

University of Colorado  
Center for Science and Technology Policy Research



# Collaboration in energy and materials sustainability

Alan J Hurd  
Los Alamos National Lab  
October 2016

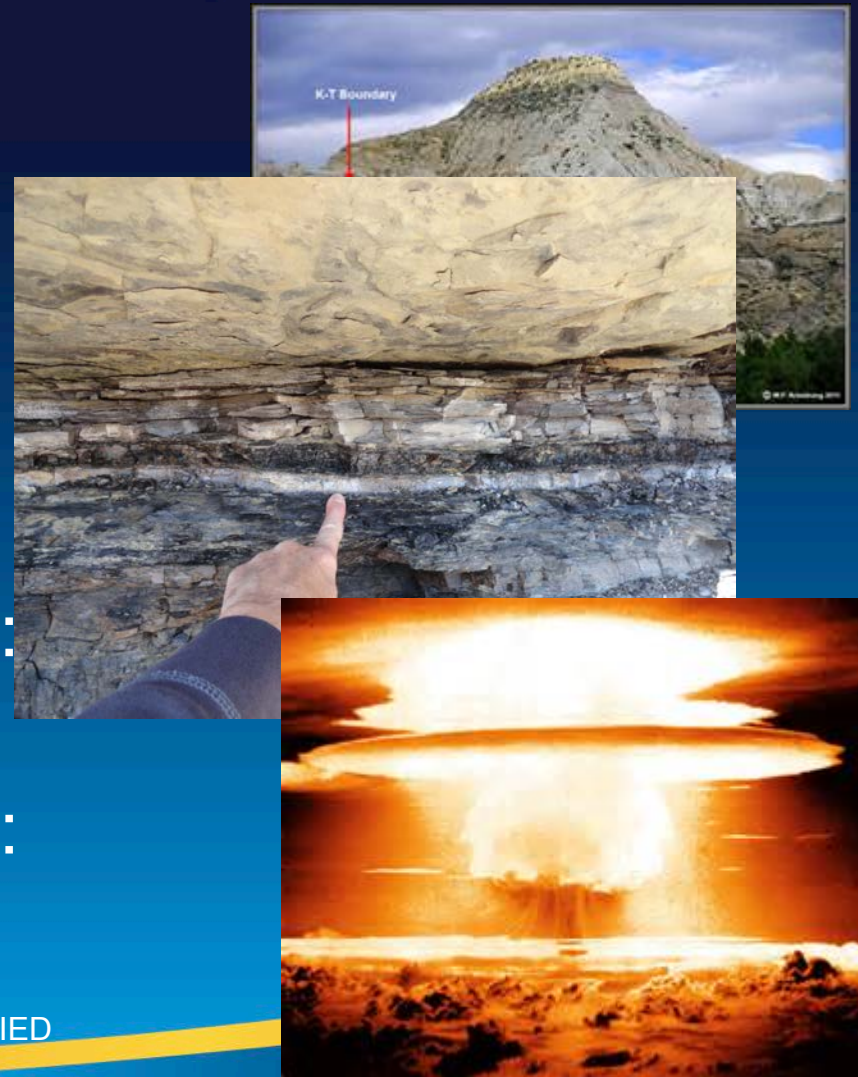
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# Welcome to the Anthropocene

- Human activity is now encoding information into the geologic record
- Boundary Markers:
  - Cretaceous-Paleogene:
    - *Ir, Pt*
  - Holocene-Anthropocene:
    - *C, Pu?*



