NASA John H. Glenn Research Center, Lewis Field
Turbomachinery and Propulsion Systems Division

NANOTECHNOLOGY AND GELLED CRYOGENIC FUELS

Presentation to

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NASA Nano / Bio Initiative

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Nanoparticulates for Gelled and Metallized Gelled Propellants

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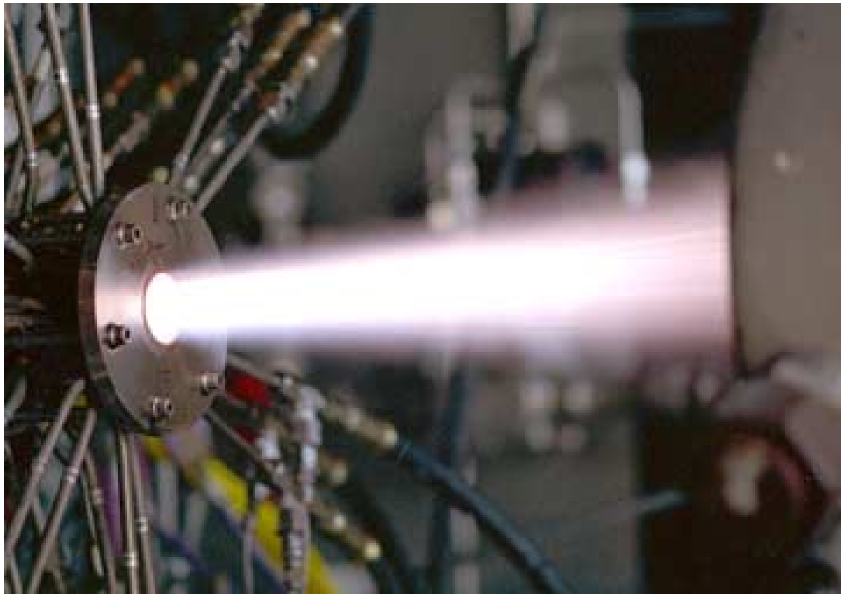
Aerogel is a highly efficient insulator (CNN)



O2 / RP-1 /Aluminum combustion – Aerogel and nanoparticulate metals can gel the fuel, making it denser, more energetic, and safer

http://www.cnn.com/TECH/9705/13/aerogel/index.html

The Benefits of Nanogellant Gelled Cryogenic Propellants and Nanoparticulates

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- *Nanogellant Gelled Propellants*
  - **Increased safety**
  - **Increased fuel density**
  - **Reduced leakage**
  - **Reduced slosh**
  - **Reduced cryogenic boiloff**
  - **Potential reduction in specific fuel consumption**
  - **Potential increases in engine thrust**
- *Nanoparticulate Metallized Gelled Propellants*
  - **All of the above and**
  - **Large increases in fuel density**
  - **Larger potential reductions in specific fuel consumption**
  - **Larger potential increases in engine thrust**

Nanogellant and Nanoparticulates

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- *What are nanogellant and nanoparticulate fuels?*
  - **Nanogellants are gellants that have a nanometer scale structure, which have enormously high surface area per gram**
    - **Gelled fuel reduce leakage and increase safety**
  - **Nanoparticulates are metal particles that are 20 nanometers in diameter, much smaller than traditional 7 micron particles used for metal additives**
    - **Smaller particles allow for more efficient combustion and lower specific fuel consumption**

Nanogellants and Nanoparticulates

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Why are Gelled Cryogenic Fuels revolutionary?

- **Gelled cryogenic fuels reduce leakage and increase safety**
- **Gelled cryogenic fuels are critical for increasing operability of cryogens for aerospace vehicles**
- **Nanogellant for gelled cryogens has a surface area of nearly 1000 m^2 /g, leading to cryogenic fuels gelled with 1-7 weight % gellant, 25 to 50% less mass than traditional gellant material**

- ***Synergy***
  - **Gelled and metallized gelled propellants have been an area of considerable interest in the rocket propulsion and explosives**

Propellant Technologies: Teams

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- *National team*
  - **NASA MSFC (large scale rocket engine testing)**
  - **NASA GRC (gelled and metallized gelled propellants, small scale engine tests)**
- *NASA partners and contacts*
  - **U.S. Army Picatinny Arsenal (potential collaboration in nanoparticles)**
  - **USAF Research Laboratory (hydrocarbons)**
  - **U.S. Army Aviation and Missile Command (metallized gelled propellants)**
  - **U.S. Naval Surface Warfare Center, Indian Head (nanoparticle aluminum, explosives)**
  - **Technanogy (nanometer aluminum particles)**
  - **Small Business Innovation Research (Argonide, Orbitec, etc.)**
  - **Many other industry, Government, and university partners**

Metallized Gelled Propulsion

Oxidizer	Fuel	Metal
O_2	H_2	Al
O_2	Hydrocarbon	Al
NTO	MMH	Al

- **Metal additives are suspended in gelled fuel and they undergo combustion with oxidizer**

Metallized Gelled Propellants: Increasing Rocket Specific Impulse for Mars Missions

