“Cold Fusion” was announced two decades ago and quickly became infamous. Since then, most researchers wouldn't touch the subject. Nonetheless, some persisted and the subject has now resurfaced in peer-reviewed journals under the names, “Anomalous Heat Effect” and “Low Energy Nuclear Reactions (LENR).” Physical evidence is mounting that suggests that some sort of anomalous effect does indeed seem to exist. But what is it and what can we do about it?
“Cold Fusion”? 

Headlines 1989 

Two electrochemists…  
Martin Fleischmann  
Stanley Pons  
claimed to have tapped nuclear power in a simple electrochemical cell. 

"It could be the end of the fossil fuel age: the end of oil and coal. And the end, incidentally, of many of our worries about global warming.” 

-- Sir Arthur C. Clarke
The Hype

The Press

Pedantic Disdain

If only:
1. Dubbed “Anomalous Heat Effect”
2. In Journals instead of Television
3. Easily repeatable

Narrated by James Doohan ("Scotty," Star Trek)
“Special Challenges”

Edge of Knowledge → Controversial ideas

+ Profound Improvements → Emotions run higher

= Skeptics and optimists reach premature, conflicting conclusions and, in their zeal, fail to communicate with the impartiality needed to rigorously identify, test, and resolve the real issues.
From “Cold Fusion” to “Low Energy Nuclear Reactions (LENR)”

[Gartner’s Research's Hype Cycle diagram]
GREEN Forum Context

WHY NOW?

- Reliable publications indicate provocative effects
- Energy investigations back in vogue

WHY US?

- NASA Langley/Glenn collaboration initiated 2009 January
- GRC Instrumentation Expertise & “Honest Broker”
- GRC Researchers *dabbled* in such notions before
  - 1996 Niedra, et al – Anomalous heat in Electrochemical cells
  - 2007 Wrbanek, et al – Anomalies in Sonoluminescence
Sensibility on Edge - Huh?

(A Necessary Primer Before Proceeding)

- Embarking into the unknown
- Solutions *NOT* in textbooks
- Science is about acquiring *new* knowledge, not just comprehending accumulated knowledge
- *Revolutionary*, not *Evolutionary* research
- History also offers lessons for proceeding sensibly on the edge of knowledge
Contrasting Advancements

Evolutionary Research
Mastery of Known

Revolutionary Research
Pioneering into Unknown
To exceed the limits of prior technology
seek entirely different technology

(Foster, *Innovation - The Attacker’s Advantage*, 1986)
Challenges of Revolutionary Research

• **Breaks from the Norm** ("Out of the Box")
  – Draws attention to what we don't know rather than flexing our prowess for the known
  – Speculation and imagination part of the process
  – Difficult to assess feasibility, quantify benefits

• **Risky**
  – Most approaches will fail to perform
  – Evokes hype, sensationalism, fringe
  – Evokes pedantic disdain
  – Difficult to sort viable 'crazy' ideas from the fringe
  – Success will be disruptive
“If I have seen further it is only by standing on the shoulders of giants.”
~ Isaac Newton

“Imagination is more important than knowledge.”
~ Albert Einstein

“Creativity is a type of learning process where the teacher and pupil are located in the same individual.”
~ Arthur Koestler

“Nearly every man who develops an idea works it up to the point where it looks impossible, and then he gets discouraged. That’s not the place to become discouraged.”
~ Thomas A. Edison
More Recent Progress

THE SCIENCE OF LOW ENERGY NUCLEAR REACTION
A Comprehensive Compilation of Evidence and Explanations about Cold Fusion
Edmund Storms

Summary Book, 2007

A low energy nuclear reaction cell used this year at the University of California, Berkeley, US, in an attempt to replicate research conducted at the US Space and Naval Warfare Systems Center, San Diego.

© Steven B. Krivit

Reputable Labs, 2007
Predominant Speculation

**FACT:**
Hydrogen (H) and its isotopes
- Deuterium (D, \(^{2}\text{H}\))
- Tritium (T, \(^{3}\text{H}\))
have an affinity for Palladium (Pd)

**SPECULATION:**
Hydrogen fits so closely within the Pd lattice that the nuclei overcome the coulomb barrier (like charges repel) and fuse into heavier nuclei…