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1944  
Los Alamos



Dirac

Feynman



Ulam



Bartlett

Metropolis



Rosen



Oppenheimer



Smith



Agnew



Fermi

Teller



Manley



Bethe



Wilson

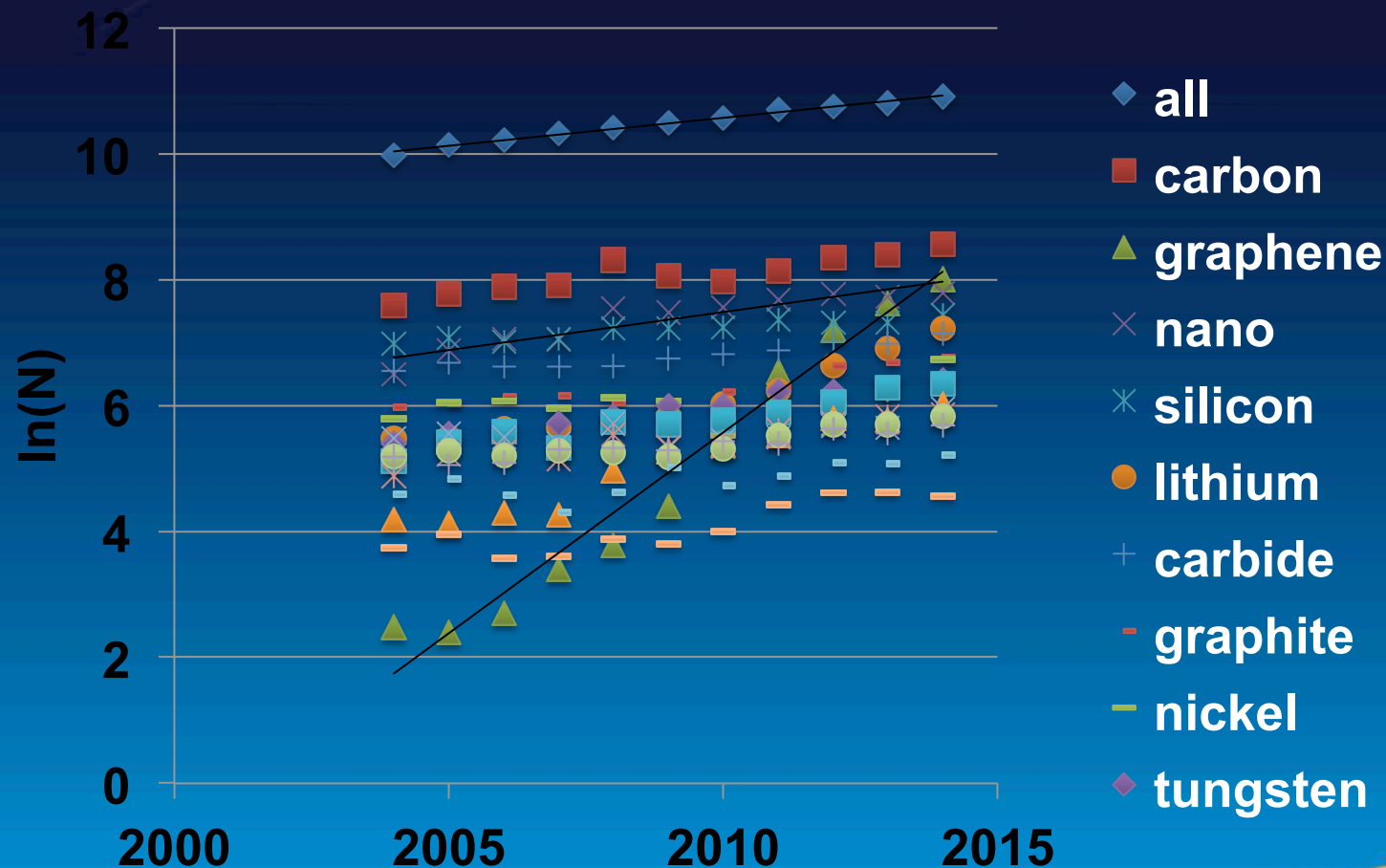


Tuck

The Human Resource

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# Research usage of elements in composites



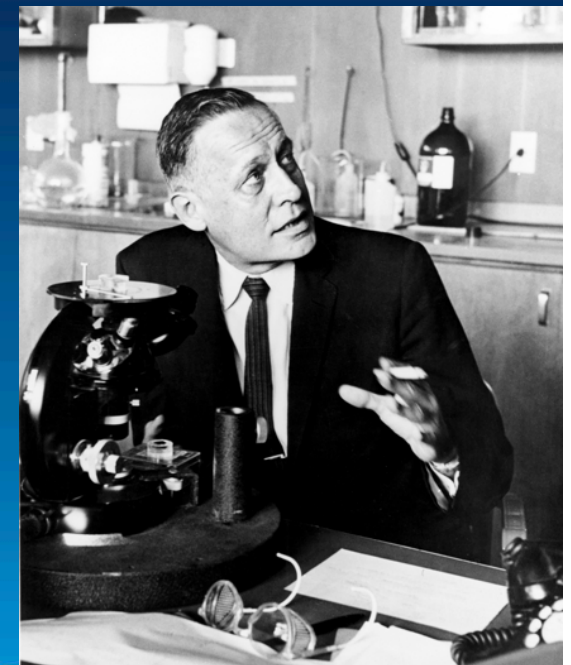
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# Is this a “CO<sub>2</sub> moment” for materials research?

