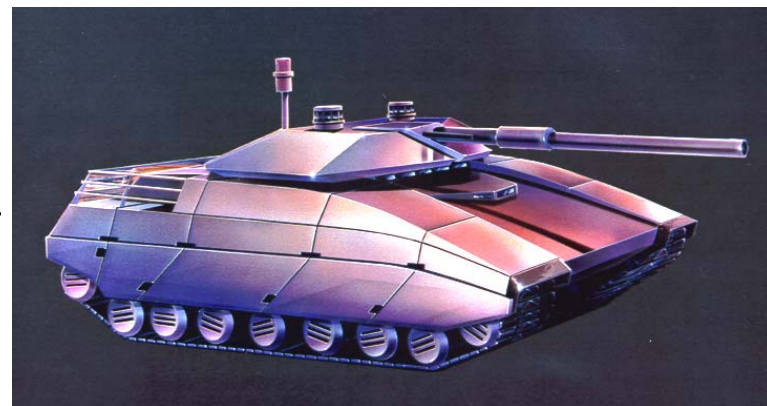
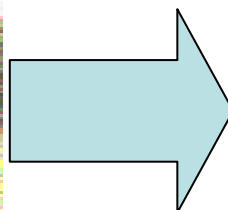
200 W microcombustor operating at 1600°K



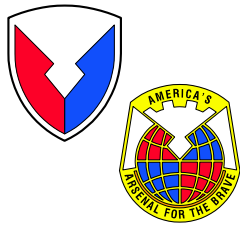
Vehicle Propulsion Research: Enabling the Army Transformation



M1 - Abrams Tank
70 tons



FCS Platform
20 tons



Future Combat System Drivers

Shrink the Logistics Burden



Typical Armored Division (6 x 4 x 2)*

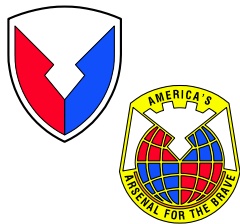
<u>Item</u>	<u>Number</u>	<u>Short Tons</u>
Tracked vehicles	1,895	51,352
Trucks	3,031	23,913
Trailers	1,627	4,206
Aircraft	127	566
Equipment	--	5,600
Subtotal		85,637
30 day sustainment		104,970

* 17,000 personnel, TOE 87000J430, 6 armored battalions,
4 infantry battalions, 2 aviation battalions

