Is There Sizzle In the Fluid Power Industry?

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Automation, Robotics and Manufacturing Group
Outline

• Describe History of ORNL
  – Birth to today

• Describe Automation, Robotics and Manufacturing Group
  – Initial work in remote handling
  – Fluid powered haptics
  – Mesoscale fluidics
  – Anthropomorphic robotics
  – Freeform fluidics

• Manufacturing initiatives
  – ORNL’s manufacturing demonstration facility
  – Impact of Fluid Power Industry
Oak Ridge National Laboratory established during the Manhattan Project

ONRL focused on Uranium production and pilot plutonium line, Hanford for large scale plutonium production and Los Alamos for weapon design and testing.

ONRL was selected due to remote location, TVA (power) and rivers (cooling).

- X-10 provided reactor research
- Y-12 developed centrifuge for isotope separation
- K-25 gaseous diffusion enrichment

ORNL in 1943
The Clinton Pile was the world’s first continuously operated nuclear reactor.
Today, ORNL is DOE’s largest science and energy laboratory

- $1.6B budget
- 4,350 employees
- 3,900 research guests annually
- $350 million invested in modernization

- World’s most powerful open scientific computing facility
- Nation’s largest concentration of open source materials research
- Nation’s most diverse energy portfolio
- Operating the world’s most intense pulsed neutron source
- Managing the billion-dollar U.S. ITER project
Core Competencies:
Energy, computing, biosciences, materials, neutron science and national security

Energy technologies

Materials at the nanoscale

Ultrascale computing

Neutron sciences

Climate and Bioenergy

National security

Nuclear energy
ORNL’s Automation, Robotics and Manufacturing (ARM) group

• Core competency is in the design and control of complex **fluid powered systems** and components
  – Initial work in remote handling. Evolved to DoD and fluid power in 1995
  – Tackle problems from large (ship motion simulation platform) to small (mesofluidics)
  – Primary sponsors include DARPA, ONR, Air Force, NAVSEA, private industry (almost 100% work for others)

• **Why fluid power?**

![Next Generation Munitions Handler](image1.png)
![High Payload Holonomic Omnidirectional Vehicle](image2.png)
![Two Stage Digital Valve](image3.png)
![30 W Hydraulic pump](image4.png)

![Ship Motion Simulation Platform](image5.png)
![Hydraulic hand with titanium fingers made via additive manufacturing](image6.png)
![Anthropomorphic Hydraulic Arm for Boston Dynamics Petman Program](image7.png)
![Single Digital Valve](image8.png)
Actuation Options and State of the Art

- In mechatronics, we are focused on controlling devices
- To control something, you need actuation (muscles)
  - Converts electrical command to mechanical power

APA230L, APA150M, APA100S
What are our options

- Conventional
  - Electric
    - Convert electrical power to magnetic to mechanical
      - Brushed, brushless, steppers
  - Pneumatic
    - Convert pressurized gas (air or steam) to mechanical power
  - Hydraulic
    - Convert pressurized fluid to mechanical power

- Smart Materials
  - Electrostatic
    - Variable capacitance to induce strain
      - Piezoelectric, Electroactive Polymers
  - Magnetostrictive
    - Variable inductance to induce strain
  - Shape memory
    - Thermal transition induces strain
How do they compare quantitatively

<table>
<thead>
<tr>
<th>Actuator</th>
<th>Stress (psi)</th>
<th>Strain</th>
<th>Power Density (W/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electromagnetic</td>
<td>1.5 – 5</td>
<td>0.5 (linear)</td>
<td>&lt; 200</td>
</tr>
<tr>
<td>Hydraulic</td>
<td>&lt; 6000</td>
<td>0.5 (linear)</td>
<td>&lt; 2000</td>
</tr>
<tr>
<td>Pneumatic</td>
<td>100</td>
<td>0.5 (linear)</td>
<td>200</td>
</tr>
<tr>
<td>SMA</td>
<td>20,000</td>
<td>0.08</td>
<td>6</td>
</tr>
<tr>
<td>EPA</td>
<td>50</td>
<td>0.5</td>
<td>6</td>
</tr>
<tr>
<td>Piezoelectric</td>
<td>5000</td>
<td>0.001</td>
<td>0.1</td>
</tr>
<tr>
<td>Magnetostrictive</td>
<td>1500</td>
<td>0.002</td>
<td>5</td>
</tr>
<tr>
<td>Muscle</td>
<td>44</td>
<td>0.5</td>
<td>50</td>
</tr>
</tbody>
</table>