- Critical materials
- Al Bartlett's warning
- Elements in composites research
- Helium
- A sustainable solution for research

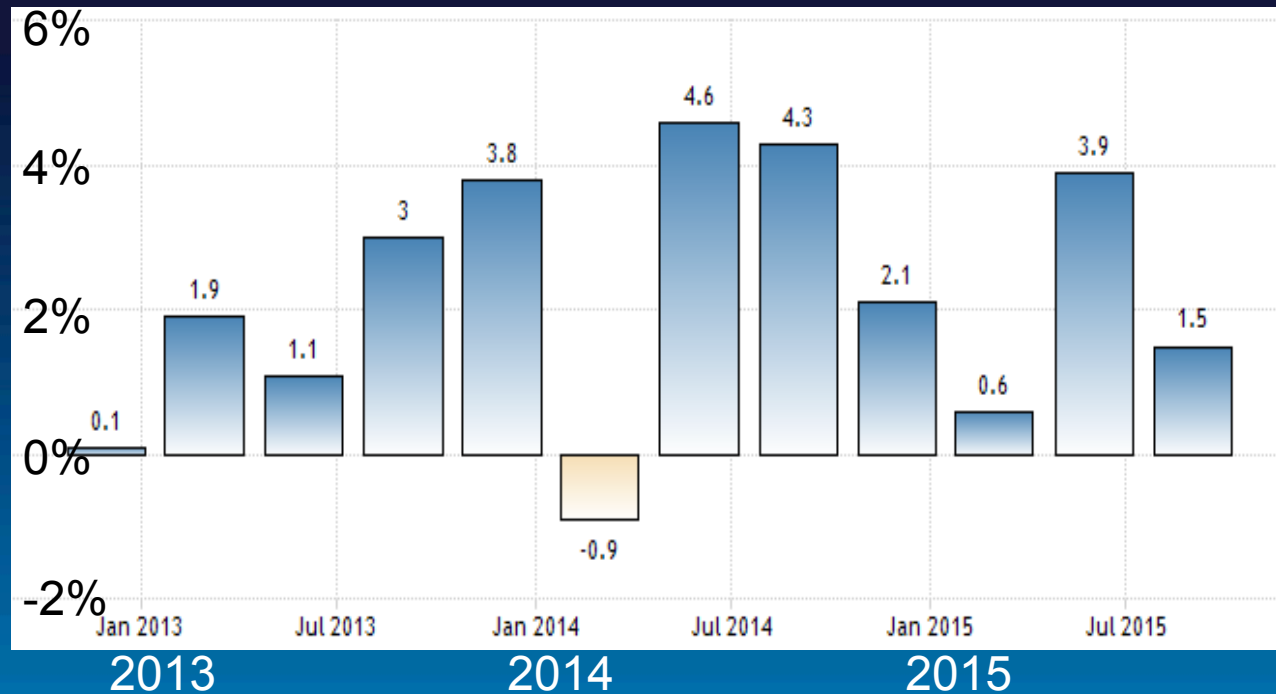
**Roger Revelle**  
**Climate Change (1950s)**



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# GDP Growth Rates

U.S.A. (annual)



***What is a sustainable growth rate for a large economy?***

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# Critical Elements & Materials

*Necessary for current and emerging technologies  
including research and whose supply is at risk*

## Examples

- In solar cells, energy-efficient displays
- Te solar cells and detectors
- Pt catalysts
- Re superalloys

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## Energy Critical Elements:

							2 <b>He</b> Helium 4.003
							10 <b>Ne</b> Neon 20.1797
13 <b>Al</b> Aluminum 26.981538	14 <b>Si</b> Silicon 28.0855	15 <b>P</b> Phosphorus 30.973761	16 <b>S</b> Sulfur 32.066				
28 <b>Ni</b> Nickel 58.6934	29 <b>Cu</b> Copper 63.546	30 <b>Zn</b> Zinc 65.39	31 <b>Ga</b> Gallium 69.723	32 <b>Ge</b> Germanium 72.61	33 <b>As</b> Arsenic 74.92160	34 <b>Se</b> Selenium 78.96	
46 <b>Pd</b> Palladium 106.42	47 <b>Ag</b> Silver 107.8682	48 <b>Cd</b> Cadmium 112.411	49 <b>In</b> Indium 114.818	50 <b>Sn</b> Tin 118.710	51 <b>Sb</b> Antimony 121.760	52 <b>Te</b> Tellurium 127.60	
78 <b>Pt</b> Platinum 195.078	79 <b>Au</b> Gold 196.96655	80 <b>Hg</b> Mercury 200.59	81 <b>Tl</b> Thallium 204.3833	82 <b>Pb</b> Lead 207.2	83 <b>Bi</b> Bismuth 208.98038	84 <b>Po</b> Polonium [209]	85 <b>At</b> Astatine [210]
65 <b>Tb</b> Terbium 158.92534	66 <b>Dy</b> Dysprosium 162.50	67 <b>Ho</b> Holmium 164.93032	68 <b>Er</b> Erbium 167.26	69 <b>Tm</b> Thulium 168.93421	70 <b>Yb</b> Ytterbium 173.04	71 <b>Lu</b> Lutetium 174.967	



### Securing Materials for Emerging Technologies

A REPORT BY THE APS PANEL ON PUBLIC AFFAIRS & THE MATERIALS RESEARCH SOCIETY



U.S. DEPARTMENT OF ENERGY

# Critical Materials Strategy

December 2011



American Physical Society and the  
Materials Research Society  
February 2011

US Department of Energy  
December 2011

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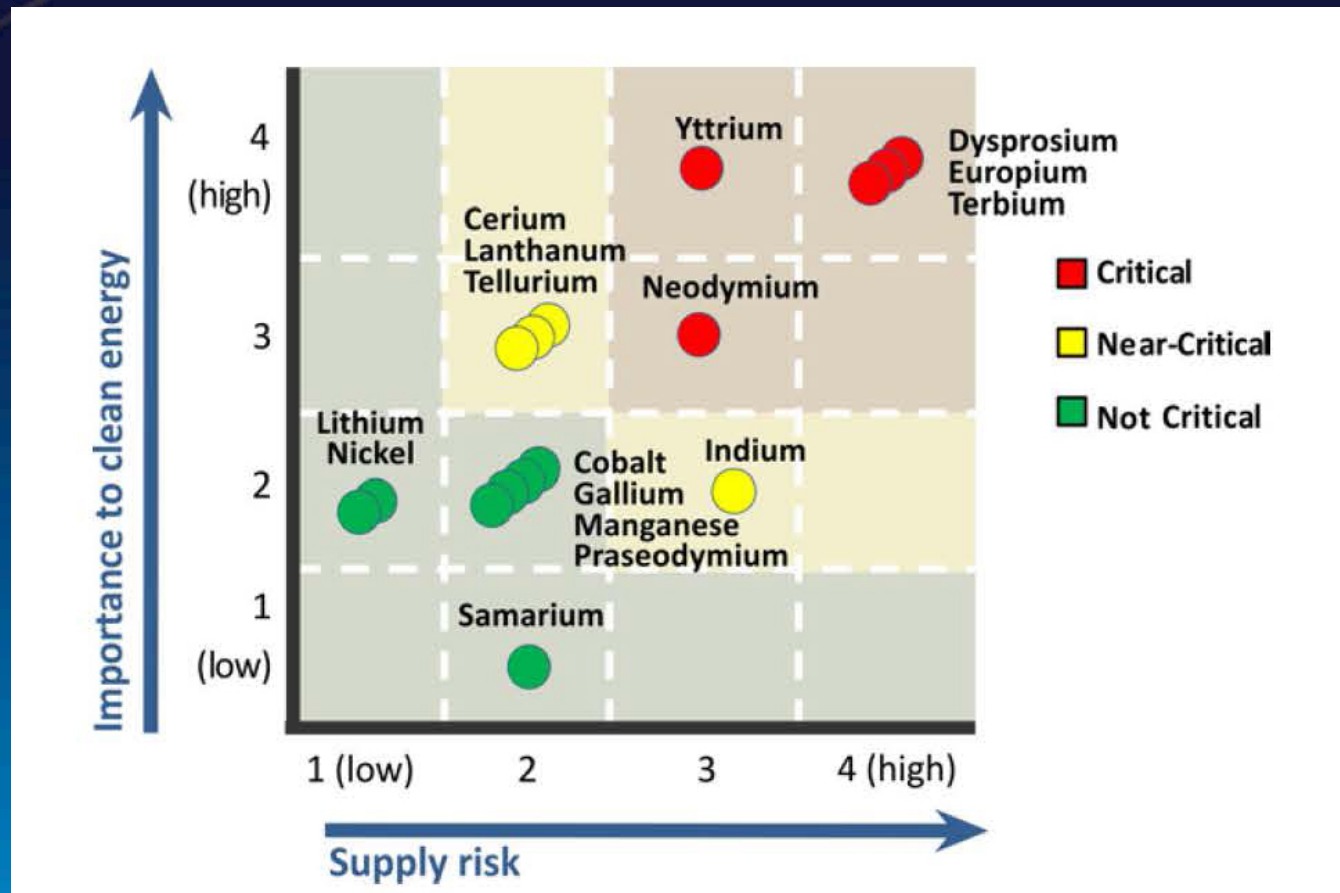