**** A heavy division consumes more than its own weight every 30 days***

**** 60% fuel, 30% ammo***

**** Combat vehicles are 56% of the weight and consume 73% of the fuel***



Propulsion System Analysis

- the key to true high power density

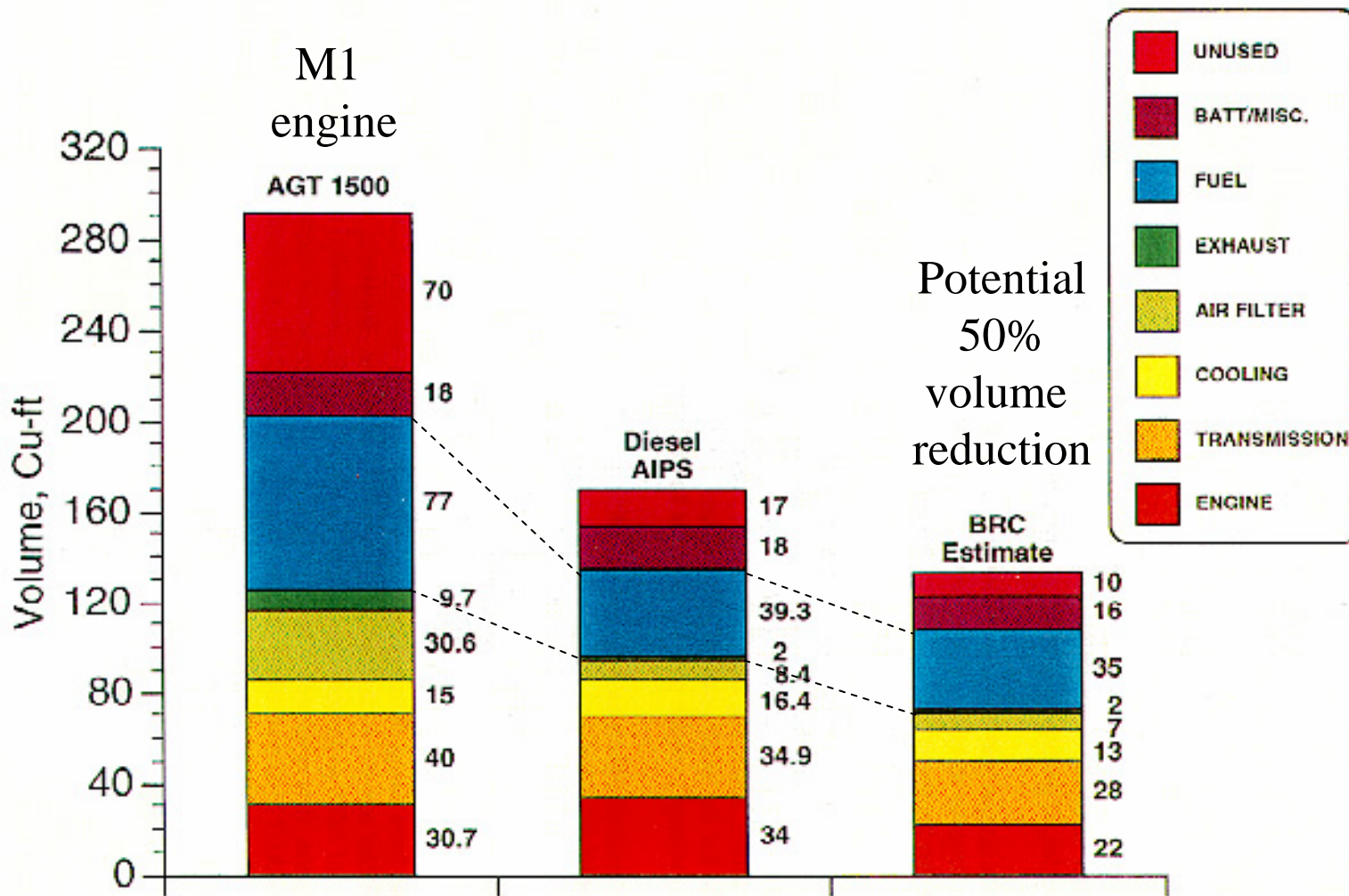
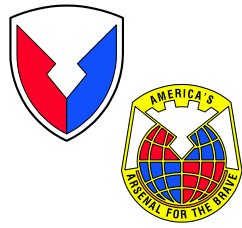


Figure 1-1. Volume reductions achievable by using high power density propulsion systems



Army Transformation for Future Army Propulsion



High Power Density

- Engine
 - High BMEP
 - Maximum air utilization
 - Near stoichiometric
 - High RPM
- System
 - Minimum propulsion system volume
 - Fuel, air handling, accessories

High Fuel Efficiency

- Low SFC engines
- Hybrid Systems

High Reliability

- Advanced diagnostics/prognostics

Reduced Logistics/Maintenance



Center of Excellence for Advanced Propulsion



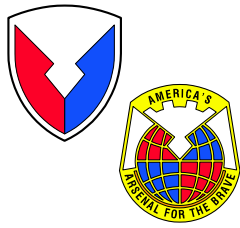
- A Major Contribution -

The development of a validated **computational capability** for the analysis and design of reciprocating engines

Enhanced capabilities to analyze:

- Engine intake flow
- In-cylinder turbulent flow
- Fuel injection - injector -> nozzle -> spray
- Liquid spray-wall interaction
- Ignition/combustion dynamics
- Pollutant formation/destruction
- Heat transfer

Which can then be used for model-based analysis of engine optimization and performance envelope determination



