Science and Technology with Neutrons

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National Institute of Standards and Technology

&

Quantum Materials Center

University of Maryland

NIST | CENTER FOR NEUTRON RESEARCH

NCNR

National Bureau of Standards

1901

National Institute of Standards and Technology

1988

National Institute of Standards and Technology

Technology Administration, U.S. Department of Commerce

CENTER FOR NEUTRON RESEARCH

NIST, Standards and Technology

- Standard Reference Materials ⇐
- Computer and Network Security
- Building Standards and Construction
- International Standards for Commerce
- Precision Measurements
- New Materials for Advanced Technology ⇐
- Fire Standards and Safety
- Smart Grid
- CHIPS and Science Act
- . . .

First Question

- How long is this talk going to last?!
- My question: Who keeps the time? And
- Then, how accurate is your clock?
- How accurate does it need to be?
- **NIST** serves as the United States' primary time and frequency standard, with a cesium fountain atomic clock.
- How accurate? Won't gain or lose more than a minute,
- In 14 billion years—the age of the universe.
- Do you really need a clock that accurate?
- Yes, for the *Global Positioning System (GPS)*.

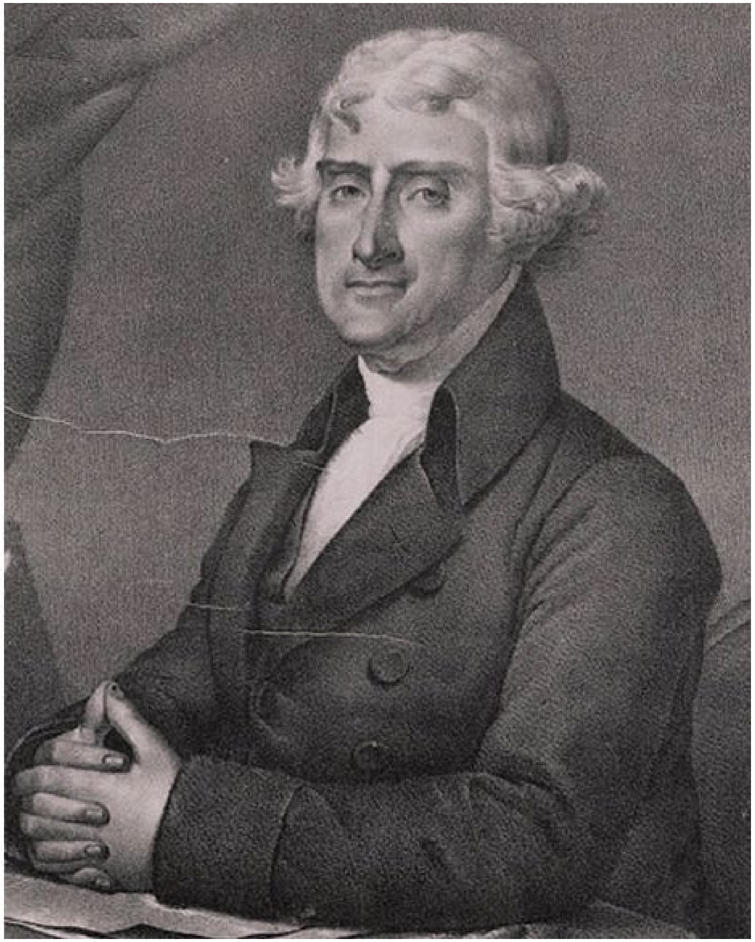
Metric Standards

- Why isn't the American public using the metric system?

Thomas Jefferson (Secretary of State)

1794
New French Standards
The meter and the kilogram

Joseph Dombey
French physician & botanist



Metric Standards

- Adoption of metric standards in U.S. delayed a century
- Congress passed the Metric Act of 1866 (but).
- United States officially adopted metric standards 1893
- Many U.S. companies use the metric system
- But widespread public use is lacking
- NIST keeps the standards
- and provides standard reference materials
- Length, mass, time, temperature, electric current, volt, luminosity, energy
- meter, kilogram, second, Kelvin, ampere, candela, Joule
- Watt (kilo-Watt – hours = kilo Joules)

Science and Technology with Neutrons

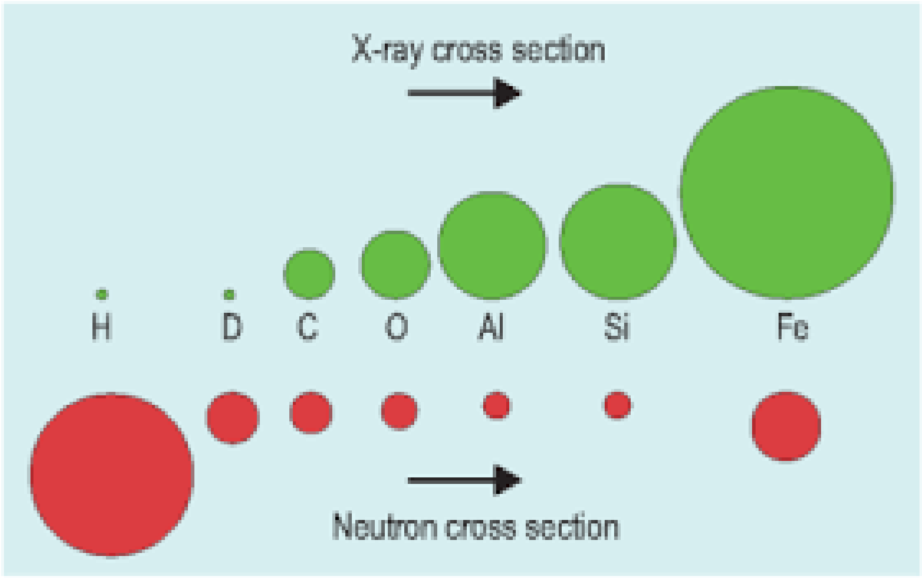
Why use Neutrons?

Neutrons have no charge, so they penetrate materials easily and deeply.

Neutron scattering strength depends on nucleus, not the element.

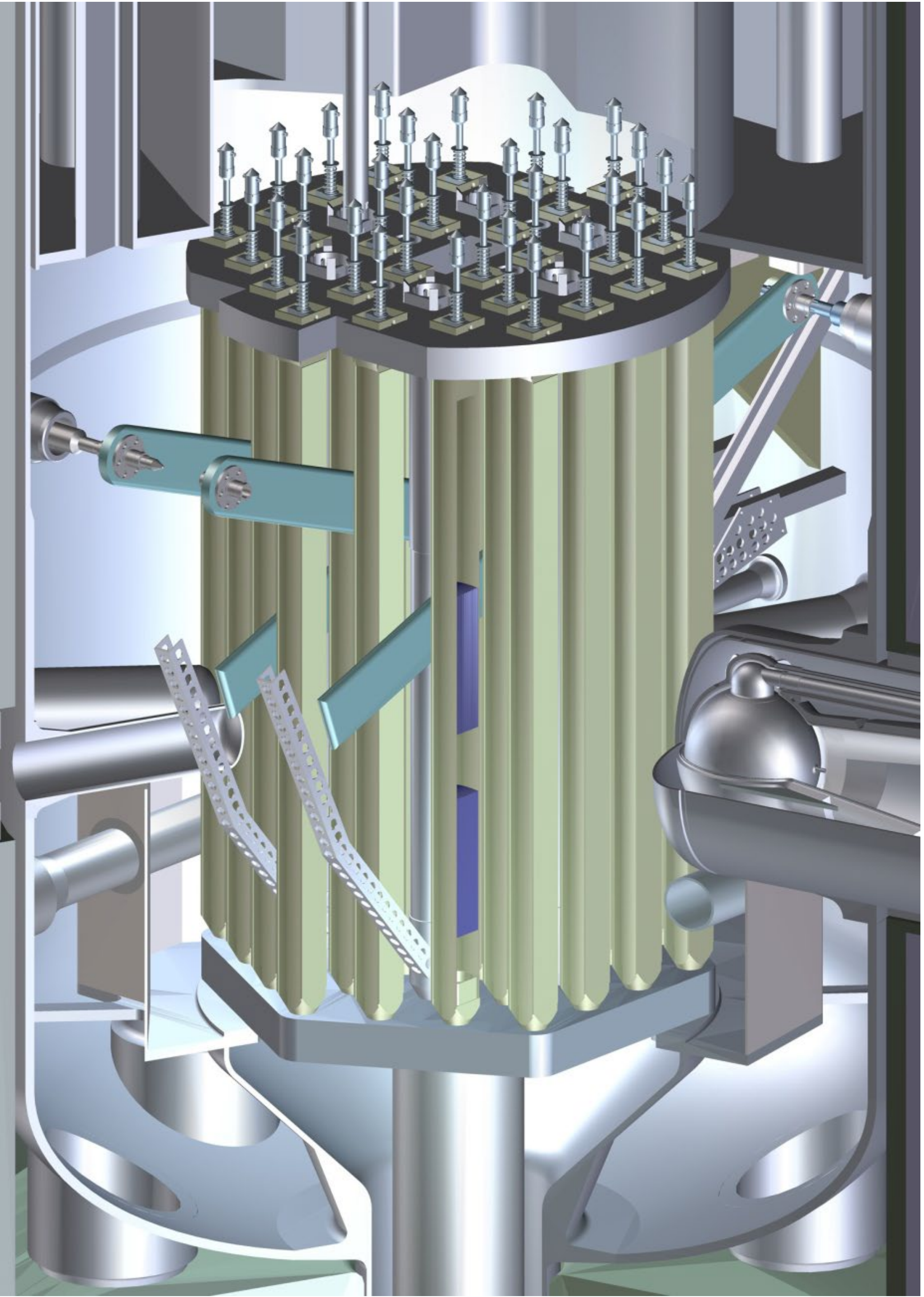
Adjacent elements, heavy + light elements, isotope substitution.