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# US Department of Energy Criticality Assessment 2010-2015

“Short term 2010-2015”

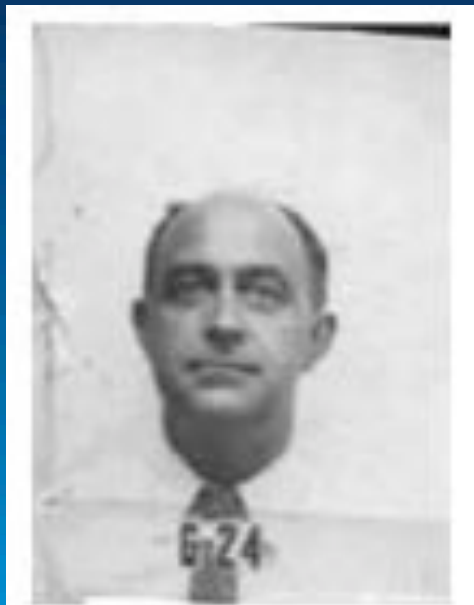


*But doesn't research consume too little to worry...?*

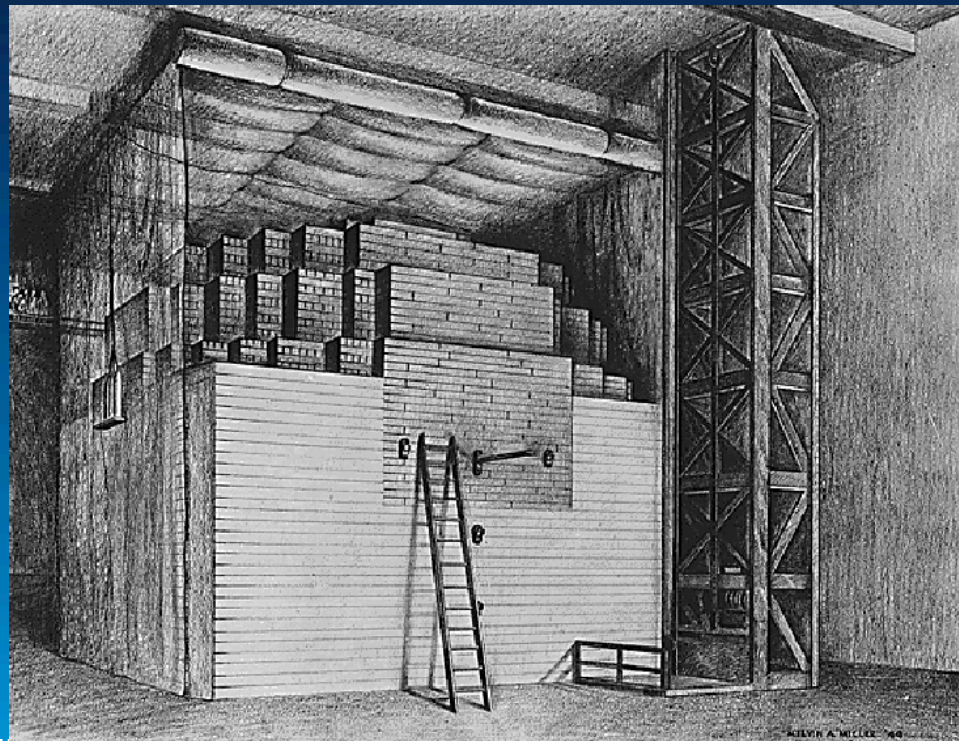
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## 1942: Chicago Critical Elements would include...