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- **Mars missions using metallized gelled O2 /H2 /Al have an Isp of 475 to 480 seconds.**
- **O2/H2 without gellants or metal particles has an Isp of 470 seconds**
- **Rocket specific impulse (Isp) increased for several reasons:**
  - **Adding metal shifts O/F ratio from 6.0 to 1.6 (with 60 wt% Al), reducing the molecular weight of the rocket exhaust**
  - **Reducing the molecular weight increases engine Isp**
  - **Adding metal actually decreases the combustion temperature by 500 K**
  - **The added metal weight percent (wt%) is 60 to 70 % of the total H2/Aluminum fuel mass**
  - **Adding 60 wt% Aluminum increases engine Isp by 5 seconds**
  - **Adding 70 wt% Aluminum increases engine Isp by 10 seconds**
  - **O/F change increases Mars vehicle volume by only 1.1 % over the O2/H2 case**
  - **References:**

    - **Palaszewski, B., "Metallized Propellants for the Human Exploration of Mars ," NASA-Lewis Research Center, NASA TP-3062, presented at the Case For Mars IV Conference, Boulder, CO, June 4-8 1990. Also in the AIAA Journal of Propulsion and Power, Vol. 8, No. 6, Nov.-Dec. 1992, pp. 1192-1199.**
    - **Palaszewski, B. and Rapp, D., "Design Issues for Propulsion Systems Using Metallized Propellants," NASA-Lewis Research Center, AIAA 91-3484, NASA TM-105190, presented at the AIAA/NASA/OAI Conference On Advanced SEI Technologies, Cleveland, OH , September 4-6, 1991.**

Metallized Gelled Propellants: How Gellants Work

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- **Gellants create a cross-linked structure in the liquid fuel, much like a long chain polymer**
- **The gelled ljquid fuel is gelled with a small amount of gellant**
  - **RP-1: 0.9 wt% nanogellant**
  - **Liquid hydrogen: 7 to 8 wt% nanogellant**
- **The resulting gelled liquid is thixotropic (shear thinning), and its viscosity is 5 to 10 times that of the liquid alone**
- **The viscosity drops to the liquid viscosity when the fuel flows**
- **Metal particles, if small enough (nanometer sized), can act as a self gellant, reducing or eliminating the need for a separate gellant**

Mars Missions:
Space Exploration Initiative (SEI) and Metallized Gelled Propellants

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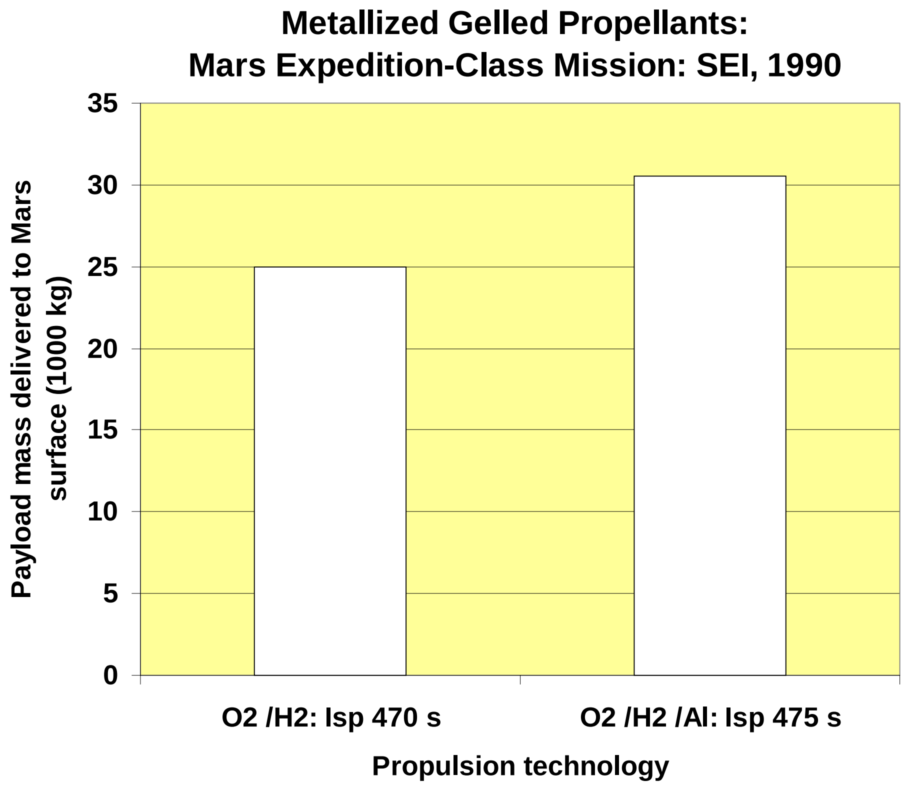
- **Mars missions using**
  - **O_2 /H_2**
  - **Metallized gelled propellants: O_2 /H_2 /Al**
- **20 to 33% higher payload to Mars surface for each flight**



Mars Missions:
Space Exploration Initiative (SEI) and Metallized Gelled Propellants