… and give off heat

Image: Wikimedia Commons.
Technical Problems

• Irregular Repeatability

• Absence of obvious reaction products

\[ D + D \rightarrow T (1.01 \text{ MeV}) + p (3.02 \text{ MeV}) \]
\[ D + D \rightarrow ^3\text{He} (0.82 \text{ MeV}) + n (2.45 \text{ MeV}) \]
\[ D + D \rightarrow ^4\text{He} (73.7 \text{ keV}) + \gamma (23.8 \text{ MeV}) \]
\[ D + T \rightarrow ^4\text{He} (3.5 \text{ MeV}) + n (14.1 \text{ MeV}) \]
\[ D + ^3\text{He} \rightarrow ^4\text{He} (3.6 \text{ MeV}) + p (14.7 \text{ MeV}) \]
Moving Forward

• Current Situation
• Relevance to NASA
• Info – via Scientific Method
  1. Define the Problem
  2. Collect Data
  3. Hypothesize
  4. Test & Iterate
Current Situation
(Executive Summary)

The Good

• Energy release comparable to nuclear reactions
  (2-Million times the energy/mass of Coal burning)
• No hazardous byproducts (apparently)

The Bad

• Repeatability not 100% (maybe 70% ?)
• Energy only in discrete spots – Bulk effect is low-grade heat
• Methods to amplify and apply not yet discovered

The Ugly

• Taint of Cold Fusion and pedantic disdain (not science)
• Salesmanship (not science)
• The pending bandwagon?
Relevance to NASA

• Possible new energy source for all NASA missions that require long-duration power beyond the reach of solar energy… Potentially replacing Plutonium (in short supply) in Radioisotope Thermal Generators (RTG)

• Stirling technology exists that can efficiently convert heat into electrical energy

• Exploring Nature
Sci. 1. Defining the Problem

• **SCIENCE:** Decipher the empirical evidence
  • Separate artifacts from genuine effects (Rigor of methods)
  • Identify apparent correlations
  • Identify unknowns to resolve

• **ENGINEERING:** Which effects might lead to practical applications?
  • Sufficient excess heat to serve functions?
  • Material transmutations?
  • Other?
Sci. 2. Collecting Data
Introductory Examples

• Heavy Water Electrolysis  *(US Navy)*
• Light Water Electrolysis  *(Univ. Illinois, UC)*
• Light Water Electrolysis  *(NASA GRC)*
• Gas Discharge Plasma  *(Univ. Illinois, UC)*
• Sonofusion  *(ORNL, UCLA, et al)*
• Sonoluminescence  *(NASA GRC)*
• Gaseous Diffusion  *(NASA GRC)*
**Heavy Water Electrolysis** (U.S. Navy)


**Hypothesis:**

Deuterium (D, \(^{2}\text{H}\)) diffuses into Palladium (Pd), produces some Tritium (T, \(^{3}\text{H}\)) and then D-T fuse into Helium

**Approach:**

- Electrolytic cell, Palladium (Pd) cathode
- Heavy Water (D\(_{2}\)O) in Electrolyte (Deuterium instead of just Hydrogen)
- Pd cathode in contact with CR-39 – solid-state nuclear etch detector, a plastic resin where reaction products leave visible tracks
Heavy Water Electrolysis (U.S. Navy)

Linking Hypothesis to Observation

- Triple tracks in CR-39 consistent with 3 alpha particles from a Carbon breakup \([^{12}\text{C}(n,n') \ 3\alpha]\) \((\alpha = ^{4}\text{He} \text{ nuclei})\)
- Carbon breakup requires \(\geq 9.6\text{ MeV} \) neutrons
- 14.9 MeV neutrons are produced when Deuterium \((^2\text{H})\) and Tritium \((^3\text{H})\) fuse into Helium four \((^4\text{He})\) \([\text{D}+\text{T} \rightarrow \text{He}\])
- Tritium present if Deuterium nuclei fuse \([\text{D}+\text{D} \rightarrow \text{T}\] )
- Hence, triple tracks in CR-39 are consistent with fusion occurring in the Pd lattice

Images: Wikimedia Commons, New Scientist, and Mosier-Boss, et al.
**Light Water Electrolysis**  
*(University of Illinois at Urbana-Champaign)*


Thin film electrolysis cells  
Designed for both Interface loading and gas flow

**Observed Anomalies**

<table>
<thead>
<tr>
<th>Anomaly</th>
<th>Observed</th>
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<tbody>
<tr>
<td>Excess Heat</td>
<td>√</td>
</tr>
<tr>
<td>Transmutations</td>
<td>√</td>
</tr>
<tr>
<td>H -versus- $^2$H Differences</td>
<td>not tried</td>
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<tr>
<td>Material Surface Changes</td>
<td>√</td>
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<tr>
<td>~ 1.7 MeV protons</td>
<td>√</td>
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<tr>
<td>~ 15 MeV alphas</td>
<td>√</td>
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<tr>
<td>Repeatability</td>
<td>√</td>
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</tbody>
</table>
Light Water Electrolysis - Observations
(University of Illinois at Urbana-Champaign)

4-peak nuclear reaction products using Pd-Ni thin films (SIMS)
(A=20-30, 50-80, 110-130, 190-210)

CR-39 tracks:
~1.7 MeV protons
~15 MeV alphas.