- U (natural)
- $^2\text{H}$  ( $\text{D}_2\text{O}$ )
- C (highly pure graphite)



Fermi



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# The APS-MRS set of Energy Critical Elements

1 <b>H</b> Hydrogen 1.01																	2 <b>He</b> Helium 4.00						
3 <b>Li</b> Lithium 6.94	4 <b>Be</b> Beryllium 9.01																	5 <b>B</b> Boron 10.81	6 <b>C</b> Carbon 12.01	7 <b>N</b> Nitrogen 14.01	8 <b>O</b> Oxygen 16.00	9 <b>F</b> Fluorine 19.00	10 <b>Ne</b> Neon 20.18
11 <b>Na</b> Sodium 22.99	12 <b>Mg</b> Magnesium 24.31																	13 <b>Al</b> Aluminum 26.98	14 <b>Si</b> Silicon 28.09	15 <b>P</b> Phosphorus 30.97	16 <b>S</b> Sulfur 32.07	17 <b>Cl</b> Chlorine 35.45	18 <b>Ar</b> Argon 39.95
19 <b>K</b> Potassium 39.10	20 <b>Ca</b> Calcium 40.08	21 <b>Sc</b> Scandium 44.96	22 <b>Ti</b> Titanium 47.87	23 <b>V</b> Vanadium 50.94	24 <b>Cr</b> Chromium 52.00	25 <b>Mn</b> Manganese 54.94	26 <b>Fe</b> Iron 55.85	27 <b>Co</b> Cobalt 58.93	28 <b>Ni</b> Nickel 58.69	29 <b>Cu</b> Copper 63.55	30 <b>Zn</b> Zinc 65.39	31 <b>Ga</b> Gallium 69.72	32 <b>Ge</b> Germanium 72.61	33 <b>As</b> Arsenic 74.92	34 <b>Se</b> Selenium 78.96	35 <b>Br</b> Bromine 79.90	36 <b>Kr</b> Krypton 83.80						
37 <b>Rb</b> Rubidium 85.47	38 <b>Sr</b> Strontium 87.62	39 <b>Y</b> Yttrium 88.91	40 <b>Zr</b> Zirconium 91.22	41 <b>Nb</b> Niobium 92.91	42 <b>Mo</b> Molybdenum 95.94	43 <b>Tc</b> Technetium (98)	44 <b>Ru</b> Ruthenium 101.07	45 <b>Rh</b> Rhodium 102.91	46 <b>Pd</b> Palladium 106.42	47 <b>Ag</b> Silver 107.87	48 <b>Cd</b> Cadmium 112.41	49 <b>In</b> Indium 114.82	50 <b>Sn</b> Tin 118.71	51 <b>Sb</b> Antimony 121.76	52 <b>Te</b> Tellurium 127.60	53 <b>I</b> Iodine 126.90	54 <b>Xe</b> Xenon 131.29						
55 <b>Cs</b> Cesium 132.91	56 <b>Ba</b> Barium 137.33	57 <b>La</b> Lanthanum 138.91	72 <b>Hf</b> Hafnium 178.49	73 <b>Ta</b> Tantalum 180.95	74 <b>W</b> Tungsten 183.84	75 <b>Re</b> Rhenium 186.21	76 <b>Os</b> Osmium 190.23	77 <b>Ir</b> Iridium 192.22	78 <b>Pt</b> Platinum 195.08	79 <b>Au</b> Gold 196.97	80 <b>Hg</b> Mercury 200.59	81 <b>Tl</b> Thallium 204.38	82 <b>Pb</b> Lead 207.2	83 <b>Bi</b> Bismuth 208.98	84 <b>Po</b> Polonium (209)	85 <b>At</b> Astatine (210)	86 <b>Rn</b> Radon (222)						
87 <b>Fr</b> Francium (223)	88 <b>Ra</b> Radium (226)	89 <b>Ac</b> Actinium (227)	101 <b>Rf</b> Rutherfordium (261)	102 <b>Db</b> Dubnium (262)	103 <b>Sg</b> Seaborgium (266)	104 <b>Bh</b> Bohrium (264)	105 <b>Hs</b> Hassium (269)	106 <b>Mt</b> Meitnerium (268)															
			58 <b>Ce</b> Cerium 140.12	59 <b>Pr</b> Praseodymium 140.91	60 <b>Nd</b> Neodymium 144.24	61 <b>Pm</b> Promethium (145)	62 <b>Sm</b> Samarium 150.36	63 <b>Eu</b> Europium 151.96	64 <b>Gd</b> Gadolinium 157.25	65 <b>Tb</b> Terbium 158.93	66 <b>Dy</b> Dysprosium 162.50	67 <b>Ho</b> Holmium 164.93	68 <b>Er</b> Erbium 167.26	69 <b>Tm</b> Thulium 168.93	70 <b>Yb</b> Ytterbium 173.04	71 <b>Lu</b> Lutetium 174.97							
			90 <b>Th</b> Thorium 232.04	91 <b>Pa</b> Protactinium 231.04	92 <b>U</b> Uranium 238.03	93 <b>Np</b> Neptunium (237)	94 <b>Pu</b> Plutonium (244)	95 <b>Am</b> Americium (243)	96 <b>Cm</b> Curium (247)	97 <b>Bk</b> Berkelium (247)	98 <b>Cf</b> Californium (251)	99 <b>Es</b> Einsteinium (252)	100 <b>Fm</b> Fermium (257)	101 <b>Md</b> Mendelevium (258)	102 <b>No</b> Nobelium (259)	103 <b>Lr</b> Lawrencium (262)							