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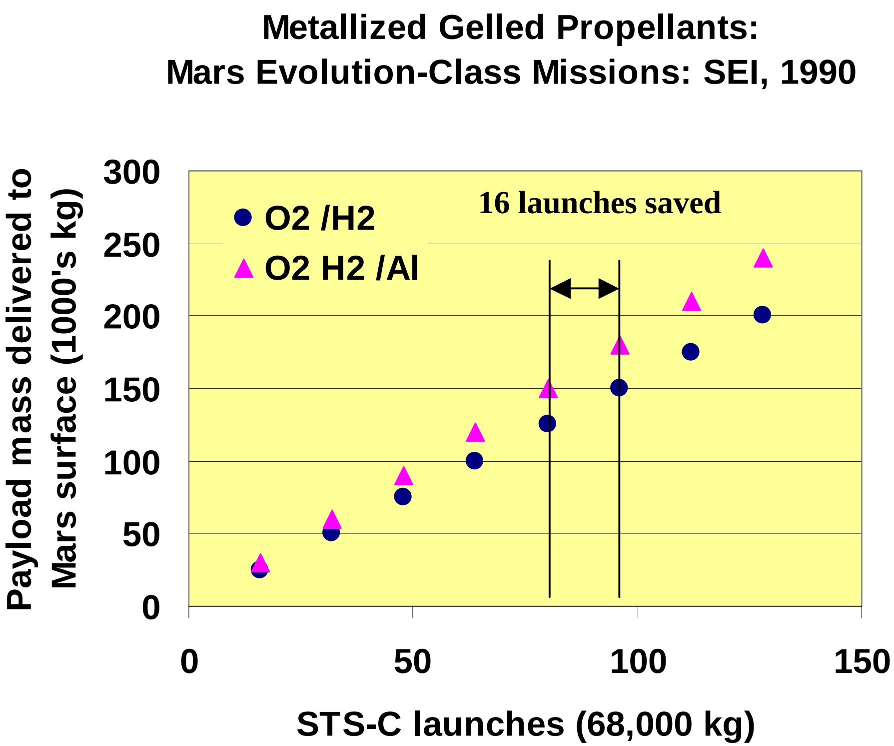
- **Mars missions using**
  - **O_2 / H_2**
  - **Metallized gelled propellants: O_2 / H_2 / Al**
- **20% more payload to Mars surface for each flight, with metallized gelled H_2 / Aluminum**
- **Significant launch vehicle savings with O_2/H_2/Al propellants**
- **16 STS-C launches saved over 5 Mars missions**
- **Faster payload delivery schedule, and billions saved**



O_2/RP-1/Aluminum Liquid Rocket Booster for Space Shuttle (Future STS)

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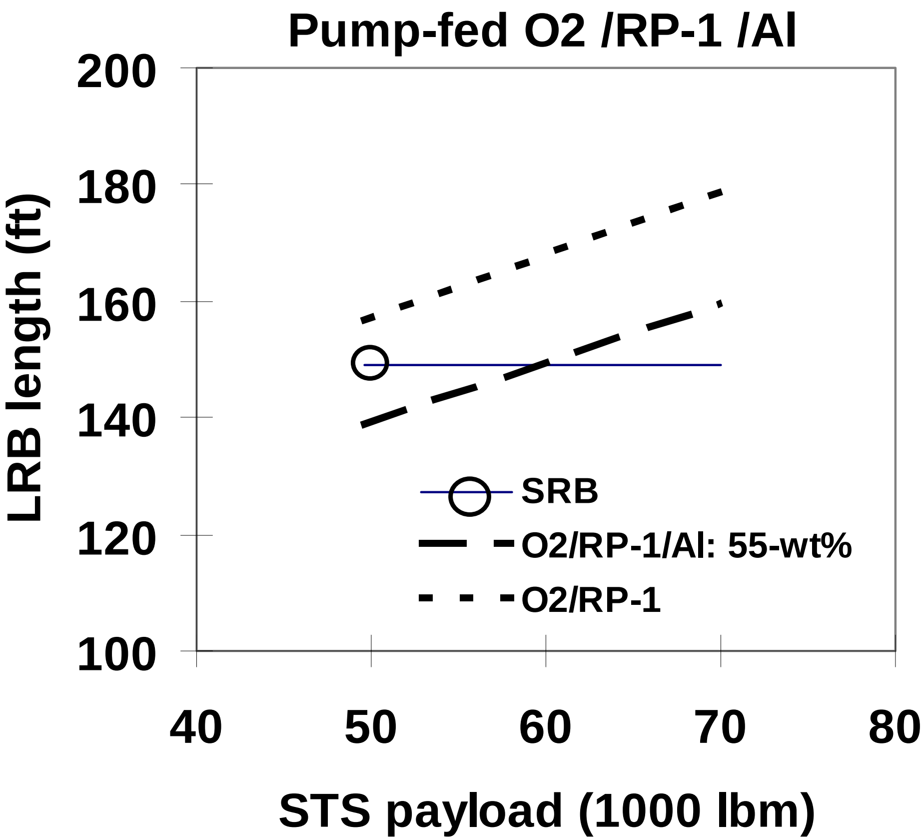
- **Payload increases of 14% possible with 55-wt% RP-1/Al (56,600 lbm)**
- **Small 1-ft diameter increase lifts payload to 70,000 lbm**
- **O2/RP-1: 324 s Isp O/F = 2.7**
- **O2/RP-1/Al: 317 s Isp O/F = 1.1**