Neutrons have magnetic moment--can measure magnetic properties.



NIST Center for Neutron Research

May 2017



NBSR

Neutron Beam Split-core Reactor

20 MW / D_2O moderated

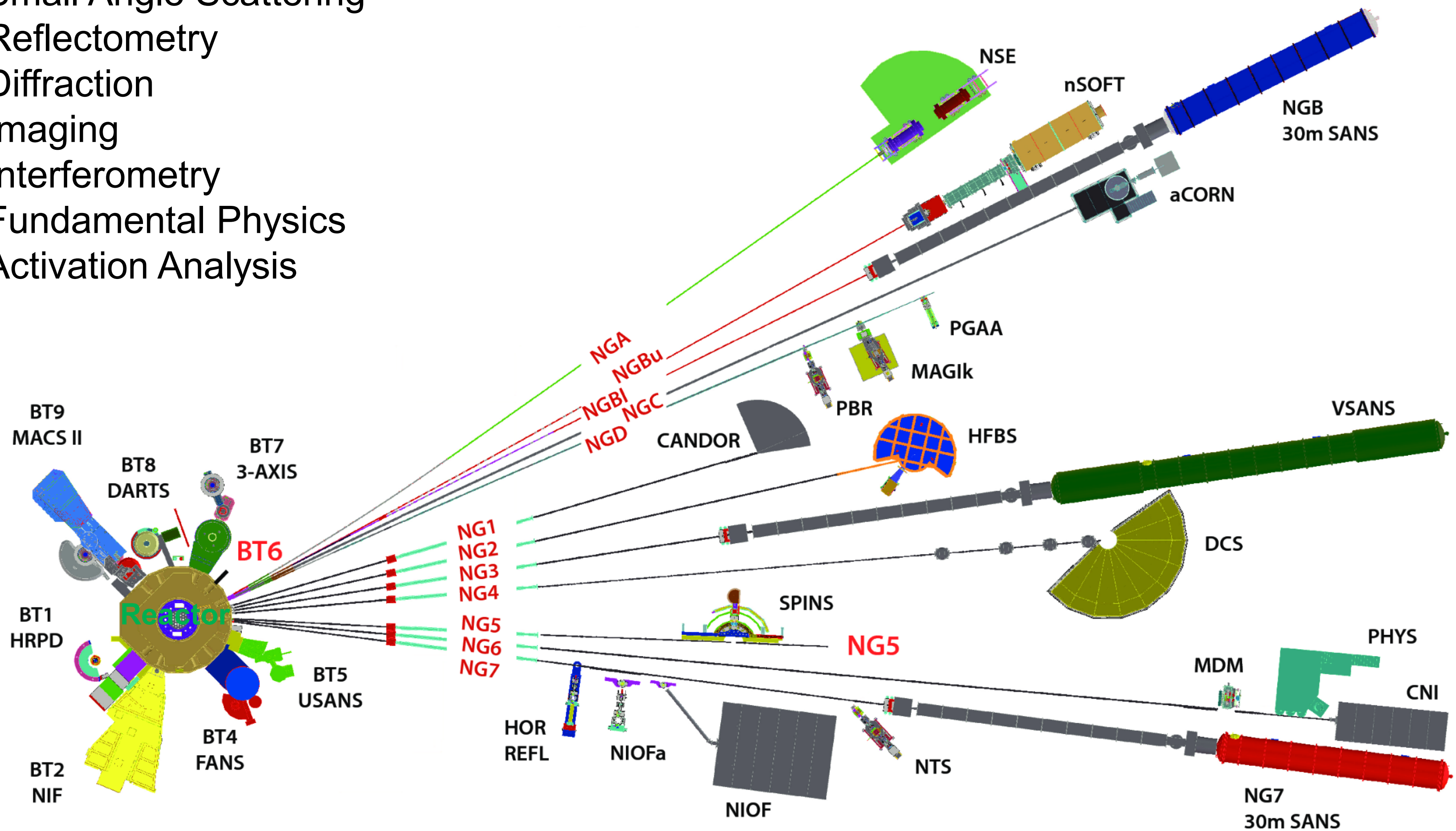
$\Phi = 1.5 \times 10^{14}$ n/cm^2/s
at mid-plane
(un-fueled region)

7 cycles/year
38 day cycles
~240 days/year

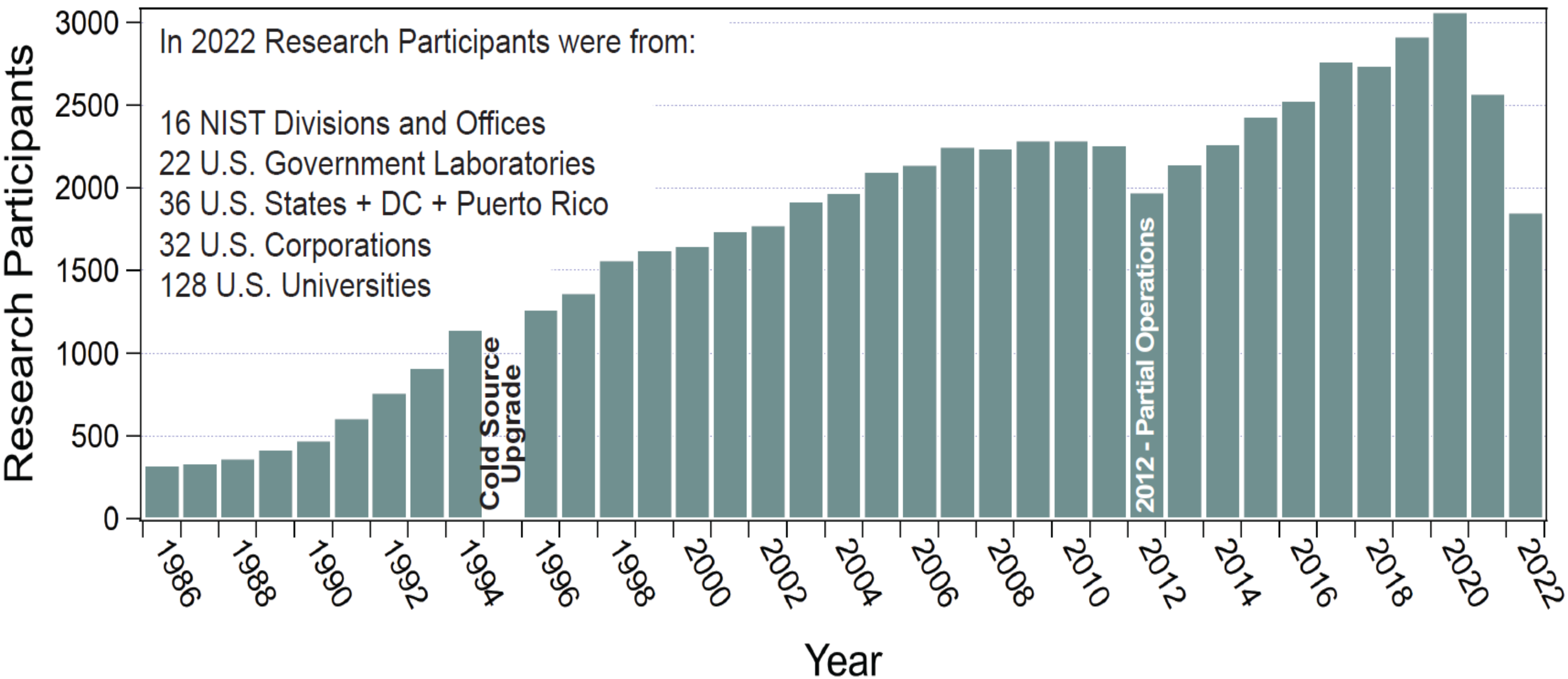
NIST Center for Neutron Research

Reactor Building: 30 beamlines + Neutron Activation Analysis

Spectroscopy
Small Angle Scattering
Reflectometry
Diffraction
Imaging
Interferometry
Fundamental Physics
Activation Analysis



RESEARCH PARTICIPANTS



Precision Measurements with Neutrons

Properties of the Neutron

Mass
1.00866491595 ± 0.00000000049 atomic mass units

Difference between Neutron and Proton mass
1.29333236 ± 0.00000049 MeV

Magnetic Moment
1.91304273 ± 0.00000045 nuclear magnetons

Electric Dipole Moment
$< 0.18 \times 10^{-25}$ e-cm

Electric Charge of the Neutron
$< 0.8 \times 10^{-21}$ e (charge of the electron).
< 0.0000000000000000000008 e

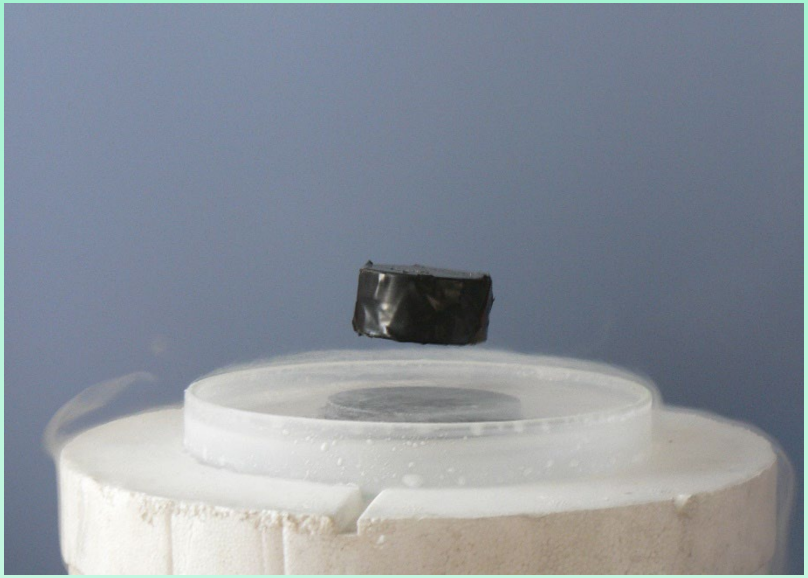
Neutron Lifetime: 878.4 ± 0.5 seconds
(proton, electron, antineutrino)

E & M
Strong Force
Gravity
Weak Force

What happened at the start of the Universe?