1 Taken from Hollerback, Hunter and Ballantyne  
2 Can go as high as 10 psi with liquid cooling  
3 Torque limited, can go to higher power density with higher speeds but requires larger transmission  
4 SMA’s have very low bandwidth, difficult for closed loop systems  
5 Piezo power scales linearly with frequency up to natural frequency (1 kW/kg/kHz)
High Dexterity Human Amplification Technology (Air Force)

- **Objective** – Merge holonomic mobility with human amplification technology (Seed projects)
  - Strength Amplification Technology – provides task specific force feedback to operator while handling very heavy payloads.
  - Holonomic Wheel – provides holonomic omnidirectionality
  - Combined locomotion degrees of freedom with manipulation degrees of freedom

- **Challenge** – Very heavy payload (>2000 lbs) with fine precision (< mm)

- **Lessons Learned**
  - Performance of fluid powered systems
  - Importance of force control for intuitive MMI (easy to learn to operate)
  - Impact of holonomic omnidirectional platform
Navy HAT
1st Challenge: Tire wear

- **Challenge:** Tire wear on deck

- **Approach:** Independent 4-wheel drive, 4-wheel steering using conventional tires.
  - Novel control methodology that monitors and manages wheel pod forces (motivated by NGMH)
  - Completely operational vehicle with 10,000 lb payload capacity. Demonstrated at sea on the U.S.S. Red Cloud and recently on Sea Fighter for LCS

- **Lessons Learned** – The benefits of redundancy and surprising performance of the system.
Navy HAT: 2nd Challenge: Force Control on Moving Ship

- **Ship is in constant motion**
  - Sea state directly measured by force sensor
  - Sea state disturbance has similar frequency content as task
    - Conventional filtering won’t work
  - Disturbance is stochastic.
    - Learning Control not effective

- **Objective:**
  - Develop force control methodologies that discriminates sea state disturbance from task forces

Example: 6000-lb load in sea state 5
Large ship; \( f_{a_H} = 420 \text{ lb}, f_{a_r} = 937 \text{ lb} \) (~23% load)
Small ship; \( f_{a_h} = 1020 \text{ lb}, f_{a_r} = 1553 \text{ lb} \) (~43% load)
What is SMCFCS  
(Ship Motion Compensation for Force Controlled Systems)

- Basic methodology is similar to noise cancellation in Bose headsets
  - Use secondary measurement of background noise (ship induced forces in the case of HAT) to cancel disturbance without modifying real signal

- Experiments confirmed that SMCFCS significantly reduces payload motion and operator forces (more than an order of magnitude) at high sea states (SS5)
**Navy Ship Motion Simulation Platform (ONR)**

- **Objective** – High fidelity ship motion simulation platform. Motivated by ONR’s desire for NGMH
- **Approach** – Novel kinematic arrangement, suitable for ship motion, enables energy efficiency and large displacements
  - Able to reduce power supply from ~1000 Hp to 150 Hp through design and hybrid control
    - Accumulators enabled energy storage during negative power phase
- **Main mast actuators provide heave/pitch**
  - Actuators have rod in tension
  - Used acceleration feedback
    - Interesting coupling between translation and torsion resulting in coupled control
- **Lesson Learned**: Potential for energy efficiency in fluid powered systems
- **Status**: Delivered to NavSea Philadelphia
Mesoscale Fluidics

- **Mesofluidics**: Actuation based on controlled movement of small volumes of fluid (<< mL/sec to 10’s of mL/sec)

- **Problem**
  - How to provide fine control of high pressure fluid at very low flow rate

- **Motivation**
  - Broad need in
    - Prosthetics, Orthotics, Rehabilitation, Remote Handling, High Dexterity/Anthropomorphic robotics

- **Challenge**
  - Design and control valve that has very low internal leakage (energy efficiency) and ability to finely control flow rate (drops/sec)

- **Approach – “Digital Valve”**
  - Instead of controlling fluid by controlled opening of an orifice, control flow by pulse width modulation
Revolutionizing Prosthetics (DARPA)