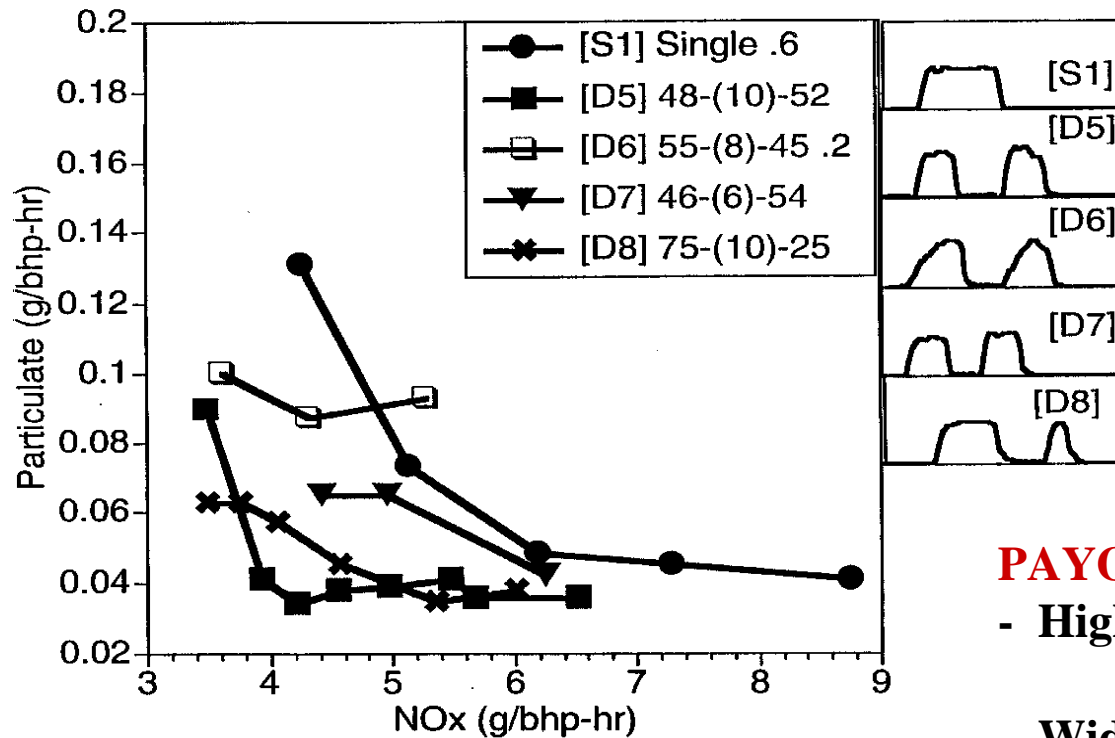
Fuel Injection Tailoring

Multi-Pulse Injection



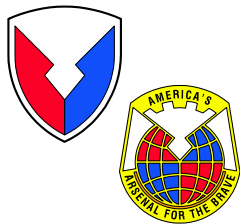
Multi-Pulse Injection Results

Particulate vs. NOx 75% Load



PAYOFF

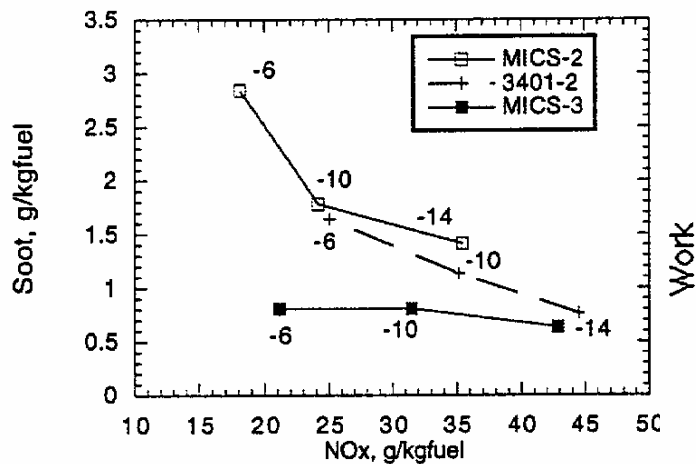
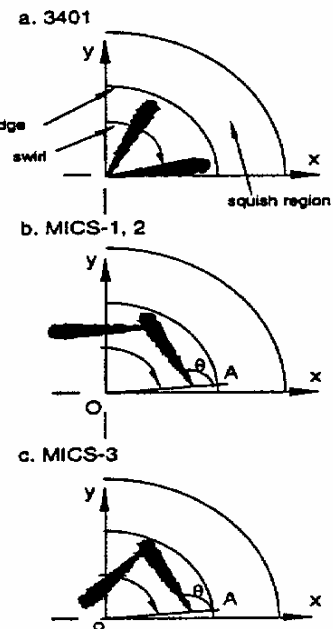
- High efficiency, Low emissions
- Wider range of engine operation
 - higher power density
 - lower, stable idle rpm