CENTER FOR NEUTRON RESEARCH

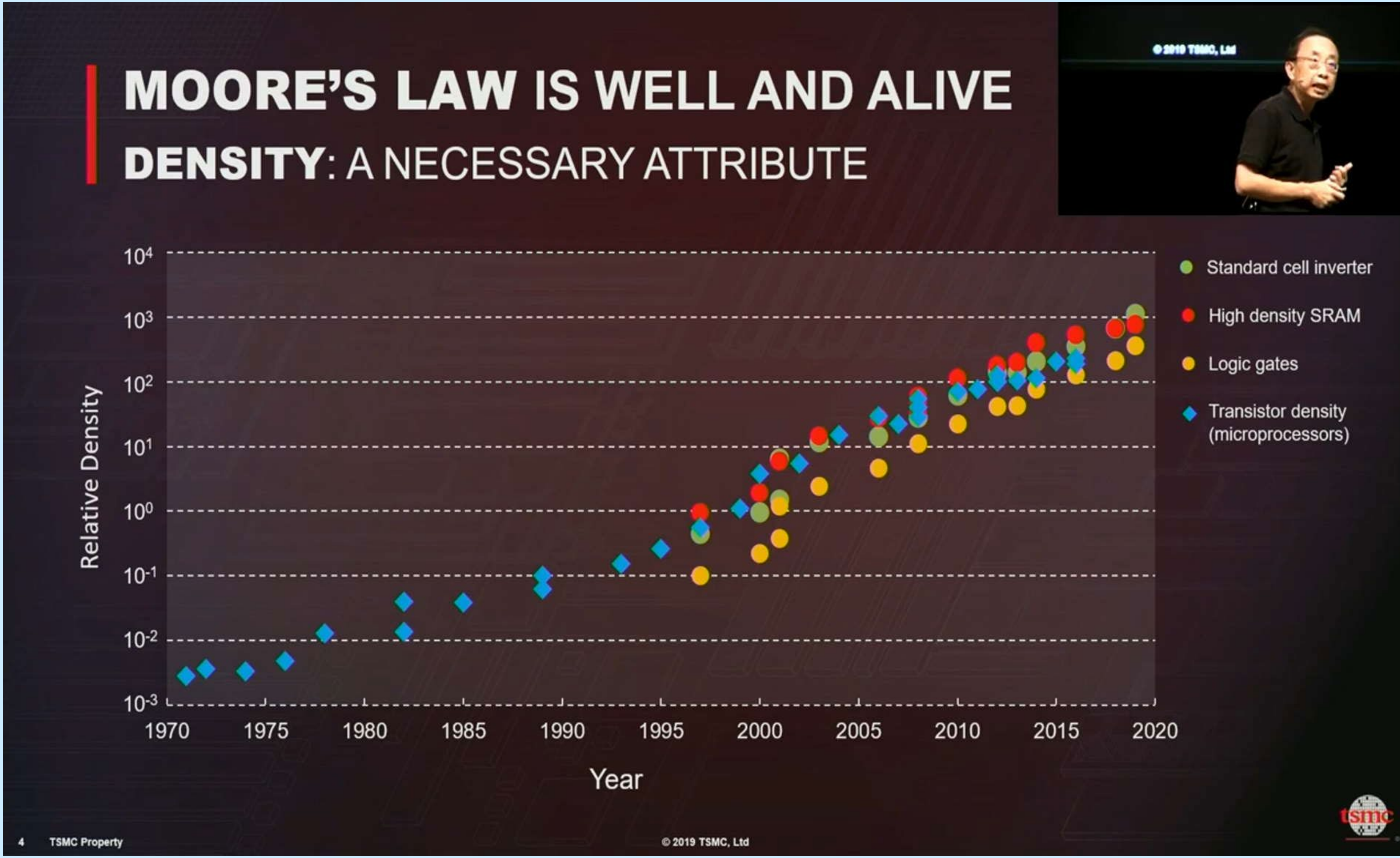
Quantum Materials:
Magnets and Superconductors



Search for New Materials with Unique and Interesting Properties

Magnets for Spintronics

Transistors and Computer Memories



Magnets for Spintronics

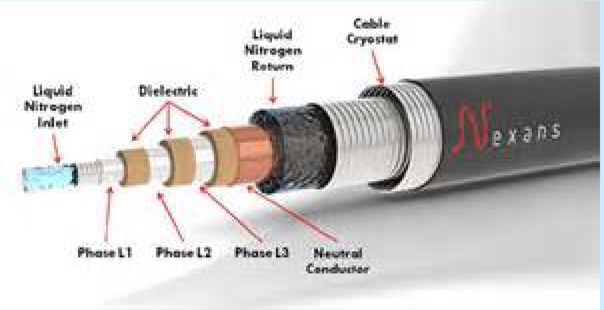
- Topological insulators
- Topological Semimetals
- Half-metallic (spin polarized) ferromagnets or antiferromagnets
- Magnetic semiconductors

Superconductors!

- Superconductivity was discovered in 1911 (Mercury, Superconducting below 4.2 K)

- Technological Applications: Research
  - Research Magnets
  - High Field Magnets for accelerators
  - High Field Magnets for fusion confinement reactors
  - Ultra-sensitive superconducting quantum interference devices (SQUIDs) to detect magnetic fields

- Technological Applications: Commercial
  - ~~Nuclear~~ Magnetic Resonance Imaging (MRI)
  - Fast Levitating Trains
  - Low loss Power Cables
  - Fast Digital Electronics
  - Microwave Filters (Mobile phone towers)
  - Energy Storage in Magnets (Power Grid)
  - SQUIDs for Magnetoencephalography (MEG) and magnetocardiography (MCG)



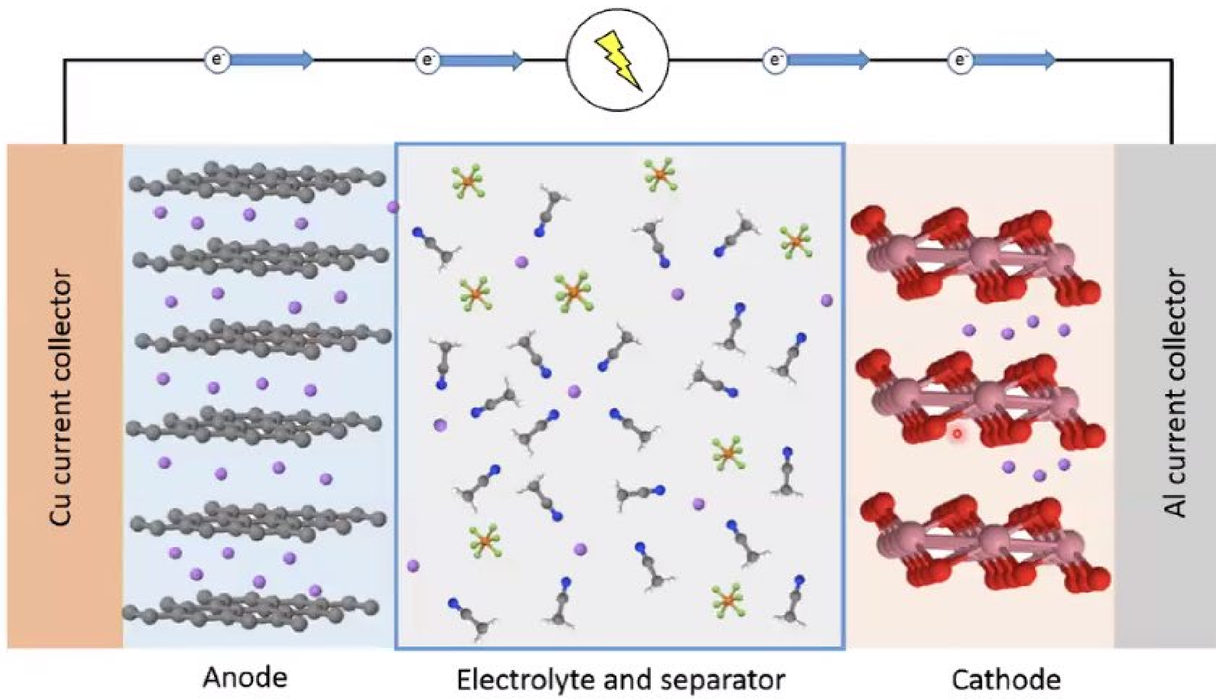
- Quantum Computers!
- Room Temperature Superconductors!