- **Objective** – Demonstrate a human finger with intrinsic actuation and control (actuators and controls within the volume of the finger).
- **Challenge** – Need for very compact actuators, pumps and controls
- **Approach** – Mesoscale hydraulics.
  - Began as an internal R&D activity
  - Series of pumps, actuators and control valves
  - Fit within the volume of a 50\textsuperscript{th} percentile human female.
- **Operational finger capable of curling 20 lbs and weighing under 60 grams**
- **Lessons learned:**
  - The amazing scalability, simplicity and performance of hydraulics
  - Tremendous potential for energy efficiency
  - Applied hybrid hydraulics to arm (single 30 W pump for hand and wrist, charges 600 J accumulator integrated in forearm for large, low duty cycle activities)
1st Generation Fluid Powered Anthropomorphic Arm (ONR EOD)

- Two enabling technologies:
  - Meso-scale fluidic actuation
    - Energy efficient multi-stage digital valve technology
    - Zero tare flow – Moog 30 spool valves have internal leakages that are equivalent to 35 Watts/valve
    - No pressure pulsation (common digital valve problem)
  - Novel involute-cam based joints
    - Large range of motion (≤ 180°)
    - Integration of actuators in structure
    - No hoses, path to leak-free manipulator, easy maintenance
    - Simple joint torque measurement

- Lesson Learned: Cams enable easy to assemble and maintain but parts are very complex (expensive)
Where is this technology being used today?

• **Automated prosthetic alignment**
  - Alignment between the prosthetic device and limb is critical
    • Misalignment is extremely painful
  - ORNL is teaming with OrthoCare Innovation to develop a mesofluidic alignment device
    • Interfaces between socket and prosthetic device
    • Mesofluidic actuation provides slight alignment correction during gait

• **Pediatric prosthetics**
  - Exploring impact of mesofluidics for development of high dexterity child prosthetics
  - Studies suggest biggest benefit could come in terms of neural development (stimulation)
  - Challenge is compact size and modularity to accommodate rapid growth

• **Lesson Learned:** Need for low cost fluid powered systems
Additive Manufacturing at ORNL (part of proposed MDF)

- Manufacturing technology in which feed material is added at specific locations to build **net-shaped components from computer models**
- ORNL has multiple technologies in one facility (**E-Beam, FDM, Laser, Plasma, Ultrasonic,**…)
- Working with both equipment providers (**advancing controls and materials**) as well as end users (**try before you buy**)
  - Exploring new materials, process feedback for quality control
  - Merging rapid prototyping with actuation and electronics
  - Potential for hybrid solutions (combining technologies)

**Direct Manufacturing Capabilities at ORNL**
- **Electron Beam Melting**
- **Laser Deposition**
- **Ultrasonic Additive Manufacturing**
- **FDM**
- **Plasma Arc Lamp**
- **Pulseforge**
- **Titanium, Aluminum, Polymers**

Production of geometrically impossible designs through conventional machining: Incorporation of mesh structure and intricate channels
ORNL Freeform Fluidics Programs

• Teaming with Boston Dynamics on Army Petman and DARPA Atlas programs
  – Developing fully anthropomorphic android for in-situ testing of chemical and biological PPE
  – ORNL developing arms and hands
  – System must have integrated sensing (chemical), perspiration, thermal management and control (hydraulics).
  – Parts have complexity that would not be possible with conventional machining

• Bluefin robotics
  – Objective is to develop titanium arm that will be neutrally buoyant (will float)
  – Has integrated fluid passages and wire ways
Early Results

• Characterization to establish design rules
  – Tubing: 0.020” wall thickness matches FEA prediction of strength. No porosity, held pressure to 6000 psi
  – Mesh structures match FEA analysis down to 0.020” thread thickness
Robotic Applications

• Lightweight hands and arms
  – Hydraulic hand with integrated pump and actuators
  – Mesh structure reduced weight by 5X

  – Anthropomorphic titanium arm with integrated actuation
    • Extremely light weight (830 grams)
    • Robotic and prosthetic applications

• Lesson learned: Potential for extremely light weight, low cost robotics
  – Complexity is free so reduced mass = reduces cost = reduces time
Energy Efficient Fluid Power is another potentially large challenge in manufacturing
Energy Flow

- U.S. consumes approximately 100 Quads/year (1 Quad = $1e^{15}$ Btu, 1 Btu = 778 ft-lb)
  - 69% is of our energy is produced domestically
  - 80% is of our energy is based on fossil fuels
- Goes to 4 main markets: residential, commercial, industrial and transportation
- Basic question: How much energy (and $) is spent on fluid power?
Impact: Cost of Energy

• How much does a Quad cost?
  – Electricity
    • U.S. industrial average cost is $.0678/kW-hr (April 09)\(^1\)
    • Equivalent to $19.87B/Quad (3412 Btu/kW-hr)
  – Gasoline
    • 2009 average cost $2.36/gal\(^2\)
    • Equivalent to $20.45B/Quad (115,400 Btu/gal)
  – Diesel
    • 2009 average cost $2.46/gal\(^2\)
    • Equivalent to $19.87B/Quad (128,700 Btu/gal)

• How much energy is devoted to fluid power?