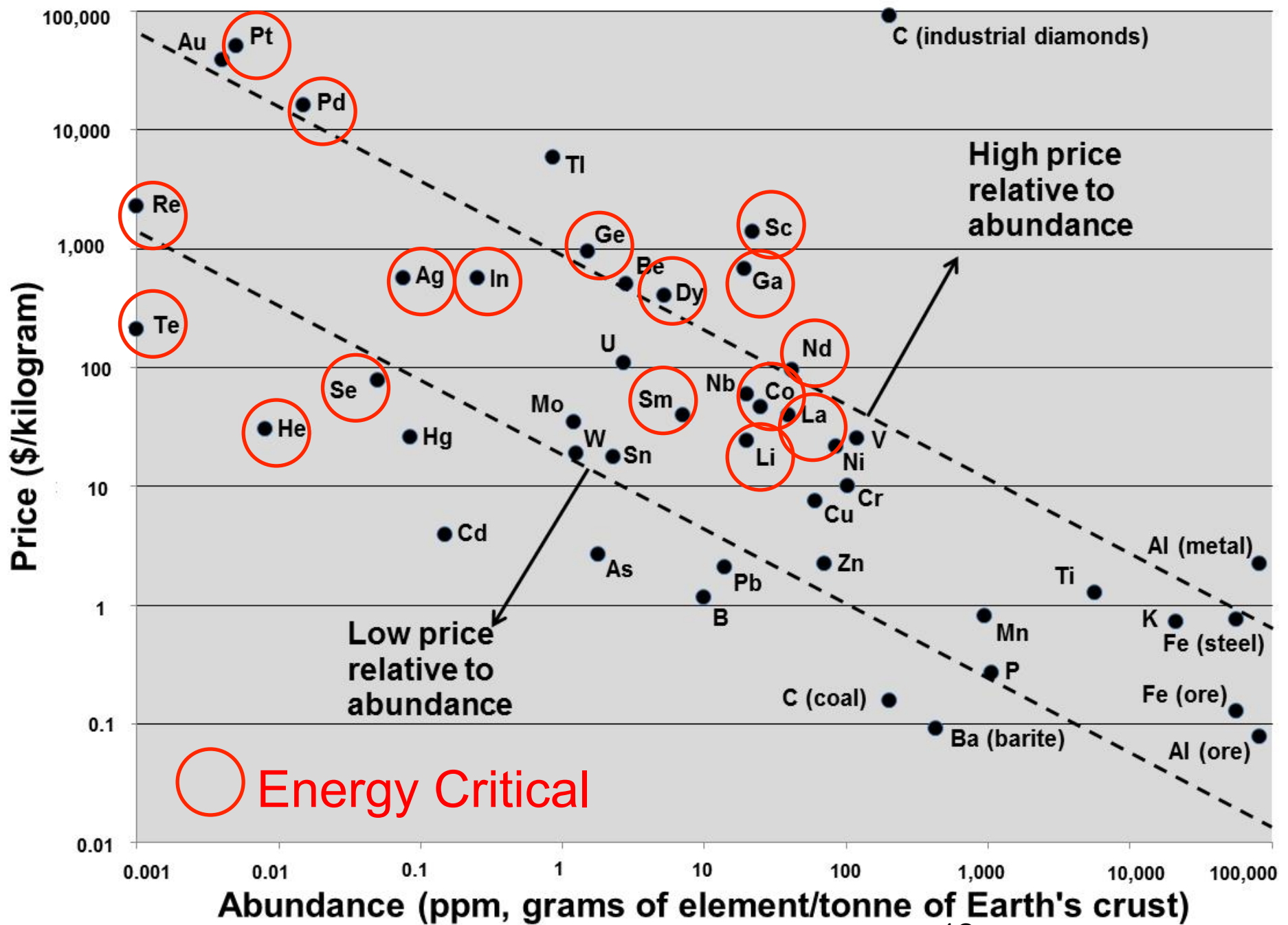
Platinum Group Elements

Other ECEs

Rare Earth Elements

Photovoltaic ECEs





Source of data: USGS, EIA, CRC Handbook of Chemistry and Physics, others