Exploration of Strategies for High Power Density

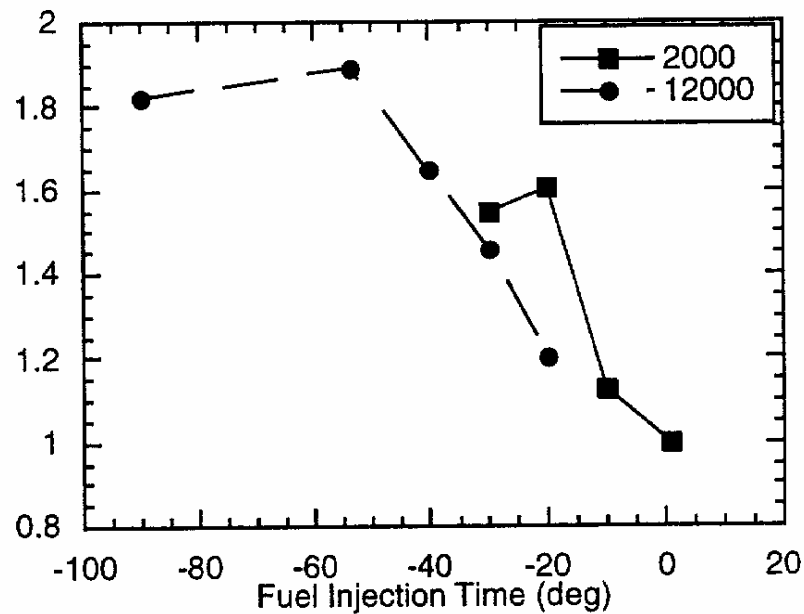


High Power Density 50% increased fueling rate

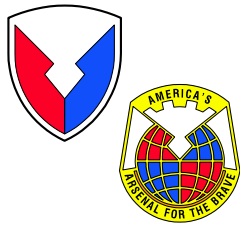


NOx and Soot with MICS-3 comparable to baseline engine at standard fueling rate

High RPM Operation

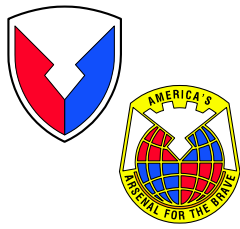


Analytical results guide selection of appropriate strategies



Weapons Propulsion

Nano-Scale Energetic Materials



6.1 Strategic Research Objective: Insensitive High-Energy Materials



Characteristics

- Major research theme to achieve significant advancement
- “Systems engineering” at the 6.1 level
- High payoff potential for future Army applications
- Stable, sustained investment for long-term (5-10 years) to achieve technology enablement

Advanced Energetic Materials

Coordinated through the
National Advanced Energetics Program

Ranked in the top 5% of
The Worlds Most Powerful Computing Sites



Past



Present



ENIAC Digital Computer
–BRL Ballistic Firing Tables

DOD High-Performance Computing – MSRC
Designer Energetic Materials & Full-Spectrum Modeling



ARL Nanoenergetics Program

Core and URI funded, WMRD and ARO collaboration



Program Thrusts

Novel Applications of Nanostructures to Propellants

Theoretical Analysis & Modeling

- Structure
- Reactivity/Sensitivity

High Rate Synthesis

- Plasma condensation, SolGel, Novel Structures, ?

Characterization

- In-situ, post-production

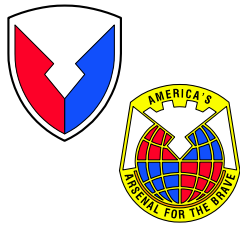
Nanoenergetics Initiatives

National Nanotechnology Initiative

- DURINT (Defense University Research Initiative in Nanotechnology)
- *Nano-Systems Energetics* (U. Minnesota)

Multidisciplinary University Research Initiative

- MURI 2004 - *Nanoengineered Energetic Materials* (Penn. State U. - start June 2004)