Localized tracks suggest cluster emission sites

SQUID magnetic measurements:
H loaded Pd/PdO layered film reacts like a type-II superconductor
**Light Water Electrolytic Cell (GRC)**


- Replication attempt of long-term excess heat in light water-Ni-K$_2$CO$_3$ electrolytic cells
- Two 28-liter electrolytic cells
  - Active test cell
  - Inactive control cell for thermal reference

**Results**

- Excess heat dependent on current for both DC and pulsed mode
- Amount of heat consistent with hydrogen-oxygen recombination catalyzed by the Pt and Ni electrodes within the cell
- Did not reproduce the large excess heat reported in literature
  (Gain Factors of $<1.7$ @ GRC vs. $>10$ in literature)
Gas Discharge Plasma
(University of Illinois at Urbana-Champaign)

Ref: George H. Miley, Heinz Hora, Andrei Lipson, Nie Luo, Joshi Shrestha, “Future Power Generation by LENR with Thin-Film Electrodes,” ACS 23rd Annual Meeting, Chicago, IL March 29, 2007

• Water-cooled Pd cathode
• Cathode & chamber grounded
• Deuterium gas
• Plasma forms between Cathode and positively charged Anode
• Cathode moveable for different separation distance
• Pulsed Power Supply
• Beryllium (Be) filter to set X-ray detection threshold
• Performed X-ray measurements during plasma and after – during room temperature desorption.
Gas Discharge Plasma - Observations
(University of Illinois at Urbana-Champaign)

X-rays produced even after plasma discharge extinguished, while Deuterium desorption from the Palladium
Sonoluminescence - Primer

- Sonoluminescence means inducing cavitation and bubble collapse in liquids using ultrasonic waves, and where bubble collapse is accompanied by anomalous emission of light.

- High temperatures and pressures in sonoluminescence (SL) as reported in literature have generated claims and theories that predict a net gain of power resulting from atomic interactions.
“Sonofusion” – A Brief History

- Putterman (UCLA) & Moss (LLNL) examined D-D and D-T fusion possibilities in Sonoluminescence (“Sonofusion”) (1994-1997+)
- George and Stringham (D2Fusion, Inc.) reported molten “ejecta craters,” vents and anomalous heating of titanium, nickel, copper and palladium metal foils under cavitation in heavy water (1997+)
- Taleyarkhan et al. of Purdue University reported the generation of tritium and neutron flux from cavitation of deuterated acetone at ORNL (2002), and repeated with a mix of other organic solvents (2006)
Sonoluminescence (GRC)


- Sonoluminescence with Palladium-Chromium (PdCr) Thin Films Over Platinum (Pt) RTD Traces on Alumina
  - No Crater seen in H₂O
  - Crater Formation seen in D₂O
- Large Grain Failures usually seen in thin films due to mismatches in coefficients of thermal expansion at high temperature (~1000°C)
**Sonoluminescence (GRC)**


- Large failure areas also seen in PdCr film over Pt in D$_2$O not H$_2$O
- PdCr nodules appear on the bottom in failure areas atop Pt
- Failures *not* seen in PdCr directly on Alumina, or in H$_2$O runs
Gaseous Diffusion (GRC)

Ref: Fralick, Decker & Blue, *Results of an Attempt to Measure Increased Rates of the Reaction* $^2D + ^2D \rightarrow ^3He + n$ *in a Nonelectrochemical Cold Fusion Experiment*, NASA TM-102430 (1989)

**EQUIPMENT**
- Hydrogen purifiers are made using Palladium membranes

**OBSERVATIONS**
- 15°C rise in purifier with Deuterium, but not Hydrogen, when pumping out gas from the Palladium
- Neutron detection not significantly ($\leq 2\sigma$) different than background, using BF$_3$ w/ Polyethylene (“Snoopy”) detectors
# Tabulating Methods & Evidence

<table>
<thead>
<tr>
<th></th>
<th>Heavy Water Electrolysis (Navy)</th>
<th>Light Water Electrolysis (UIUC)</th>
<th>Light Water Electrolysis (GRC)</th>
<th>Gas Discharge Plasma (UIUC)</th>
<th>Sonofusion (ORNL) (UCLA) (Perdue)</th>
<th>Sono-luminescence (GRC)</th>
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</table>
### Anomalies and Unknowns