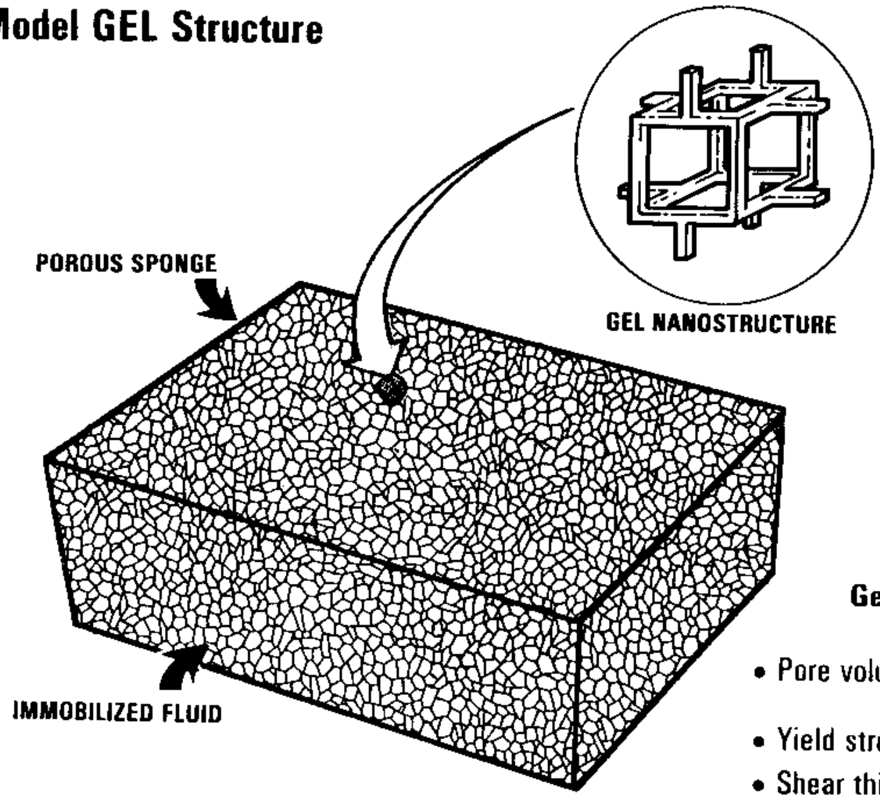


Nanogellant Gelled Propellants: Past Work

- **Worked with TRW (1989-1996) developing nanoparticulate gellants**
- **Nanogellants are hydrocarbon alkoxide materials, created with a supercritical processing method**
  - **Nanogellant for gelled cryogens has a surface area of nearly 1000 m^2 /g, leading to cryogenic fuels gelled with 0.9 to 7to 8 weight % gellant,**
  - **25 to 50% less mass than traditional gellant material**
- **Liquid hexane, RP-1, propane (cryogenic), etc. gelled with less that 0.9 wt% of nanogellant**
- **Liquid hydrogen gelled with 7 to 8 weight % nanogellant (NAS3-25793, 1994 and NAS3-26714, 1996)**
- **Extensive data base on gelled propellants at NASA Glenn**
- **Joint NASA /TRW work in nanogellants being reinvigorated**

Model GEL Structure

TRW



Gel Merit Figures

- Pore volume = $\frac{V_{GEL} - V_{SKEL}}{W_{SKEL}}$
- Yield strength
- Shear thinning
- Energy density

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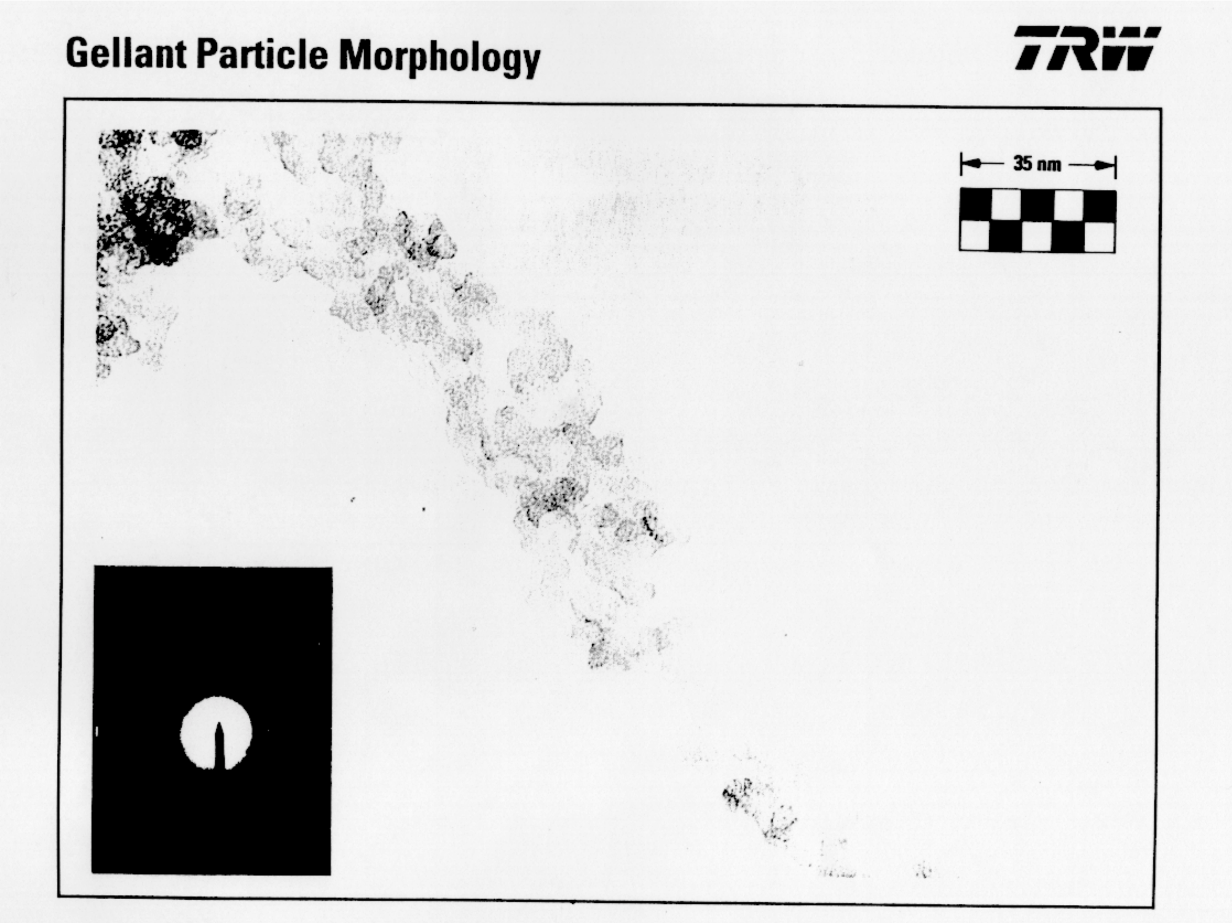
Transmission Electron Microscopy (TEM) photo of nanogellant