\(^1\) [http://www.eia.doe.gov/cneaf/electricity/epm/table5_6_a.html#_ftn1](http://www.eia.doe.gov/cneaf/electricity/epm/table5_6_a.html#_ftn1)

\(^2\) [http://www.eia.doe.gov/steo](http://www.eia.doe.gov/steo)

Fuel graphs: [http://tonto.eia.doe.gov/](http://tonto.eia.doe.gov/)
2010 DOE/ORNL/NFPA Energy Study

- Fluid power is defined as the application of pumped or compressed fluid (liquid or gas) to provide force and motion to mechanisms

- In 2010, DOE ITP contracted ORNL to conduct a fluid power study
  - Objective was to estimate market size, energy consumed, emissions generated and existing efficiency levels
  - ORNL teamed with the NFPA and 31 industrial partners spanning all major application areas
  - Industrial partners provided proprietary data on systems, energy consumption, duty cycles and efficiencies
Study Results
Annual Energy Consumed By Fluid Power

• Approach: Divide market into 4 segments
  – Industrial hydraulics, pneumatics, mobile hydraulics and aerospace

• Industrial partners provided data on size, units, power, fuel consumption rate, duty cycles, energy and efficiency
  – Estimate the market share of data we obtained and extrapolate to entire market

• Between 2.281 and 3.001 Quads/year producing more than 160 MMT of CO\textsubscript{2}/year average efficiency ~21% 
  – Industrial hydraulics: 1.096 Quads/year producing approximately 74.72 MMT of CO\textsubscript{2}
    • Injection molding, presses, metal forming
  – Pnuematics: Between 0.470 and 0.509 Quads/year producing close to 32 MMT of CO\textsubscript{2}
    • Food, textiles, paper, material handling, machinery and manufacturing
  – Mobile hydraulics: 0.597 to 1.260 Quads/year consuming 4.3 billion gallons of fuel producing more than 46.84 MMT of CO\textsubscript{2}
    • Construction, agriculture, mining
  – Aerospace: 0.119/year Quads/year producing 10 MMT of CO\textsubscript{2} due to embedded hydraulics
Study Results
Efficiency: Energy losses and what can be done

• Well defined losses (typically 14% efficiency)

- Industrial partners suggest that 5% gain in efficiency achievable in next 5 years with Best Practices
- This would save industry more than 0.44 Quad/yr, >$9B/yr in energy costs, 30 MMT of CO₂

• Best Practices

- Industrial partners suggest that 15% gain in average efficiency easily achievable within next 15 years with Research and Development
- This would save industry more than 0.95 Quads/yr, >$19B/yr in energy costs, 90 MMT of CO₂
Fluid Power Challenge

*Long term R&D in the area of Fluid Power*

- **Sensing and Controls**
  - Advanced controls for power management
    - Hybrid and regenerative controls
    - Energy efficient pumps and control valves
    - Wireless sensing and control
    - Integrated diagnostics
    - Next generation modeling and simulation

- **Materials**
  - Environmentally friendly and energy efficient fluids
  - Leak-proof, low friction seals
  - Lightweight, low-cost materials

- **Nanotechnology**
  - Fluid additives for thermal/viscous effects
  - Surface treatments
    - Superhydrophobic/oleophobic materials

- **Manufacturing**
  - Additive Manufacturing (Design optimization)
    - Light weight structures, integrated systems
New initiative in manufacturing: Composites, MFP, Low-temperature synthesis, Lightweight materials, roll to roll processing, additive manufacturing

Innovations in Manufacturing
Enabling the future of industry in the United States