**Old Theories ≠ New Observations**

<table>
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<tr>
<th>“3-Miracles”</th>
<th>Traditional Predictions</th>
<th>Observations</th>
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<tr>
<td>D-D Rates @ 300˚K</td>
<td>if 1</td>
<td>$10^{42}$ Inferred by heat</td>
</tr>
<tr>
<td>Branch Ratios</td>
<td>Expect predominantly $^3$He, neutrons, protons, and Tritium</td>
<td>Predominantly find $^4$He</td>
</tr>
<tr>
<td>Byproducts</td>
<td>If $^4$He, then also expect: 14MeV neutrons &amp; Gammas</td>
<td>Evidence of ≥9.6 MeV neutrons</td>
</tr>
</tbody>
</table>

But Wait, There’s More

- Slight Tritium ($^3$H) production from Deuterium ($^2$H), even less from Hydrogen (H)
- Low rates of prompt neutron, alpha ($^4$He), beta ($^e$), gamma and x-ray emissions
- No secondary radiation emissions
- What energy bands of neutron and gammas should be targeted in detection?
- Localized reactions at cracks, dislocations, voids and nano-scale particles
- Transmutations of Z+4, A+8
- Generation of Fe, Zn, Cu from Pd
Skepticism

Healthy Skepticism

- Ensure experimental artifacts, contaminations, removed from data
- How else can observed nuclear products be present?
- Repeatability not 100% - which means not all factors identified
- Alert to possible self-deception (pro or con)
- Alert to possible fraud (when salesmanship exceeds evidence)

Unhealthy Skepticism

“In the Wall Street Journal, June 6, 2009, Eugenie Reich discussed ‘the five best books on scientific fraud,’ including my ‘Voodoo Science’ (Oxford, 2000), which she referred to as ‘devastating’ on the subject of ‘cold fusion.’ Cold fusion 20 years later remains a curious mix of self deception and outright fraud.” — Robert Park, WHAT’S NEW, Friday, 12 Jun 09
Sci. 3. Hypotheses

“Pet Theories”
(Hypotheses where proponents already convinced)

- **Electron Screening** (Parmenter & Lamb)
- **Band States** (Chubb & Chubb)
- **Shrunken Hydrogen** (Maly, va’vera & Mills)
- **Ultra Low Momentum Neutrons** (Widom & Larsen)
- **Dislocation Loops** (Hora & Miley)

None of these encompass all the observations

- **Our Hunch: More than one effect occurring**
Sci. 4. Test & Iterate

The Steps We Are Considering

• Study experimental observations, preference to those with the most rigor and impartiality

• Repeat prior anomalous GRC experiments, now with improved instrumentation
  - GRC thin-film sensor expertise
  - Improved neutron detectors and elemental detection
  - Attempting to devise means to detect “chubby electrons” (W-L)
  - GRC electrolytic cell expertise

• Characterize phenomena
  - To assist test/development of theories
  - To assess/improve application implications
  - To check for detrimental side-effects on materials and sensors used for aerospace applications
Strategic Instead of Reactionary

Typical Reactionary Approach

- New 'hot topic' gains attention.
- Funds sought for hot topic only.
- Other approaches not comparatively assessed in a rigorous manner.

**Typical Results**

- Success is defined in terms of whether the approach worked.
- Negative results not published.
- In the event of a null result, support ebbs.
- Window closes on all other approaches for addressing these same challenges.

Strategic Approach

- Lead person acts as an impartial broker.
- Various approaches compared.
- Devise tasks to focus on key issues/discriminators.
- Scope of each task set to the minimal effort needed to resolve an immediate “go / no-go” question.

**Results Sought**

- Success defined as gaining reliable knowledge to guide next steps.
- Results, pro or con, published to set foundation for future decisions.
- Opportunity open for sequels to the positive results, and to redirections around null results.
The Alchemist in Search of the Philosophers Stone, by Joseph Wright (1771)
CHART ARCHIVE / RESERVE
Electron Screening (Parmenter & Lamb)

- Explains the increased D-D fusion rates solely on charge screening of the D⁺ by the 4d electrons in the PdD lattice
- Does not attempt to explain anything else
**Pet Theories 2**

**Band States (Chubb & Chubb)**

- Relies on the formation of a Bose-Bloch condensate (BBC) of D+ ions in the surface of the PdD lattice
- Transmutations are explained as condensates of He-4 generated and absorbed into the lattice
- Does not fully explain lack of high energy gamma rays
- BBCs are typically cold – There is some debate on how thermal lattice vibrations do not prevent the BBCs from forming