New Materials for High Capacity Batteries

Batteries are part of our everyday life

Aleksandar Matic

Lithium Ion Batteries



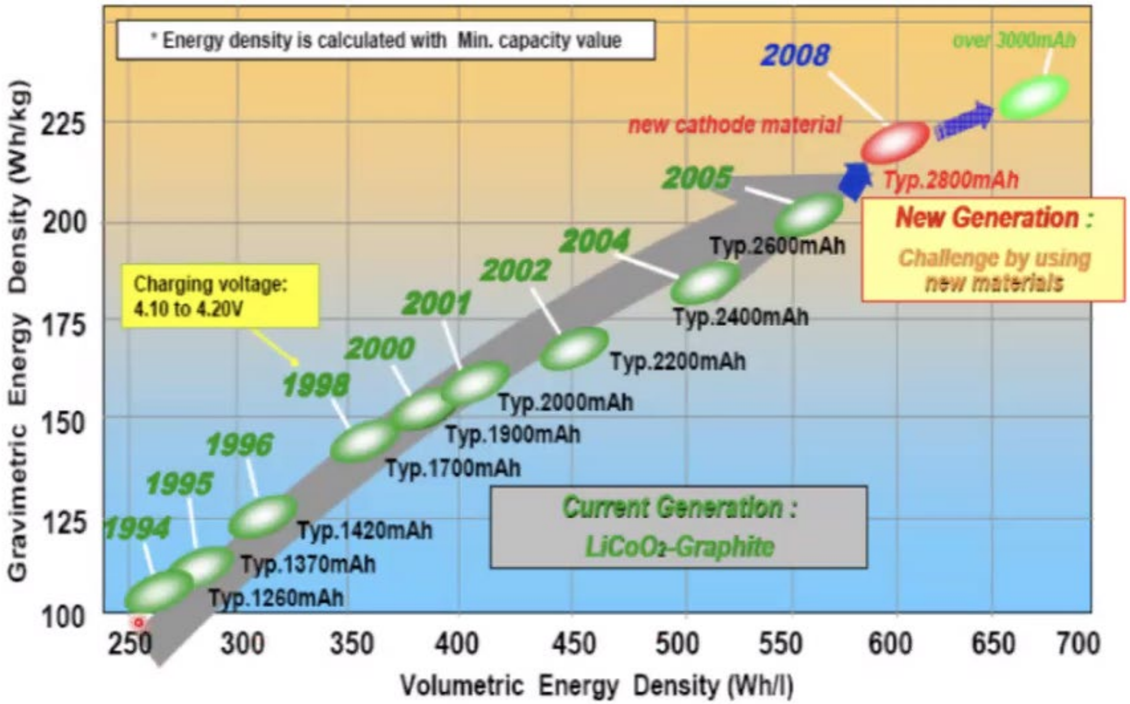
$LiC_6^{\,-} \rightleftharpoons C_6 + Li^+ + e^-$

$2Li_{0.5}CoO_2 + Li^+ + e^- \rightleftharpoons 2\ LiCoO_2$

Aleksandar Matic

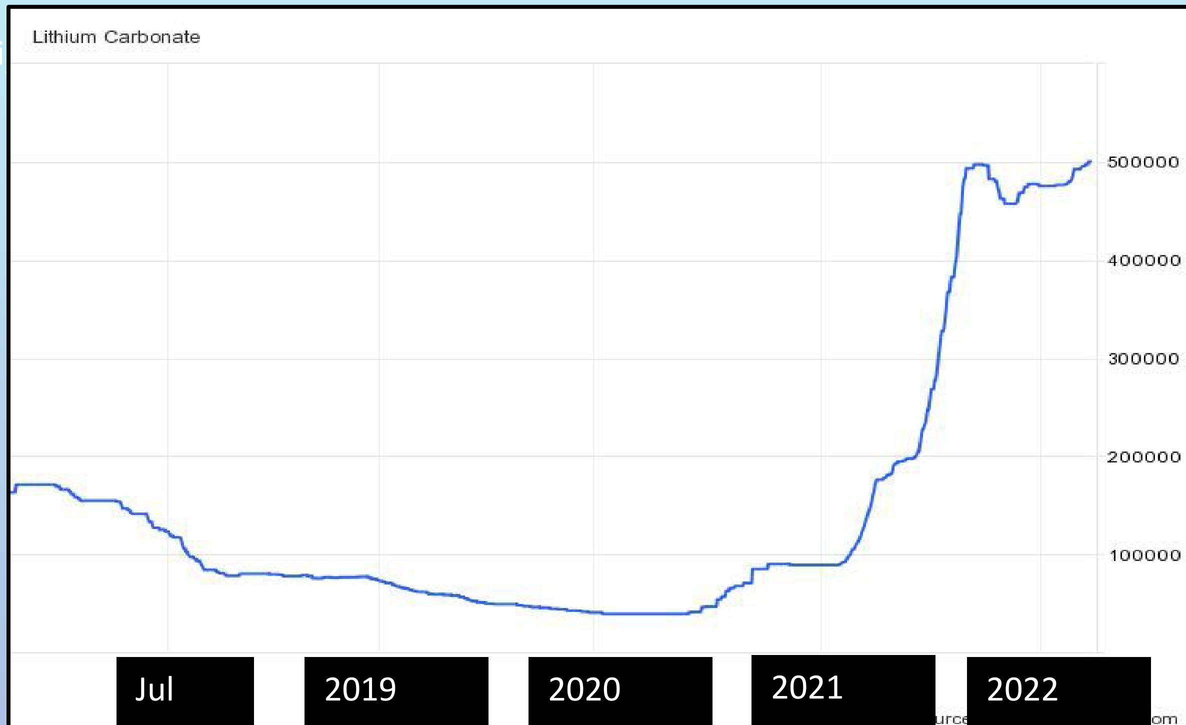
Li-ion batteries

2023



Aleksandar Matic

Surge of Li (and Ni, Co) price is a limiting factor to commercial Li-ion battery



- disruptive storage technology will emerge

Abundance of Elements

In Upper Continental Earth Crust

Order of Abundance	Element	Presence in the Earth's Crust (%)	Order of Abundance	Element	Presence in the Earth's Crust (%)
1	O	49.5	16	N	0.03
2	Si	25.8	17	F	0.03
3	Al	7.56	18	Rb	0.03
4	Fe	4.7	19	Ba	0.023
5	Ca	3.39	20	Sr	0.02
6	Na	2.63%	21	Cr	0.015
7	K	2.4	22	V	0.01
8	Mg	1.93	23	Ni	0.008
9	H	0.83	24	Zn	0.007
10	Ti	0.46	25	Cu	0.006
11	Cl	0.19	26	Li	0.004%
12	Mn	0.09	27	Co	0.004
13	P	0.08	28	Sn	0.004
14	C	0.08	29	Pb	0.0015
15	S	0.06	30	Mo	0.0013

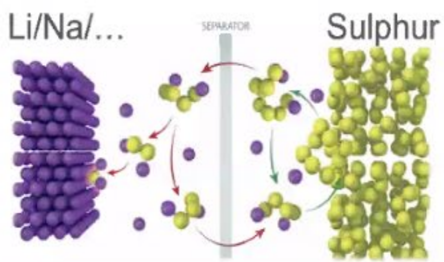
HARVARD
John A. Paulson
School of Engineering
and Applied Sciences

Aleksandar Matic

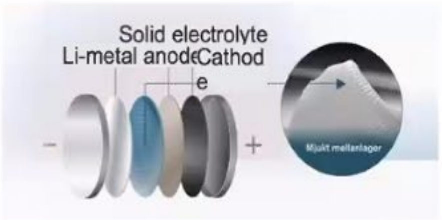
Next generation batteries

Sustainability | Capacity | Safety

M-ion (Na, Mg, …)



Solid state batteries

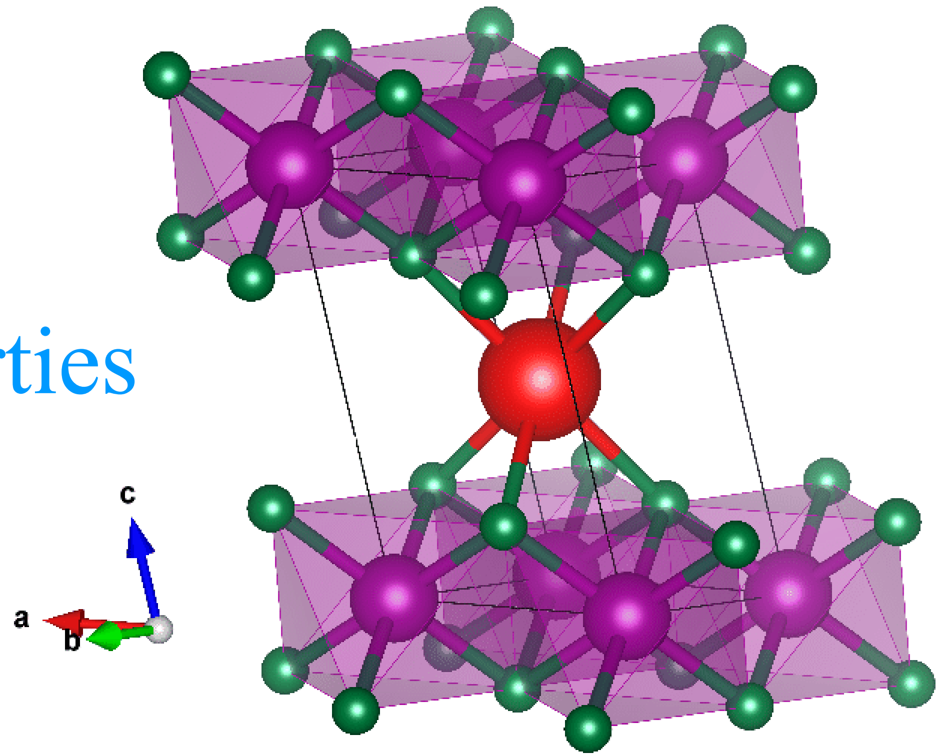


Conversion chemistries

Metal batteries (Li, Na, Mg, Zn, …)