- Composites and Carbon Fiber
  - Low-cost, lightweight, and higher-performance carbon fiber through advanced energy-efficient manufacturing
- Magnetic Field Processing
  - Dramatically enhances material properties beyond today’s limits, including increasing fatigue life and strength, and providing stress relief
- Low-Temperature Material Synthesis
  - Bio-Synthesis of unique materials at room temperature, enabling low-cost products
- Lightweight Metal Processing
  - Technologies for low-cost titanium, magnesium and metal matrix composite components
- Roll to Roll Processing
  - High-temperature processing over broad areas on low-temperature substrates
- Additive Manufacturing
  - A broad range of direct manufacturing technologies, including electron beam melting, ultrasonic, and laser metal deposition

Unique Capabilities

- Spallation Neutron Source
  - The world’s most powerful accelerator-based neutron source
- Advanced Characterization
  - Ultrasonic, wet-heating materials characterization facilities

Products

- Additive Manufacturing, Enabling Rapid, Near-Net-Shape Complex Components
  - Out of Autoclave Processing
  - Titanium prosthetic arm with 4 times reduction in cost and weight
- Multifunctional Surface Systems
  - Rapid Energy-Efficient Heating Technologies for Improved Aluminum Products
  - Scalable manufacturing process for nanostructured materials exhibiting superhydrophobic properties
- Structural Amorphous Materials
  - Low-Cost Titanium
  - A million plus impellers have been deployed in Cummins diesel engines
- Advanced Manufacturing
  - 30-40% weight reduction demonstrated on Joint Light Tactical Vehicle door
  - Over 30% improvement demonstrated in disc cutter life for Tunnel Boring Machine applications

ORNL
Basic & Applied Research
Technology Demonstration
Engineering Development
Manufacturing Process Dev.
Limited Production

INDUSTRY

A unique partnership, from concept to final product
Basic message

- ORNL is DOE’s largest Science and Energy lab
- ORNL ARM has long history in design and control of fluid powered systems
- Research is not slow and methodical, but very dynamic.
  - Projects build off each other but can push you in different directions
- Interesting shift occurring in U.S. There are emerging technologies that can change the future of U.S. manufacturing
- ORNL is working closely with government and industry to rapidly mature and transition these technologies from R&D to industry
- Economy is chaotic but, out of this chaos, we can shape the future.

Questions?
**Bio-Synthesis of Nanomaterials**

- **Nanofermentation:** Why are we interested in bacterial synthesis of nanoparticles?
  - Great potential in terms of low-cost mass production of size controlled (10 nm to 100 nm) nanomaterials

- **Bacteria first discovered in oil and gas deposits in 1992**
  - Strains of thermophilic anaerobic bacteria produce *extracellular particles* of magnetite
  - In 2006, ORNL discovered size and shape control
    - Addition of specific control agents control size and shape of final material
      - Combined (in-situ) particle synthesis with surfactant
    - Named 2006 R&D 100 and Micro/Nano-25 in 2006

- **How does process work?**
  - In fermentor, bacteria replicate every 3 hours until they reach an optimal population density (e.g., scale invariant), low temperature (4 – 70°C), ambient pressure, pH values of 6.5 – 9
  - Bacteria act like a catalyst transforming precursors to nanomaterials (nucleation at cell membrane)
  - Low temperature, inexpensive salts for precursors and cheap fuel (glucose) drive low cost
    - (~$60/kg, 30 nm) compared to $1340/kg (99.5%, 25 nm) magnetite
“Game changing” approach to Nanomanufacturing

- **Very scalable**
  - 50,000 gal fermentor provides 500 kg/month
  - *Equivalent to 10.8 MW of PV material/year*

- **Energy efficient**
  - Organometallic synthesis occurs at 500°-600° C [Roca et al., 2006]
  - Sol-gel requires 250° - 400° C annealing under vacuum [Xu et al., 2007]
  - Nanofermentation occurs between 10° and 60° C [Phelps et al., 1998], *glucose is primary fuel!*

- **Potential for very low cost**
  - Inorganic process: >$500,000/kg (CIGS), ~50% of raw materials used [Kaelin, 2005]
  - Nanofermentation: <$8,000/kg (CIGS), ~100% of raw materials used

- **Highly refined final product**
  - In-situ integration of synthesis and surfactant yields highly dispersed materials
    - No other process can do this
  - ‘One-pass’ generation of multi-component compounds
    - Other techniques require multiple processes, increased cost and decreased control

- **Environmentally-friendly process**
  - Chemical approaches require environmentally unfriendly solvents to control size [Sun, 2004]
  - Nanofermentation is a naturally occurring biological process.
    - Nature’s been doing it for hundred of millions of years
    - We’ve just a) relocated where it’s occurring and b) modified some of the parameters to control the product
Discovered Extremophiles in Many Harsh Environments