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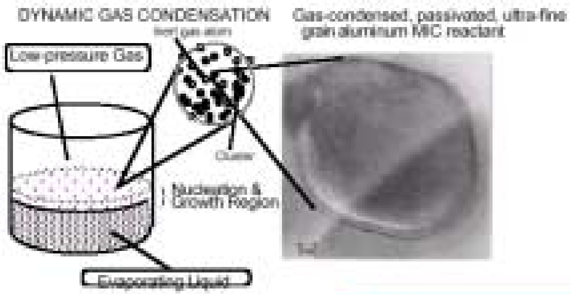
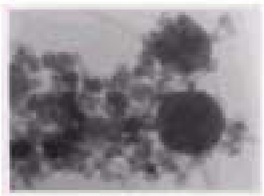
TRW aerogel type nanogellant, Circa 1990

Dynamic Gas Condensation Is Used At LANL To Fabricate MIC Reactants

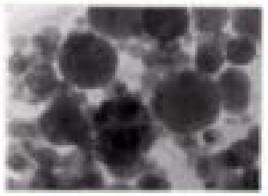


- Ultra fine particles (~20 nm)
- Uniform size distribution
- Size easily controlled
- Amenable to continuous production (currently ~25g/hr)
- Process self-purifies source metal

LANL Al Powder



Russian Al Powder ("ALEX")