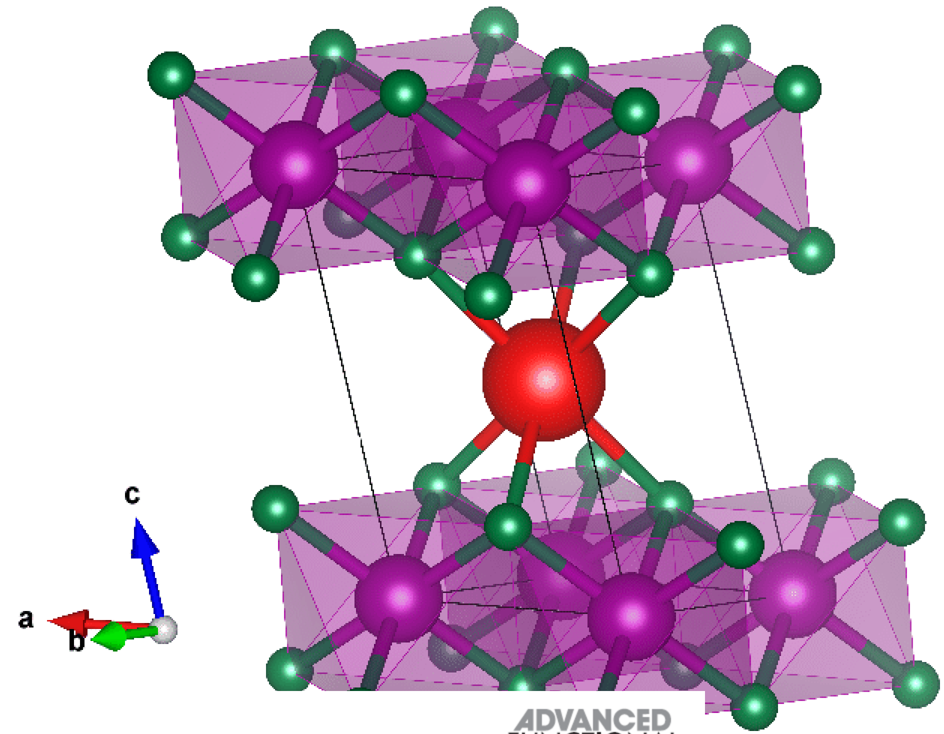
$NaMnO_2$

Novel Magnetic Properties



Amplitude mode in the Planar triangular antiferromagnet $Na_{0.9}MnO_2$,
Rebecca L. Dally, Yang Zhao, Zhijun Xu, Robin Chisnell, M. B. Stone, Jeffrey W. Lynn,
Leon Balents, and Stephen D. Wilson, Nature Communications **9**, 2188 (2018)

Na_xMnO_2 battery electrodes



FULL PAPER

ADVANCED FUNCTIONAL MATERIALS
Na-Ion Batteries
www.afm-journal.de

Reversible Flat to Rippling Phase Transition in Fe Containing Layered Battery Electrode Materials

*Xi Chen, Sooyeon Hwang, Robin Chisnell, Yichao Wang, Fan Wu, Sooran Kim, Jeffrey W. Lynn, Dong Su, and Xin Li** *Matter* **5**, *1, 2022*

Neutron Research

- Hydrogen Fuel Cells
- Natural Gas and Oil Pipelines
- Vaporization of Jet Fuel
- Injectable Pharmaceutical (Eli Lilly)
- Shear Thickening Fluids
- Standard Reference Materials

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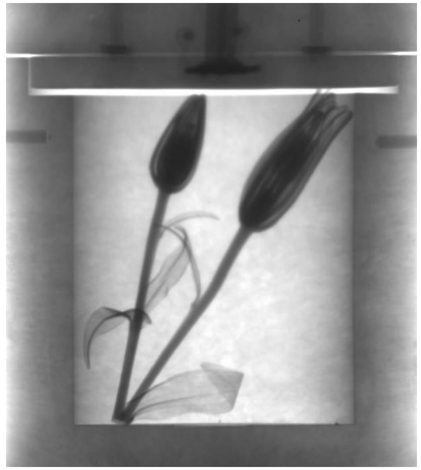
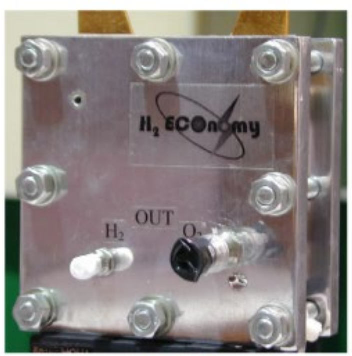
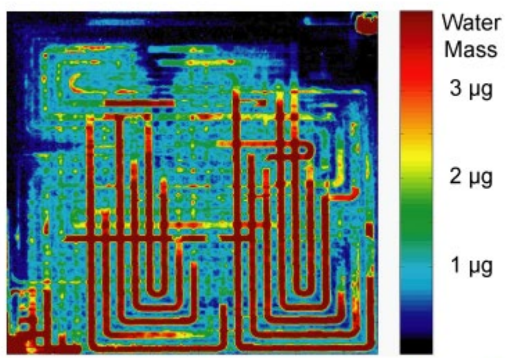
Neutron Imaging for the Hydrogen Economy

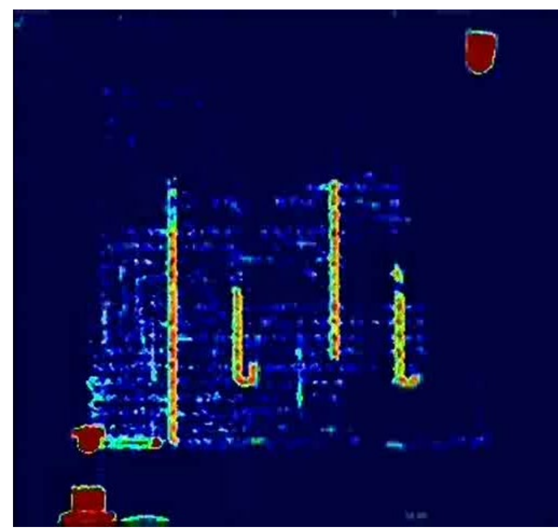


- Neutrons see material differently than x-rays
- The fine details of the water in this Asiatic Lily are clear to neutrons even in a lead cask
- Subtle changes in the water distribution inside a running fuel cell impact performance and durability
- Neutron Imaging measures these small changes at video frame rate

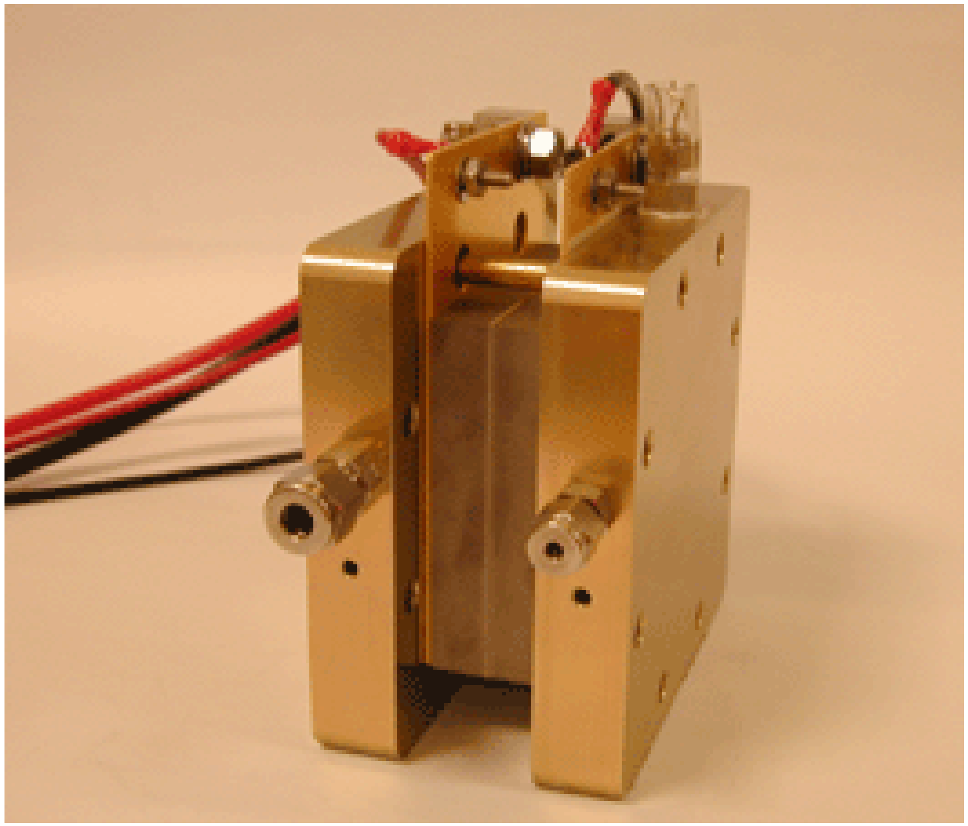




Hydrogen Fuel Cells: A little water inside a metal matrix - an ideal problem for neutron imaging.