---

**D2 Molecular Wavefunctions vs. D+ Bloch Wavefunctions**

**Theoretical Single-Ion D+ Distributions in Nickel along (100), (110) and (111) faces**
Pet Theories 3

Shrunken Hydrogen (Maly, Va’vera & Mills)

- Relies on existence of deep-Dirac fractional electron levels to pull nuclei closer together

Schematic showing hydrogen transitions to fractional states in the presence of a catalyst

Emission of Ar-H2 showing R(0) transition to claimed fractional states
Pet Theories 4

Ultra Low Momentum Neutrons (Widom-Larsen)


- A three-step process:
  - Effective electron mass increases x20 in presence of Surface Plasma Polaritons
  - Increased-mass electrons allow conversion of protons to neutrons with very little energy (~$10^{-15}$ eV) (=ULM neutrons)
  - These ULM neutrons combine with other nuclei to form transmutated atoms and alpha particle decays (He-4)

- Some debate whether the increase in electron mass assumed independent of SPP wave vector potentials
- Cooling process for ULM neutrons not fully explained
- Predicts more reactions for H-H fusion than for D-D fusion
- Does explain lack of a large amount of nuclear products in transmutations
Pet Theories 5

Dislocation Loops (Hora & Miley)

- Relies on metallic deuterium clustering in lattice dislocations to allow formation of compound nuclei to generate transmutation distribution seen in experiments
- Some debate over whether the thermal lattice vibrations will even permit metallic deuterium to form in the dislocations

Schematic of H Cluster in Pd Lattice

Fit of Compound Nucleus Products to Data
Tactics For Pioneering Research

1. **Combine** Vision & Credibility
2. Identify "Important Problems"
3. Use appropriate comparisons
4. Small increments of progress (affordable, less provocative)
5. Emphasis on physical observables
6. Publish reliably, publish often

Consider the possibilities
Research rigorously & impartially
Evaluate rigor and impartiality – not feasibility

Marc G. Millis, 2009
Great Researchers & Important Problems
1986 lecture, Richard Hamming, distinctions between good and great researchers

• Have courage to tackle Important Problems
  – Grand challenges that will make a real difference, not just "safe" research
  – Attackable; there is a way to begin solving the problem

• Start with independent thoughts and then collaborate

• Make steady progress, driven and focused

• Learn things beyond own work; "Knowledge is like compound interest"

• Redirect what is difficult to something easier (convert liabilities to assets)

• Honest with personal flaws & work to overcome

• Tolerate ambiguity
  – Believe in self enough to proceed
  – Doubt self enough to honestly see flaws
## Research Organization Responsibilities

### Reliability and Performance of Information, not Hardware

<table>
<thead>
<tr>
<th>Risks</th>
<th>Mitigations</th>
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</table>
| Credibility damaged by non-rigorous reporting                        | • Emphasize **reliable advances** in knowledge, rather than requiring breakthroughs (*the journey, not the destination*)
|                                                                      | • Collaborate with academia and other institutions for peer reviews |
| Leadership stature damaged by neglecting relevant advancements       | • Sustain active scouting for ongoing development inside and external to the organization |
|                                                                      | • Pursue visionary research beyond the known - beyond what other organization address |
|                                                                      | • Forge widespread collaborations |
| (For commercial research) Competitive advantage weakened from premature disclosure | • Threshold of attention is when device can be *engineered* |
|                                                                      | • Disclose only enough for independent verification of key principles, not device, not best demo |
|                                                                      | • After independent verification, advertise improved version whose performance is more pronounced than verification demo |
Some Physics Anomalies

- **Pioneer Anomaly** (unknown sunward acceleration of space probes)
- **Dark Matter** (needed to explain galaxy spin)
- **Dark Energy** (needed to explain universe expansion)
- **Neutrino Spin & Mass** (its own anti-particle?)
- **Superconductivity** (superfluid Cooper pairs)
- **Magnetic Pole Drift** (increasing drift rate of magnetic poles)
- **Ultra-High Energy Cosmic Rays** (some cosmic rays possess energies that are too high: $>>10^{15}$ eV/amu)
- **Sonoluminescence** (light from cavitation in liquids)
- **Cold Fusion** (anomalous heat generation in some highly-loaded hydrides)
Stages of Progress

Conjecture
"I want to believe"

Speculation
Sci-Fi

Science
Nature

Technology
Devices

Commerce
Profitable Devices

What do I know… and not know?

Compare "what-ifs" to real nature

From theory to hardware

Make it valuable and affordable

This Research