Conventional vs. Nanoscale Propellants



Combustion Characteristics of **Conventional Propellants** Governed by Characteristics of Composite Formulations:

- > **Multi-scale, Multi-component: Particulates plus binder**
- > **Particulate size distributions lead to local non-uniformity and clustering of smaller components**
- > **Significant agglomeration of aluminum (if present) prior to ignition**
- > **Rate of Reaction limited by species and thermal diffusivity**

A **Novel** Approach to Propellants Might Have:

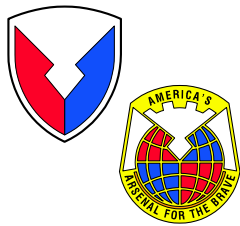
- > **Reduced size dispersion**
- > **Greater uniformity**
- > **Reduce agglomeration of aluminum**
- > **Higher reaction rates**

A **Radical** Approach to Propellants Might Have:

- > **Controllable energy release**

**NANOSCALE ENERGETIC MATERIALS MAY BE THE PATHWAY TO
ADVANCED ENERGETIC MATERIALS**

Approaches to Nanoenergetics



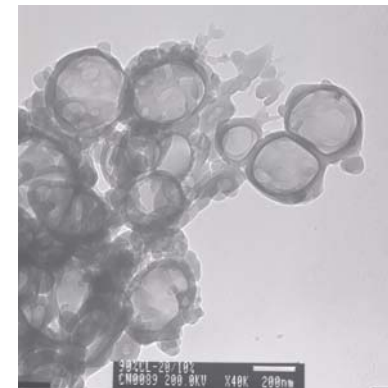
1st Generation (pre 2000)

- Nanometer-sized Al powder/conventional propellants
- Some performance gain, variable results

2nd Generation (current efforts)

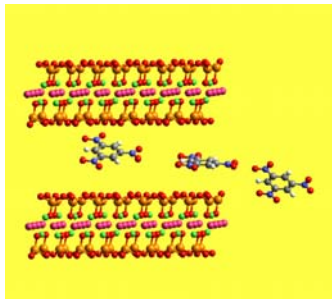
- Coated nanometer-sized metal powders
 - Controlled oxidation, improved storage lifetime
- Quasi-ordered nanometer-sized inclusions in energetic matrix
 - Cryo-Gel/Sol-Gel processing

CL-20/NC Cryogel



(DURINT - Brill, U. Del.)

Self-Assembled Energetic Materials



3rd Generation (new MURI program)

- 3-dimensional nanoenergetics
 - Structured/ordered
 - Controlled reactivity
 - Improved manufacturability/processing