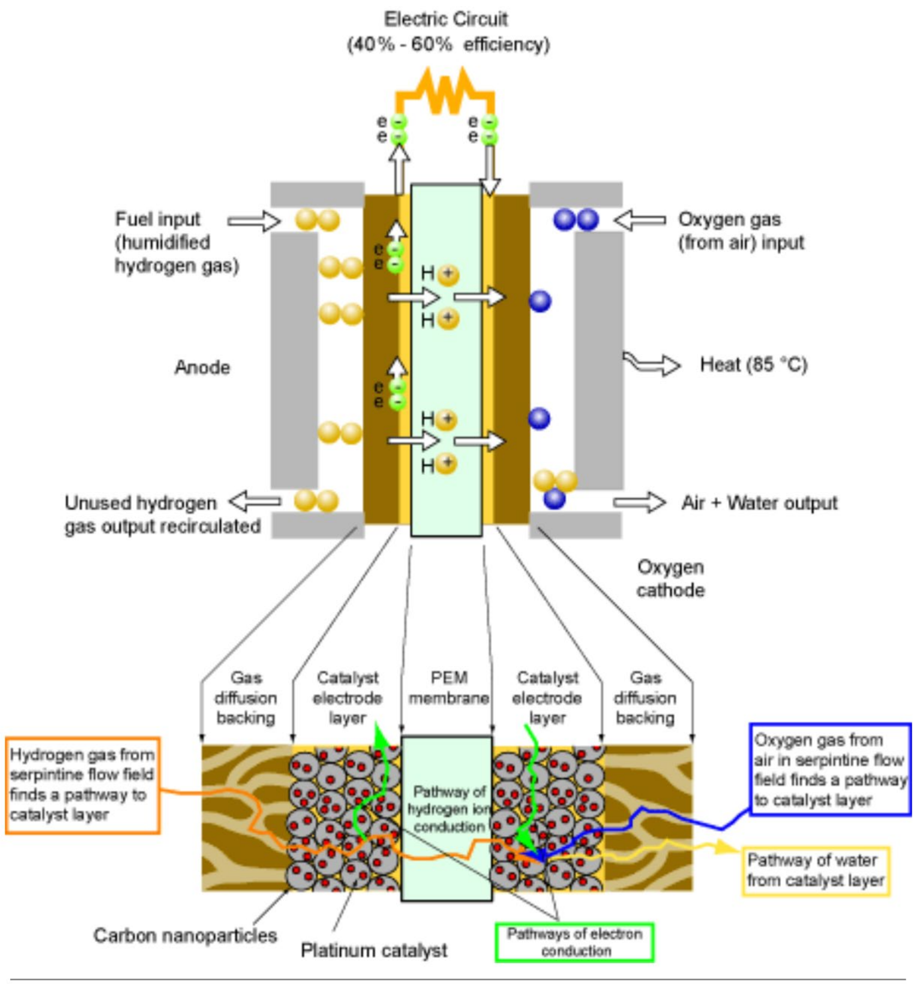


Hydrogen Fuel Cell

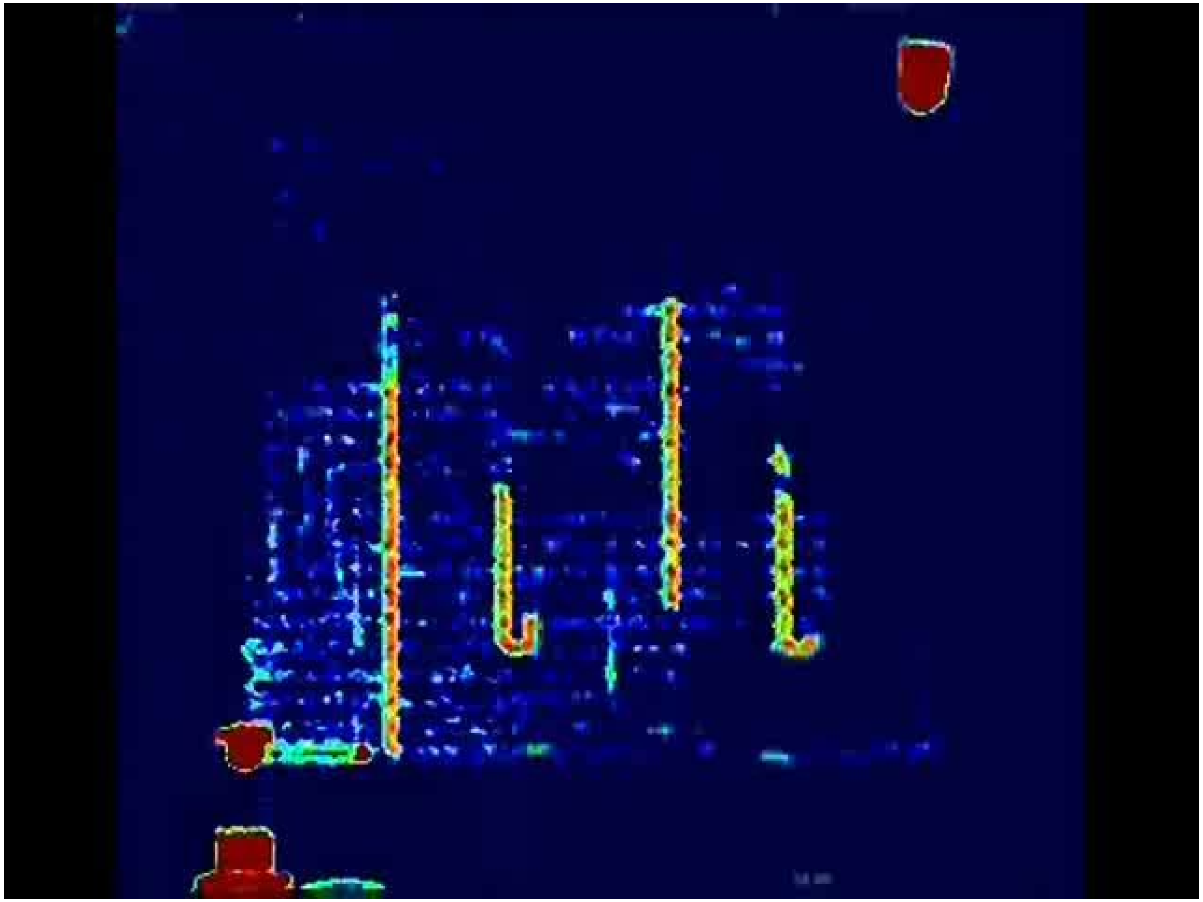


8 cm thick
3 inches thick
13 cm across
5 inches across

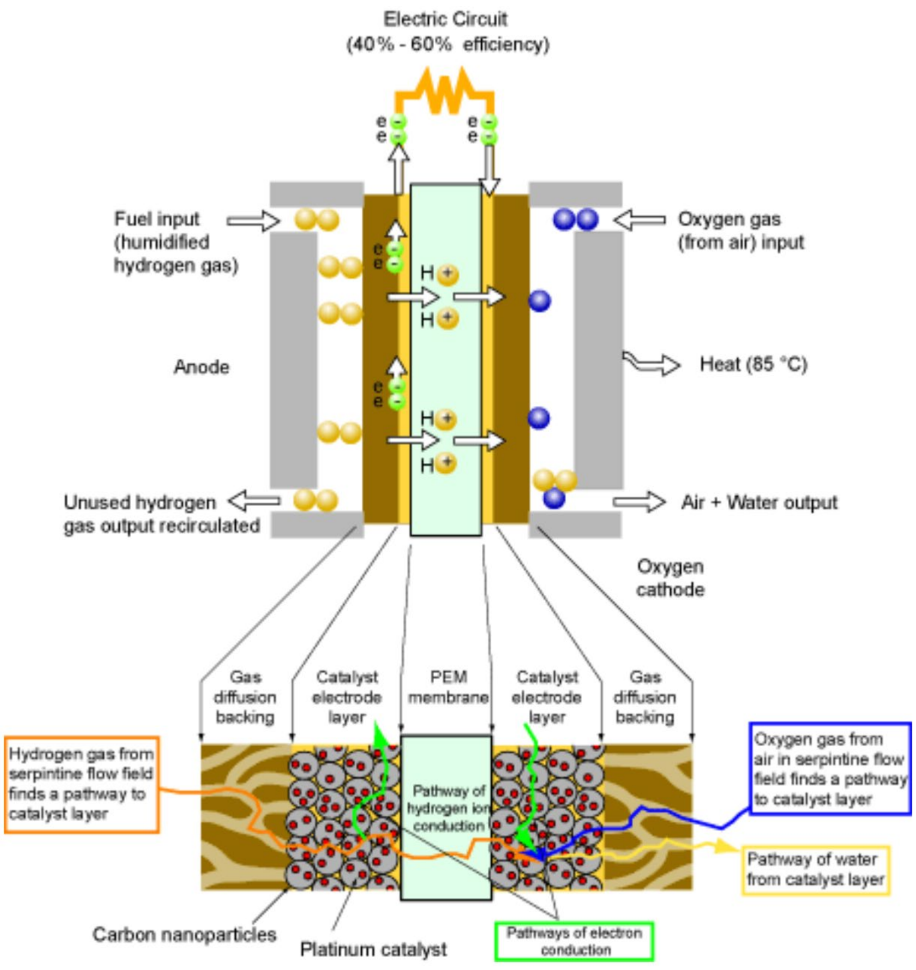
Hydrogen Fuel Cell



Hydrogen Fuel Cell



Hydrogen Fuel Cell



Neutron Research

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Pipeline Failures

Blowout of a gas pipeline

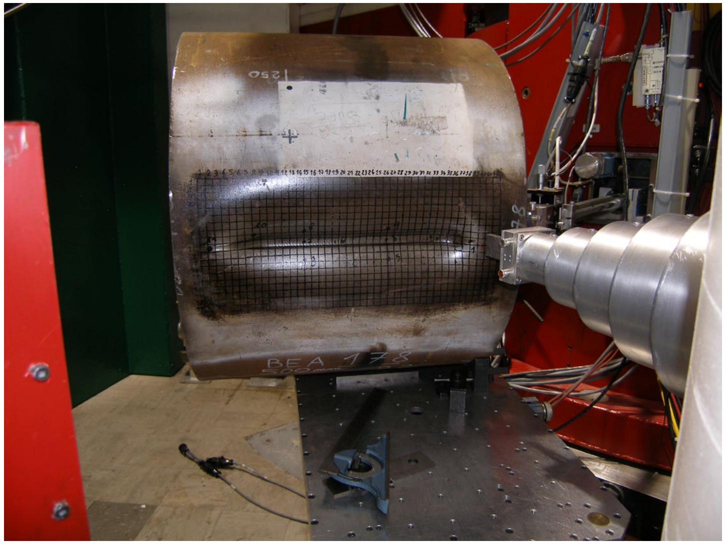
Rupture after hydrotesting

Safety - Gas pipelines have an enviable safety record in transporting energy; this is due to detailed materials characterization, stress analysis and continued analysis during service.

Modes of failure – fracture, fatigue, stress corrosion cracking, and external damage. Failures are affected by residual stress in the pipeline after manufacture and welding, excessive flexing during transport.

External damage is caused by construction and agricultural activity, often by backhoes and excavators. Pipelines are buried!