Explore deep mines in search of deep underground bacteria

Use ROVs for extract bacteria from deep sea sediments. Extract bacteria from oil and gas exploration rigs

Extract bacteria from caustic springs in Yellowstone
• **How does material compare to commercial nanomaterials?**
  – Good match (x-ray diffraction, SQUID) between published magnetite particles and ORNL bio-synthesized particles
    • Goya (2003)
      – Ms = 77.8 emu/g (T=5K), 65.4 emu/g (T=300K)
    • Bio-synthesized
      – Crysal size – 35.1 nm
      – Ms = 76.9 emu/g (T=5K), 67.5 emu/g (T=300K)

• **What about metal-substituted magnetite?**
  – Discovered bacteria can synthesize wide range of metal-substituted magnetites: $\text{Fe}_{3-x}\text{Co}_x\text{O}_4$, $\text{Fe}_{3-x}\text{U}_x\text{O}_4$, $\text{Fe}_{3-x}\text{Cr}_x\text{O}_4$, $\text{Fe}_{3-x}\text{Ni}_x\text{O}_4$, $\text{Fe}_{3-x}\text{Pd}_x\text{O}_4$, $\text{Fe}_{3-x}\text{Zn}_x\text{O}_4$, $\text{Fe}_{3-x}\text{Gd}_x\text{O}_4$, $\text{Fe}_{3-x}\text{Mn}_x\text{O}_4$, $\text{Fe}_{3-x}\text{Nd}_x\text{O}_4$. 
Bacterial Synthesis of Quantum Dots

- Until recently, focus of nanofermentation was on magnetic materials
  - Did not realize bacteria could facilitate production of other nanomaterials
- In 2007, discovered bacteria could synthesize quantum dots
  - Quantum dots are a critical material for photovoltaics, thermoelectric, solid state lighting...
- Preliminary synthesis and analysis looks very promising
  - Very scalable in terms of production of materials
  - Potential for low cost
    - CdS (2.8 nm) is somewhat harmful to bacteria so production cost ~$50/g
    - ZnS (6.5 nm) is much less toxic to bacteria and has potential for ~$1/gram
Recent Accomplishments
Bio-Synthesis of CdS and CIGS Nanoparticles

• Successfully used bacteria to synthesize CIGS and CdS nanoparticles
  o Demonstrated feasibility and scaling from 10 mL to 30 L batches
    o > 3 orders of magnitude
  o Verified no degradation in material quality (PL and TEM) and production rate as a function of scale
    ▪ Target was 3 g/L/month; achieved 6.8 g/L/month
  o Quantified cost at $2667/kg (much less than ~$500K/kg from Lux). Materials for PV would be pennies per watt.
Nanofermentation Activities
Stoichiometry Control

Дemonstrated
- stoichiometry of the particles is getting close to optimal

$\text{CuIn}_{0.4}\text{Ga}_{0.6}\text{Se}_2$ (nominal composition)

$\text{CuIn}_{0.74}\text{Ga}_{0.26}\text{Se}_2$ (final composition is close to highest efficiency CIGS cell (Jackson et al., 2007))

$\text{Cu}_{0.87}(\text{In}_{0.74}\text{Ga}_{0.31})\text{Se}_2$
## Material Development