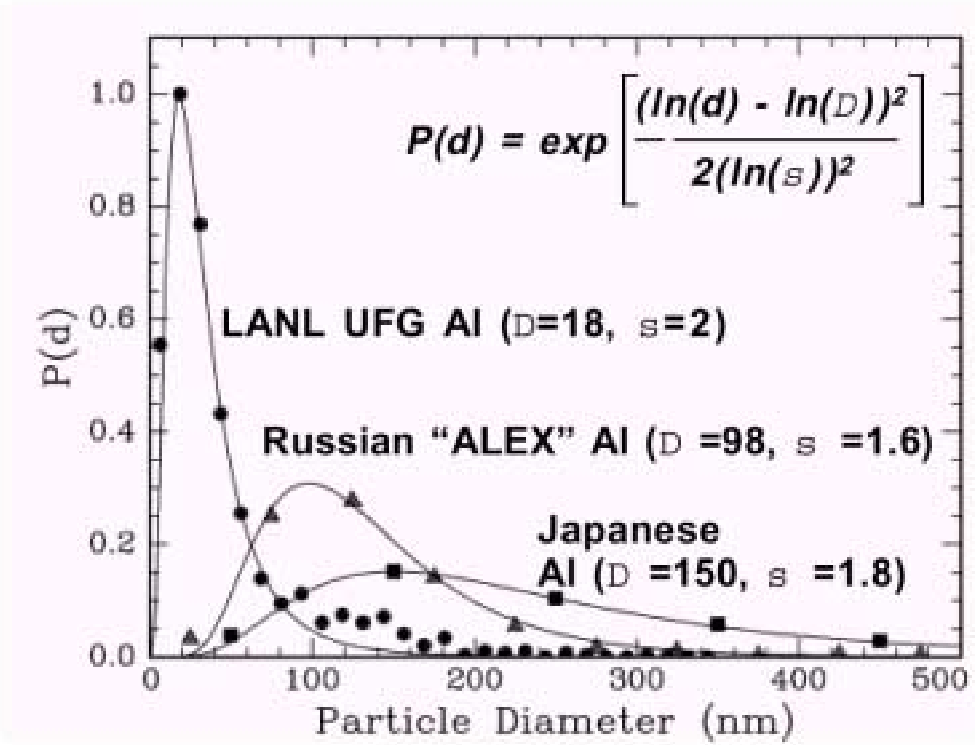


Japanese Al Powder

other fabrication techniques used

500 nm

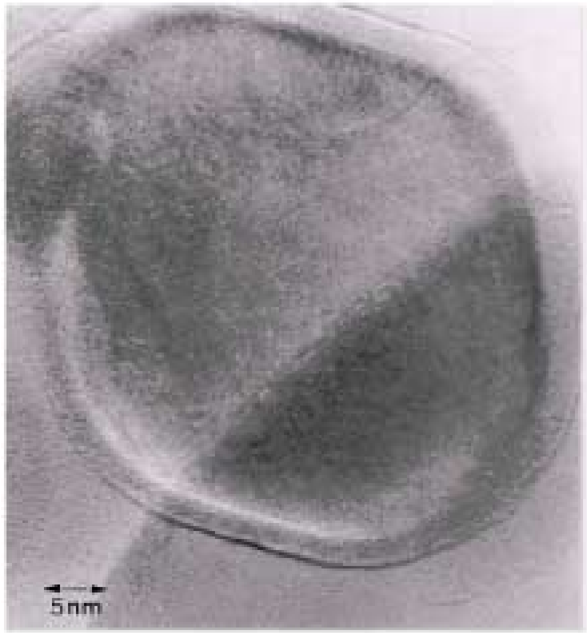
LANL Al Powders Have A Smaller Mean Size And A Narrower Size Distribution Than Commercial Powders



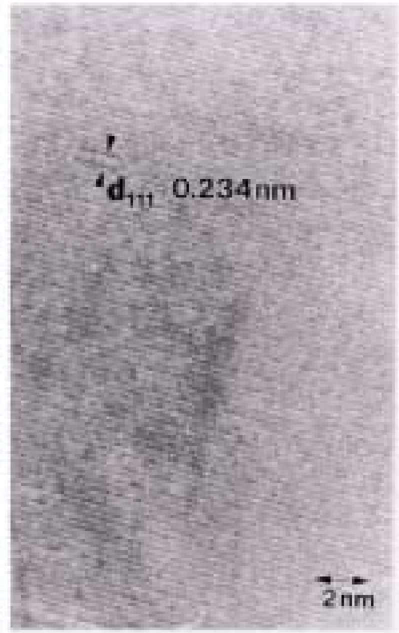
- log-normal distribution function fits measured data well
- D = peak position
- s fixes distribution width

LANL UFG ALUMINUM PARTICLES ARE SINGLE CRYSTALS WITH NEGLIGIBLE STRUCTURAL DEFECT DENSITY

GAS-CONDENSED Al PARTICLE



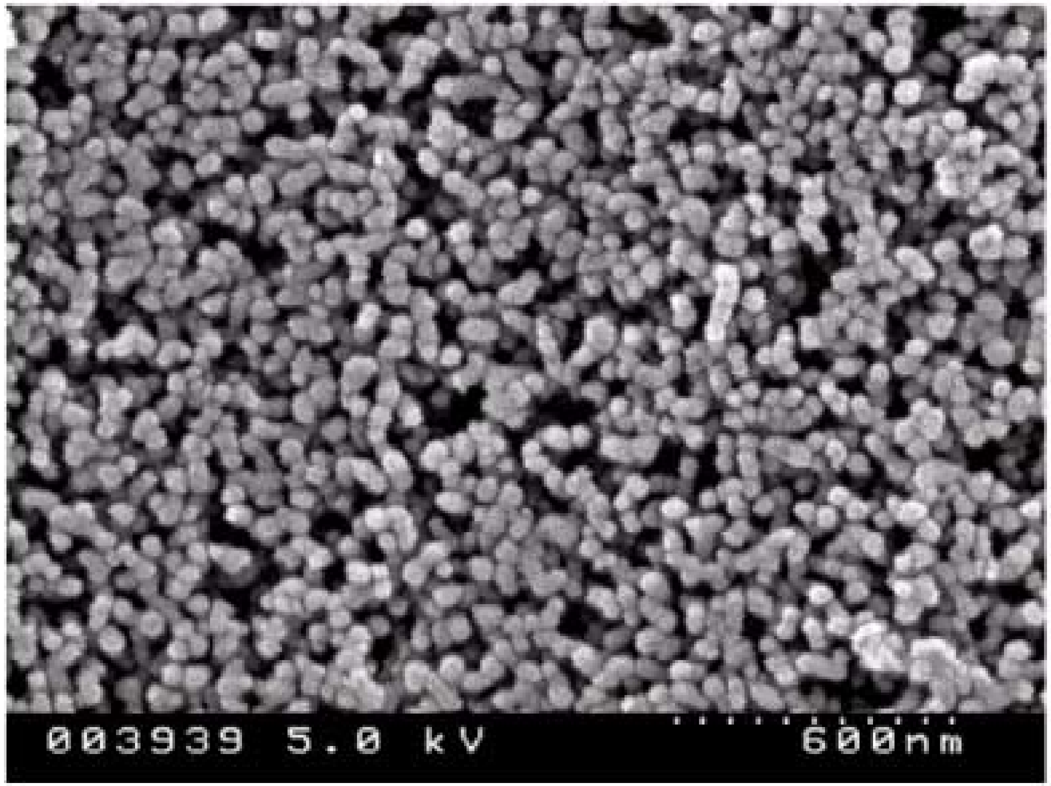
Al (III) LATTICE FRINGES



- interior aluminum is crystalline
- no structural defects apparent
- 2.5 nm thick Al_2O_3 passivation layer