Dents and gouges produced by the Stress Aggression Rig



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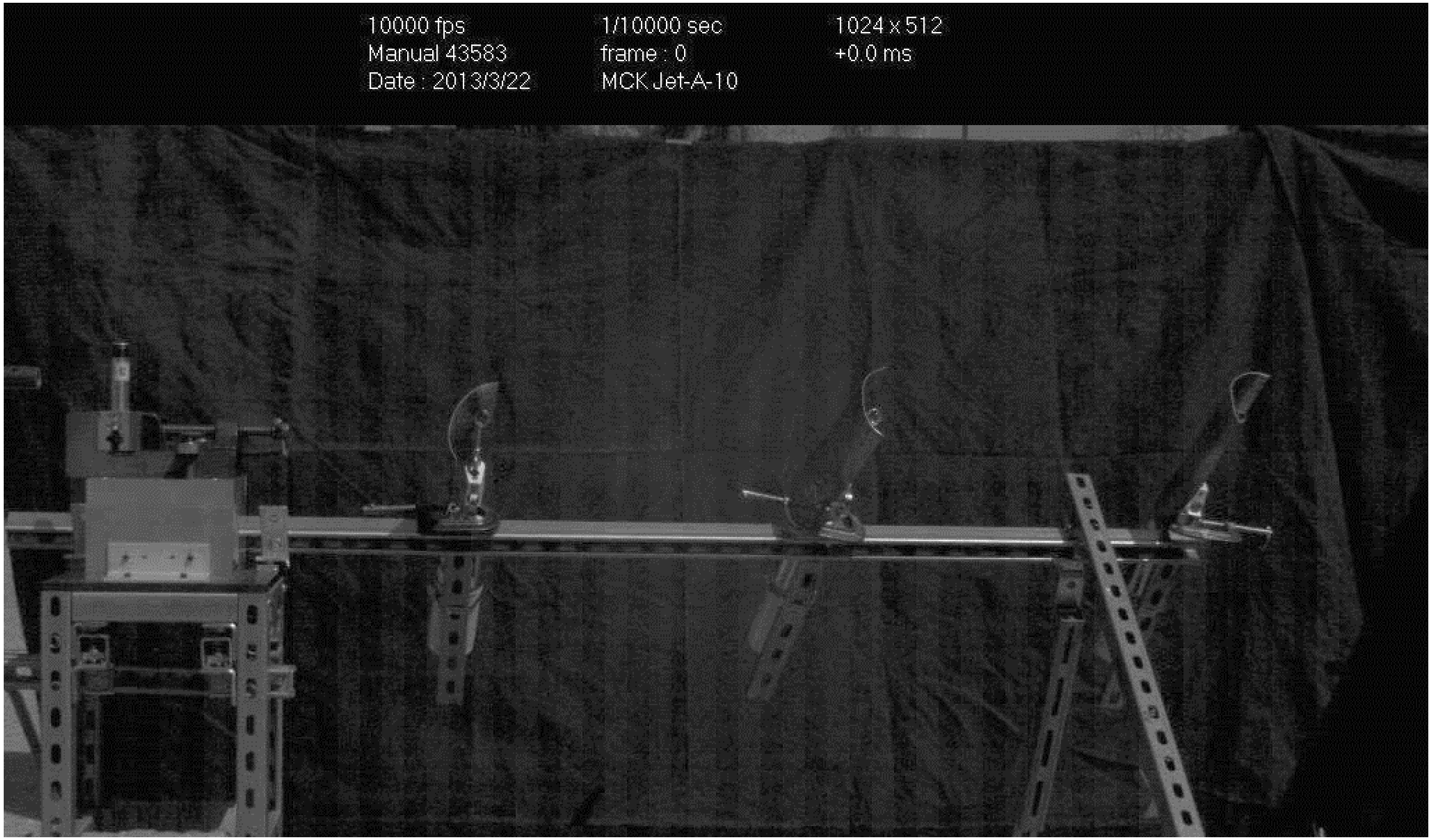
Jet Fuel

- Prevent jet fuel fires
  - For safety
  - National security

Jet Fuel


10000 fps
Manual 43583
Date : 2013/3/22
1/10000 sec
frame : 0
MCK Jet-A-10
1024 x 512
+0.0 ms

Jet Fuel

- Prevent fuel fires for safety and national security
- Addition of small amounts of polymers can reduce misting
- But they break down under normal fuel handling
- And can also clog jet engines
- The challenge is to find a mist-control polymer that is stable
- Research by Cal Tech team found new polymers using neutron scattering that are stable in real world conditions
- Megasupramolecules (100 ppm) don’t degrade and don’t affect the jet engine performance

Jet Fuel with Polymer additive

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Eli Lilly and Company Pharmaceuticals

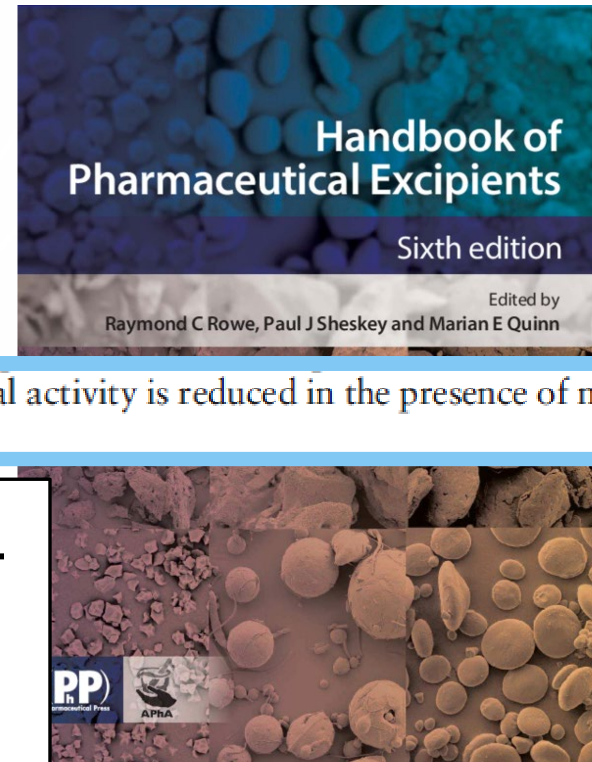
Injectable Pharmaceutical Formulation Challenges…

What is in an injectable therapeutic?

- Therapeutic Protein/Drug
- Buffer
- Tonicity Agent (Ionic/Nonionic)
- **Surfactant**
- **Antimicrobial Preservative**

Requirements…

- No ‘large’ aggregates
- Stabilized proteins
- No microbial growth



Antimicrobial activity is reduced in the presence of nonionic surfactants.