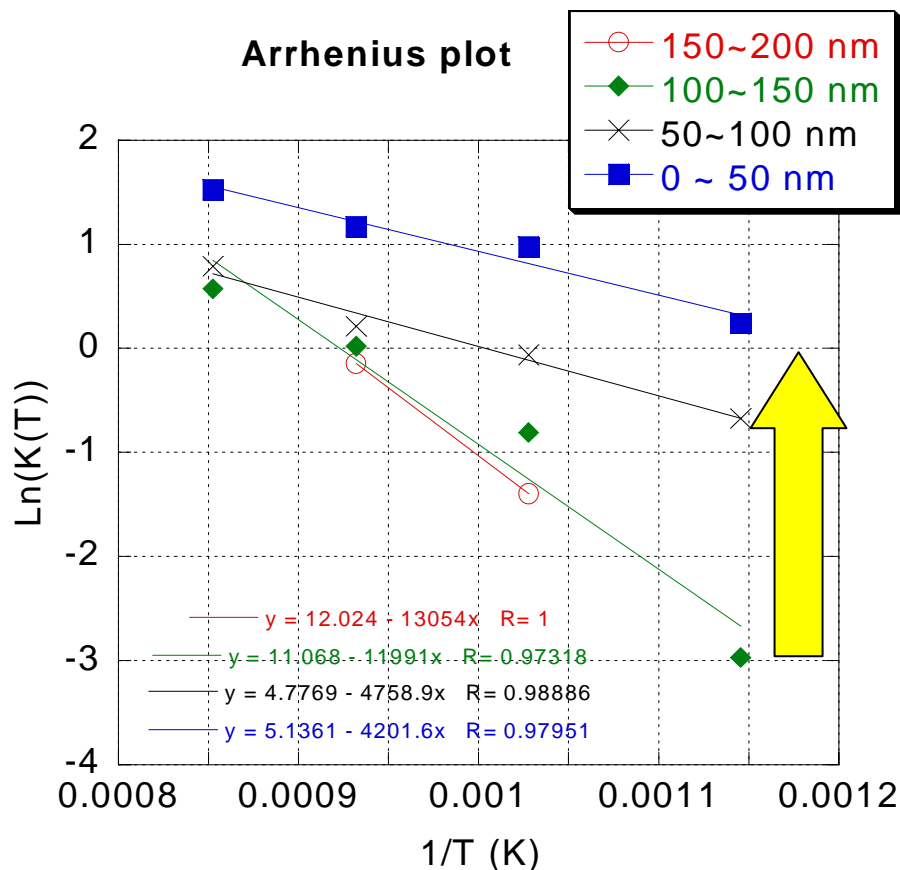


Size-dependent Oxidation of Al Nanoparticles

DURINT - M. Zachariah, U. Maryland



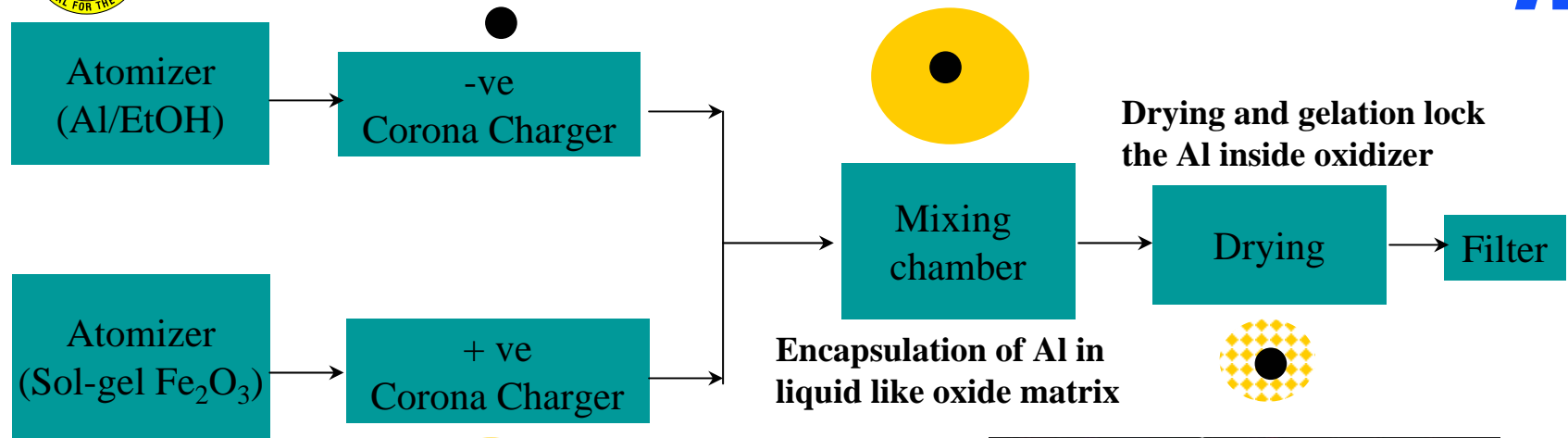
Particle produced in DC Plasma Discharge



First Measurement of Size Dependent Reaction Kinetics.

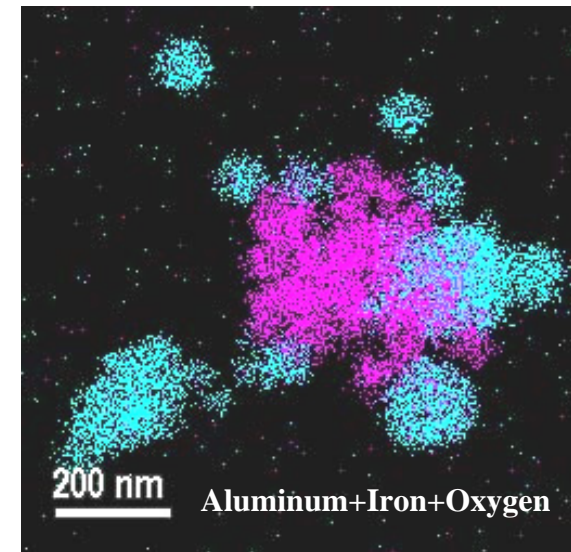
Encapsulation of Al in Fe₂O₃ matrix

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Aerosol - plus - Sol Gel Chemistry for creation of novel Nanostructures