Materials Science and Technology

SEM of LANL UFG ALUMINUM PARTICLES



Nanoparticle and Nanogellant Fuels: Small Business Innovation Research (SBIR)

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- *Argonide (Sanford, FL)*
  - Title: Metastable electroexploded nanophase aluminum based gels as a component of propulsion fuels
  - SBIR Phase II completed - 2001
  - Alex and other metals produced by the electroexplosion of metal wire are metastable, producing additional energy and burning rate
  - Discovered reduction of ignition delay with gelled Oxygen /RP-1/ Aluminum fuels
- *Orbitec (Madison, WI)*
  - Title: Gelled LH2 /UFAL /LOX propellant system
  - SBIR Phase I underway -2001
  - Uses ultra-fine aluminum powder (UFAL) to develop a gelled LH2 fuel and LOX propellant system.
  - This innovation will increase the performance, density, and combustion efficiency of LH2/Al/LOX for use in rockets and combined-cycle vehicles

Propellant Technologies – Applications and Fuels

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- *Nanogelled Cryogenic Propellants with Nanoparticulate Additives*
  - **Revolutionary Aeropropulsion vehicles**
  - **Next generation aerospace vehicles**
  - **Many others**
- *Planned fuels:*
  - **Liquid methane**
  - **Liquid propane**
  - **Liquid nitrogen**
  - **RP-1**
  - **Jet A**
  - **JP-8**
  - **Liquid hydrogen (last to be addressed in testing)**

Approach

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- ***First year goals:***
  - **Determine the location for Nanogellant Production**
    - **Produce nanogellant**
    - **Characterize the nanogellant production uniformity**
    - **Determine the effects of storage (shelf life) of the nanogellant**
  - **Determine the location for Nanoparticulate Production**
    - **Produce nanoparticles**
    - **Characterize the particle size and uniformity**
  - **Determine the location for the multi-fuel test area**
  - **Ambient temperature check out**
    - **Produce gelled aviation fuel (high H/C ratio fuel)**
    - **Produce an aviation fuel doped with nanoparticulates**
    - **Produce a gelled aviation fuel doped with nanoparticulates**
    - **Determine the characteristics of the gelled-doped aviation fuel**

Approach

- *Second year and third year goals*
  - Liquid nitrogen (LN2) check out
    - Produce gelled LN2 using nanogellants
    - Produce a mixture of LN2 and nanoparticles
    - Produce doped-gelled LN2
    - Determine characteristics of the doped-gelled LN2
  - Determine cryogenic fuels of interest (potential fuel include but are not limited to liquid propane, liquid methane, and liquid hydrogen)
  - Fuel 1 to N testing
    - Produce gelled Fuel 1 to N using nanogellants
    - Produce a mixture of Fuel 1 to N and nanoparticles
    - Produce doped-gelled Fuel 1 to N
    - Determine characteristics of the doped-gelled Fuel 1 to N
    - Optimize production process if necessary to obtain desired results

Approach

- *Fourth and fifth year goals*
  - **Build up combustion test area**
  - **Produce sufficient quantities of gelled-doped fuel in production area to support combustion tests**
  - **Develop diagnostic techniques**
    - **Measure uniformity of nanogellant/nanoparticulate dispersion in fuel**
    - **Effect of nanoparticulates on rotating machinery**
    - **Combustion process**
    - **Emissions**
  - **Perform initial combustion tests**
  - **Optimize fuel formulation and repeat combustion tests**

Gelled and Metallized Gelled Propellants

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Fuels and Space Propellants Web Site
http://www.grc.nasa.gov/WWW/TU/launch/foctopsb.htm

Gelled Hydrogen Propellants

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Past Results

- First gelled cryogen (nitrogen) was formulated circa 1960
- Evaporation (boiloff) of gelled hydrogen
  - reduced by factor of 2 to 3 (NAS3-4186, 1966)
  - reduced by factor 25 to 50 % (NAS3-2568, 1964)
    - variations due to tank geometries, heat leaks
  - both used silica gellants, at high weight percentages (36 weight %)
- Work with Lockheed (LMSC) and MSFC, with frozen ethane (NAS8-20342, 1968)
- Later work used frozen ethane or methane gellant, at 4 to 10 weight % (Aerojet, SNP-1, 1970)
- Work with TRW using nanoparticulate gellants, at 7 to 8 weight % (NAS3-25793, 1994 and NAS3-26714, 1996)
- Extensive data base on gelled propellants at NASA Lewis