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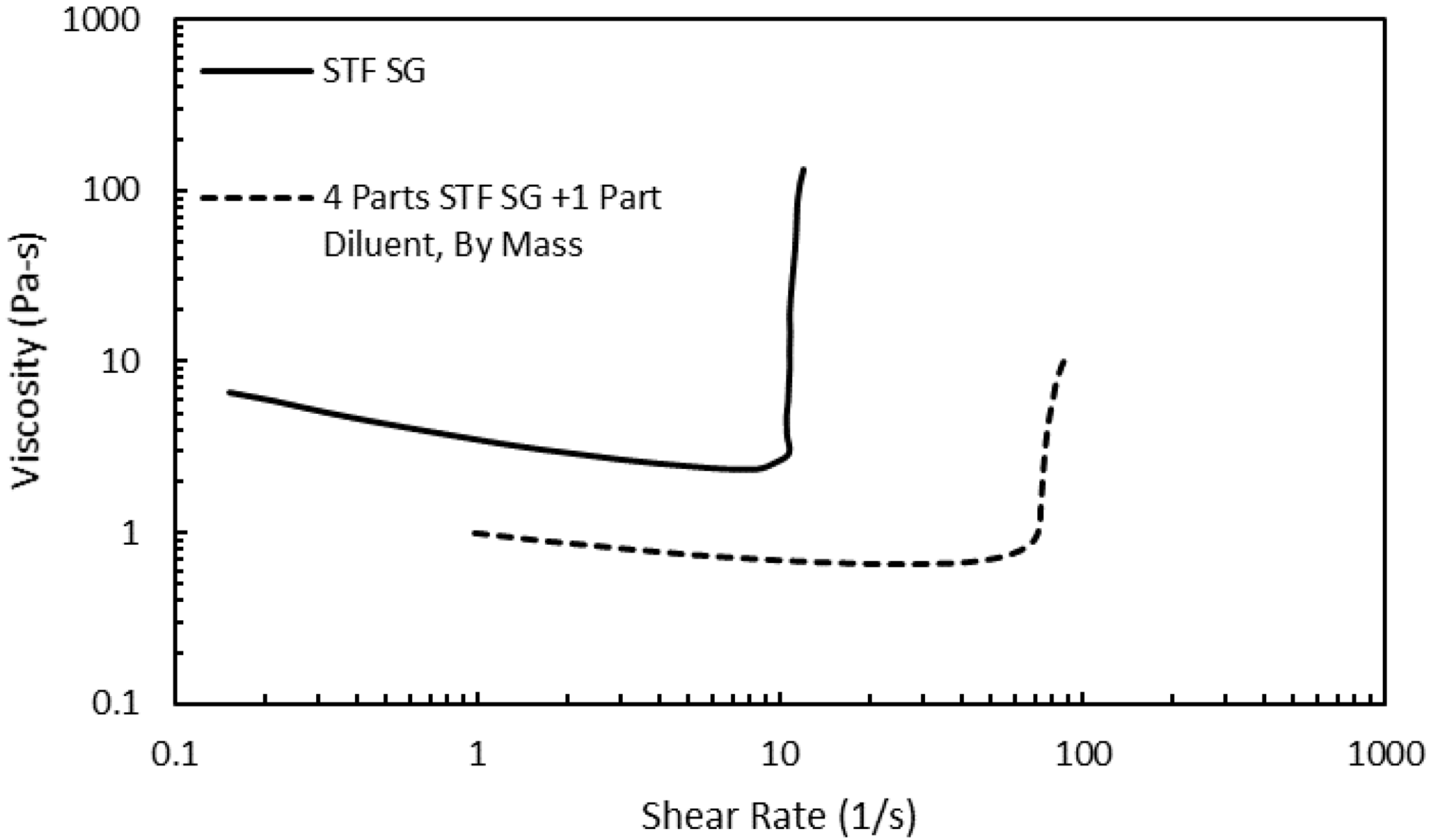
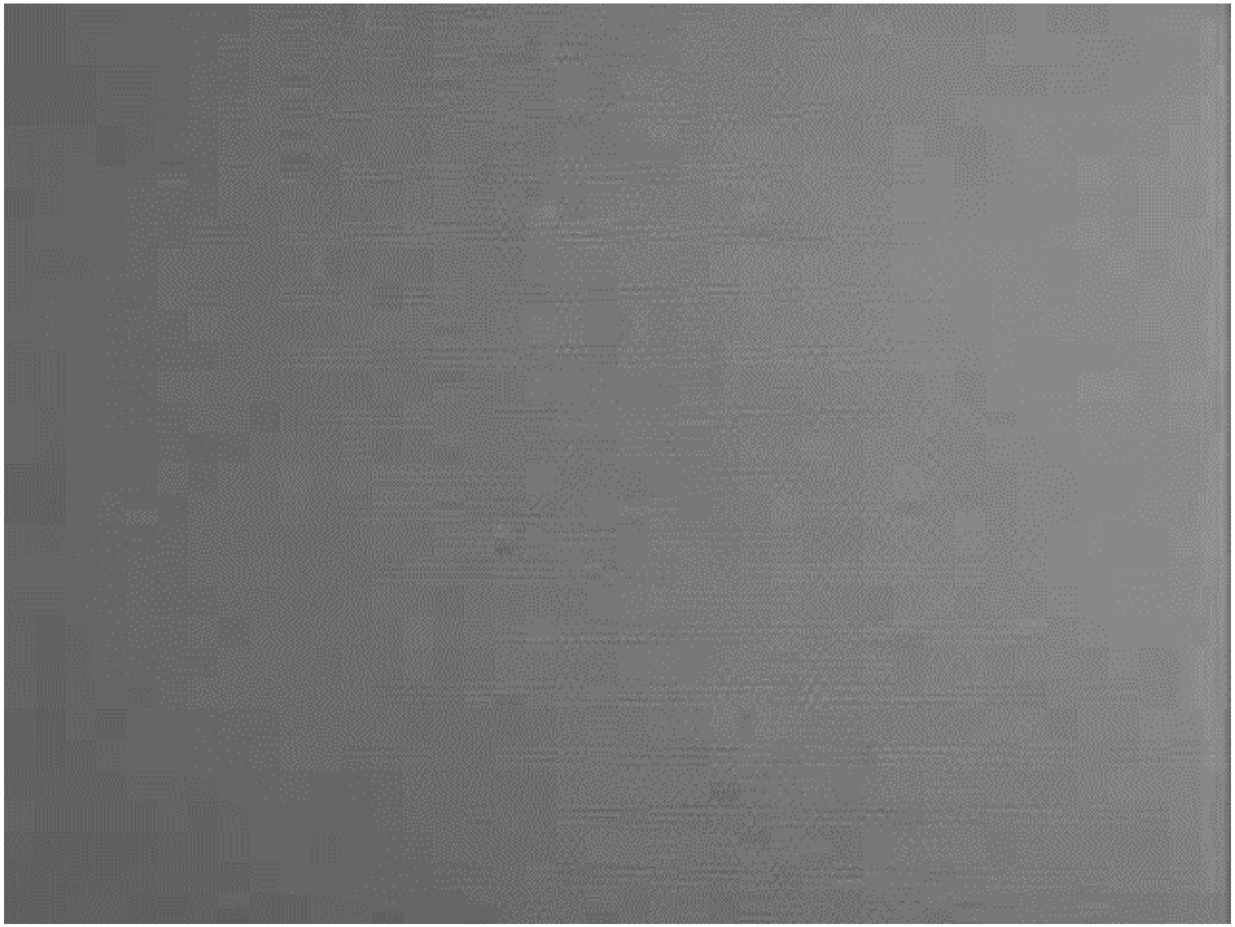
NCNR

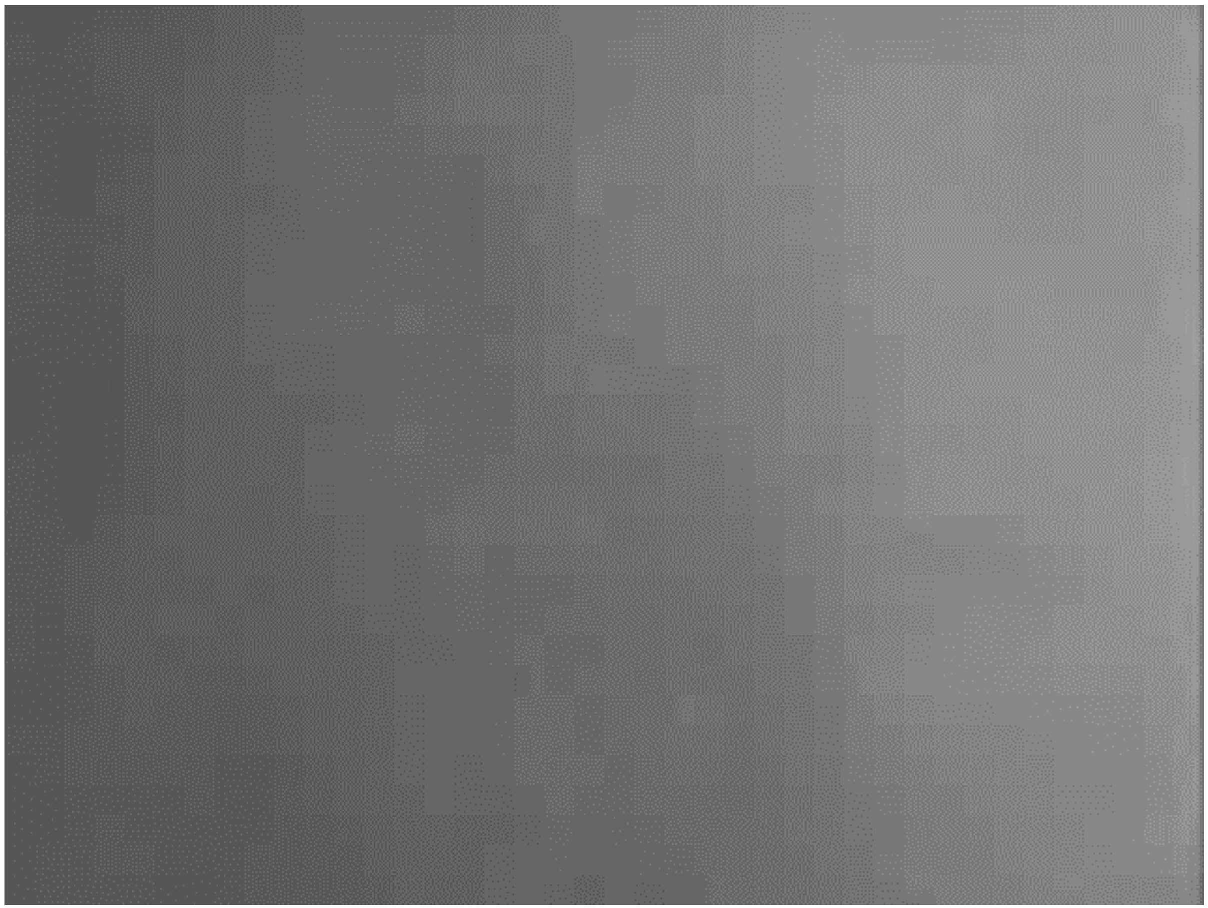
Shear Thickening Fluid



Three layers of untreated ballistic nylon



Two layers treated with STF polymer



STF Technologies

- Medical Gloves
- Liquid Armor for Military & Police
- Space Suits
- Athletic Safety
- Athletic Clothing (Reebok)

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Standard Reference Materials (SRMs) Measured by Neutrons

Group 5, Chemical Sciences Division

Material Measurement Lab

NIST SRMs are Measured for:

NIST Measures for:

Concentration, Homogeneity, Stability

(and much more!)

Measurements involve bench scientists, topic area specialists, statisticians, and support staff (storage and distribution of SRMs).

Requires two (2), independent certifying measurement methods:

Example:

ICP-MS and ***Neutron Analytical Methods***

Average of apx. 5 years between SRM proposal and market availability.

SRM 2454a – H in Ti Alloy

- Developed in collaboration between NIST and industry stakeholders in 2010’s
- Uptake of H by Ti alloys can cause embrittlement, leading to material failure
    - Ti alloys are used in automobiles and airplanes
- Two certifying methods:
    - Inert gas fusion with thermal conductivity detection and standard additions calibration
    - **Prompt Gamma Activation Analysis**

SRM 2173 – Boron in Si Wafer

- Developed in collaboration between NIST and semiconductor industry stakeholders in 2010’s
- Boron is a common dopant in semiconductor materials and used to control electrical properties
- Two certifying methods:
  - Scanning Ion Mass Spec.
  - **Neutron Depth Profiling**

Summary

- Tried to give you a flavor of some of the things NIST does
- And some examples of the research and technology being done at the NIST Center for Neutron Research
- And now I’m getting hungry.

Thank You for Your Attention

Further information is available
https://www.nist.gov/people/jeffrey-w-lynn
NCNR homepage: https://www.nist.gov/ncnr
NIST homepage: https://www.nist.gov/