- Difficult to match time scales of drying and coagulation.
- Can not tell from TEM if Al is inside the oxidizer particle, because Al is lighter.
- STEM elemental map shows Al particle embedded in oxidizer

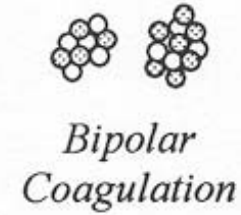
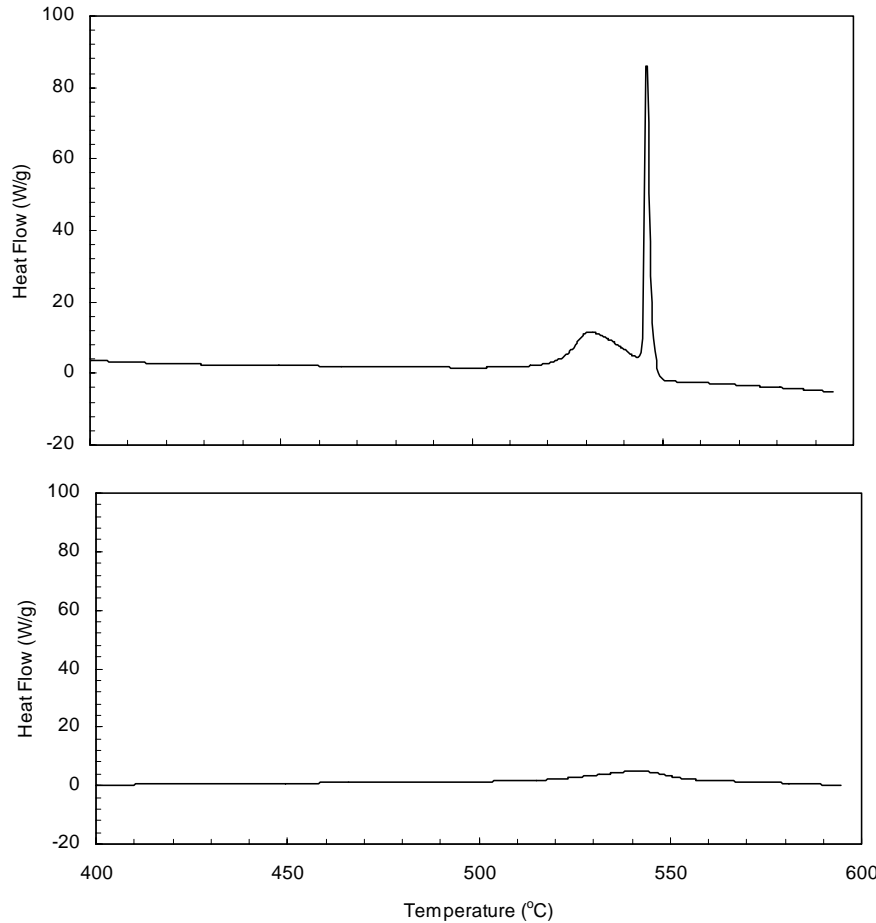


STEM elemental map of coagulated nanoparticle



Reactivity of Al in Fe_2O_3 matrix

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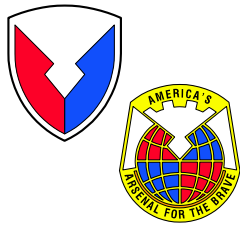


ordered



random

Ordered Nanoparticles Exhibit 10 X Energy Release Rate (Power)



Summary



Army research in energy conversion is addressing key challenges;

- Compact Power for the Dismounted Soldier
- High Performance/Efficiency Vehicle Propulsion
- Advanced Energetic Materials

Army research couples extramural academic and industrial programs with in-house capabilities

Army research is laying the foundation for the Army's future systems.