Metallized Gelled Propellants

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- **Goal**
  - **Determine combustion and heat transfer characteristics of metallized gelled RP-1 /Al propellants in a rocket engine**
  - **Evaluate fuels including traditional RP-1 and metallized gelled RP-1 /Al with 0-, 5-, and 55-wt % loadings of aluminum, with gaseous oxygen as the oxidizer**
- **Hardware**
  - **Experiments conducted with a 40-lbf thrust engine composed of a modular injector, igniter, chamber, and nozzle**
  - **31 cooling channels for chamber calorimeter measurements, with temperature and pressure sensors**
- **Results**
  - **Gelled fuel coating, composed of unburned gelled fuel and partially combusted RP-1, formed in the 0-, 5- and 55-wt % engines**
  - **Coating caused a decrease in calorimeter engine heat flux in the last half of the chamber for 0- and 5-wt % RP-1 /Al propellants**

Metallized Gelled Propellants

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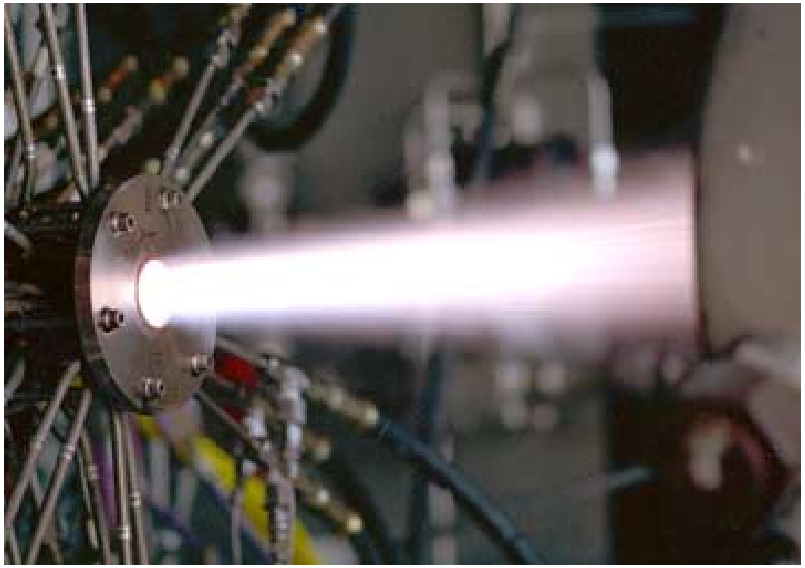
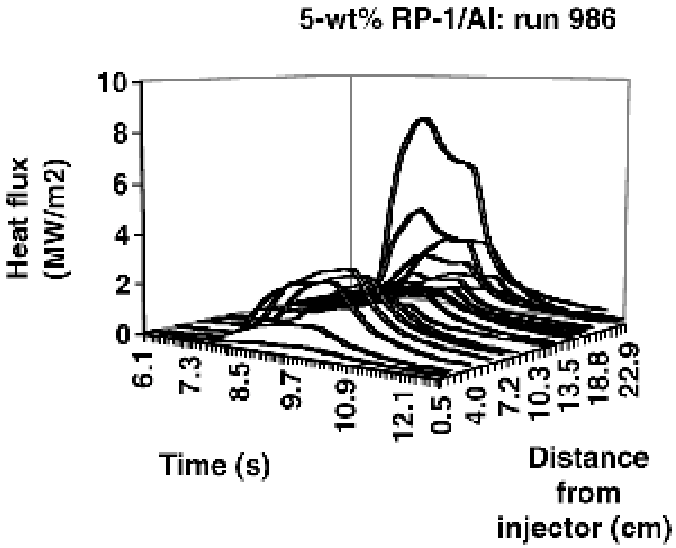


5 wt% RP1-Al rocket engine test firing at the GRC.



Three-dimensional roller-coaster plot of metallized gelled propellant heat flux: 5-wt % RP-1/Al.

The Benefits of Gelled and Metallized Gelled Propellants

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- **Gelled propellants**
  - Increased safety
  - Increased fuel density
  - Reduced leakage
  - Reduced slosh
  - Reduced cryogenic boiloff
  - Increases in engine specific impulse (in some cases)
- **Metallized Gelled Propellants**
  - All of the above and
  - Large increases in fuel density
  - Large increases in engine specific impulse (in some cases)

Propellant Technologies: Nanotechnology

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- **Nanotechnology is applied to rocket and aerospace propellants**
  - **Gellants**
    - **for hydrocarbons**
    - **for liquid cryogenic fuels (hydrogen, methane, propane)**
    - **Nanoparticulate materials used for gellants (hydrocarbon alkoxides)**
    - **Gellants increase fuel safety, density, and energy**
    - **Gellants reduce fuel slosh, and reduce the vehicle dry mass with higher fuel density**
  - **Nanophase aluminum particles added to rocket and aerospace fuels**
    - **Metallized gelled propellants**
      - **RP-1 /Aluminum**
      - **Hydrogen / Aluminum**
      - **Others (MMH / Aluminum, etc.)**
    - **Adding metal particles can increase engine exhaust velocity and fuel density**

The Benefits of Gelled and Metallized Gelled Propellants

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- **Gelled Propellants**
  - Increased safety
  - Increased fuel density
  - Reduced leakage
  - Reduced slosh
  - Reduced cryogenic boiloff
  - Reduction in engine specific fuel consumption (in some cases)
  - Increases in engine specific impulse (in some cases)
- **Metallized Gelled Propellants**
  - All of the above and
  - Larger increases in fuel density
  - Larger reductions in engine specific fuel consumption (in some cases)
  - Larger increases in engine specific impulse (in some cases)