<table>
<thead>
<tr>
<th>Application</th>
<th>Target materials (using nominal composition)</th>
<th>Synthesis status</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic oxide</td>
<td>Pure &amp; Cr, Mn, Co, Ni, Zn, Nd, Gd, Tb, Ho, Er. U-doped magnetite (□,Fe₃₋ₓO₂)</td>
<td>+++</td>
<td>10-30 g/L/month</td>
</tr>
<tr>
<td>Solid State Lighting</td>
<td>CdS, ZnS</td>
<td>+++</td>
<td>6.8 g/L/month</td>
</tr>
<tr>
<td>Solar cell (sulfide)</td>
<td>CuₙGa₉₋ₓS₄ (0≤x≤1)</td>
<td>+++</td>
<td>1.5 g/L/month</td>
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<tr>
<td>Solar cell (selenide)</td>
<td>CuₙGa₉₋ₓSe₄ (0≤x≤0.4)</td>
<td>+++</td>
<td>0.75g/L/month</td>
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<tr>
<td>Binary solar cell</td>
<td>CuS, Cu₂S, CuSe, In₅Se₈, Ga₅Se₈</td>
<td>++</td>
<td>Most look promising</td>
</tr>
<tr>
<td>Binary</td>
<td>InS, InSe, GaS, GaSe</td>
<td>+</td>
<td>Preliminary investigation, no experience to date</td>
</tr>
<tr>
<td>Solar cell (selenide)</td>
<td>CdSe</td>
<td>++</td>
<td>Early attempts made amorphous phase</td>
</tr>
<tr>
<td>Semiconductor</td>
<td>ZnO (± freeze drying)</td>
<td>++</td>
<td>We make using wet chemistry</td>
</tr>
<tr>
<td>Other oxides</td>
<td>ITO</td>
<td>+</td>
<td>No experience to date</td>
</tr>
<tr>
<td>Phosphors</td>
<td>ZnGa₂O₄ (blue), metal-doped ZnGa₂O₄ (red, green)</td>
<td>+++</td>
<td>&gt;1g/L yield for blue</td>
</tr>
<tr>
<td>Pd-related catalyst</td>
<td>Pd⁰ using γ-Al₂O₃ support</td>
<td>+++</td>
<td>Pursue green and red light</td>
</tr>
<tr>
<td>Metals</td>
<td>Pd⁰, Au⁰, Ag⁰, Se⁰, Pt⁰, Fe⁰, Ni⁰, Cu⁰, Si⁰</td>
<td>+++ (++)</td>
<td>Pt, Cu, Si not tried; Fe, Ni requires R&amp;D</td>
</tr>
<tr>
<td>Battery cathode</td>
<td>LiFePO₄, Li(Mn, Co, Mn, Ni, Fe)O₂</td>
<td>++</td>
<td>(Currently Li₂Fe₂⁺⁺(PO₄)₂·8H₂O form)</td>
</tr>
<tr>
<td>Ce-related oxides</td>
<td>CeO₂⁰, Ce₂O₃</td>
<td>++</td>
<td>(Currently Ce⁺³⁺O(CO₃)₂·2H₂O using Ce⁺⁺)</td>
</tr>
<tr>
<td>Zr-related oxides</td>
<td>ZrO₂</td>
<td>+</td>
<td>requires R&amp;D</td>
</tr>
<tr>
<td>Infrared detector</td>
<td>PbSe</td>
<td>+Nd</td>
<td>high toxicity of lead is problematic need more information</td>
</tr>
<tr>
<td>IR pigment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar cell (telluride)</td>
<td>CdTe</td>
<td>++</td>
<td>Significant potential but likely with a different microorganism</td>
</tr>
<tr>
<td>Structural</td>
<td>Titanium and Iron based metals</td>
<td>+</td>
<td>More information on stoichiometry</td>
</tr>
<tr>
<td>Thermoelectrics</td>
<td>Ca₃Co₃O₈</td>
<td>+</td>
<td>Potential but likely requires different microbes</td>
</tr>
<tr>
<td>Biomedical (imaging)</td>
<td>Pure &amp; doped magnetite with medicine</td>
<td>+++</td>
<td>Yields &gt; 10g/L</td>
</tr>
<tr>
<td>Pb-free solder powder</td>
<td>Sn, Cu, Co alloy</td>
<td>+++Nd</td>
<td>No experience with these metals</td>
</tr>
<tr>
<td>Transparent conducting oxide</td>
<td>Al-ZnO</td>
<td>+</td>
<td>Dissolved aluminum is highly toxic (0.01)</td>
</tr>
<tr>
<td>Fuel cell cathodes</td>
<td>B, Ga, Antimony doped–ZnO</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Transparent transistor</td>
<td>Zinc tin oxide</td>
<td>Nd</td>
<td></td>
</tr>
<tr>
<td>Ceramic flux</td>
<td>Li-oxide</td>
<td>Nd-0</td>
<td></td>
</tr>
</tbody>
</table>

1. ++++, demonstrated and controlled; ++, demonstrated; +, good potential; +, some potential; Nd, no data and no idea; 0, not expected (Note: Four years ago Phelps would have given CIGS a 0.0)
2. All demonstrated nanoparticles were produced by reducing Thermoanaerobacter except underlined items produced by Shewanella.
3. Yield can have range depending on precursor composition (each metals’ toxicity and hydrolysis constant), dosing format, incubating period, and bacterial specie.