## Conflict minerals

- Tin
- Tantalum
- Tungsten
- Gold



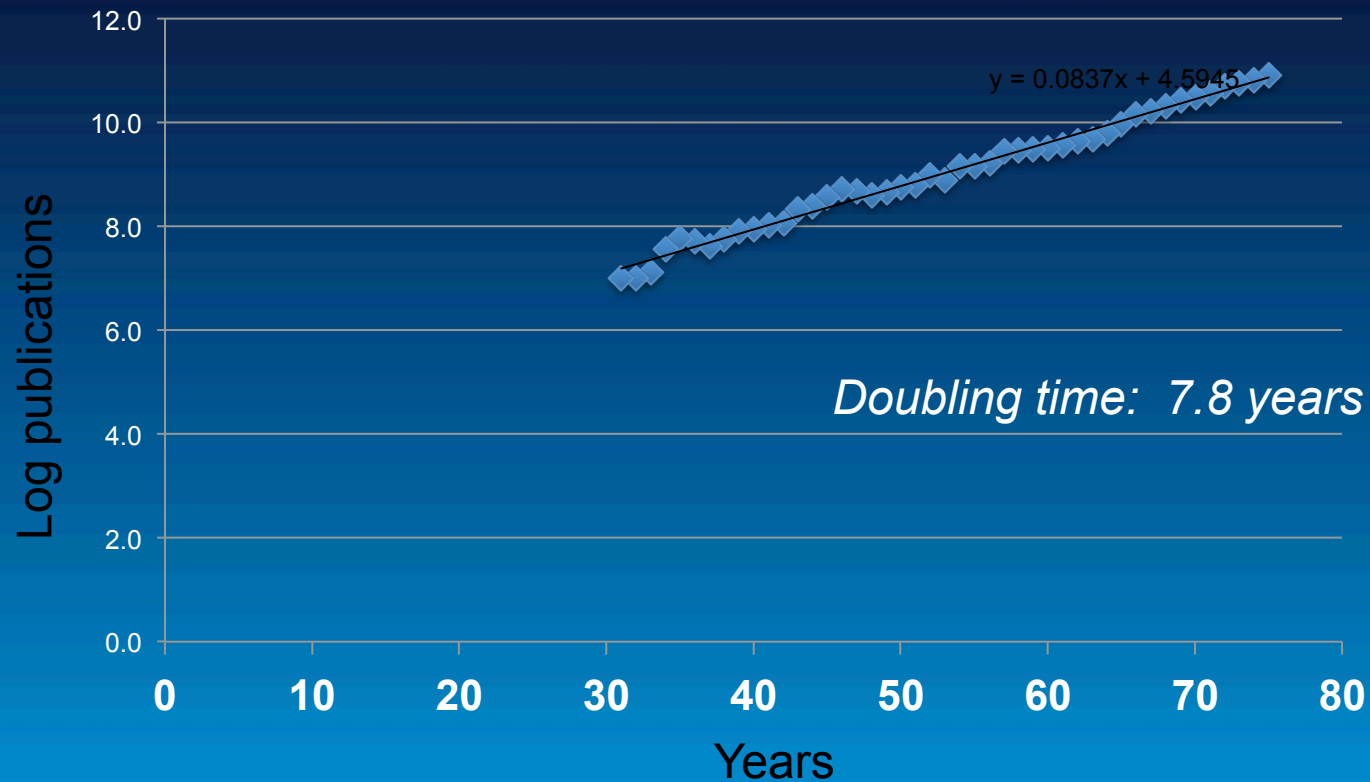
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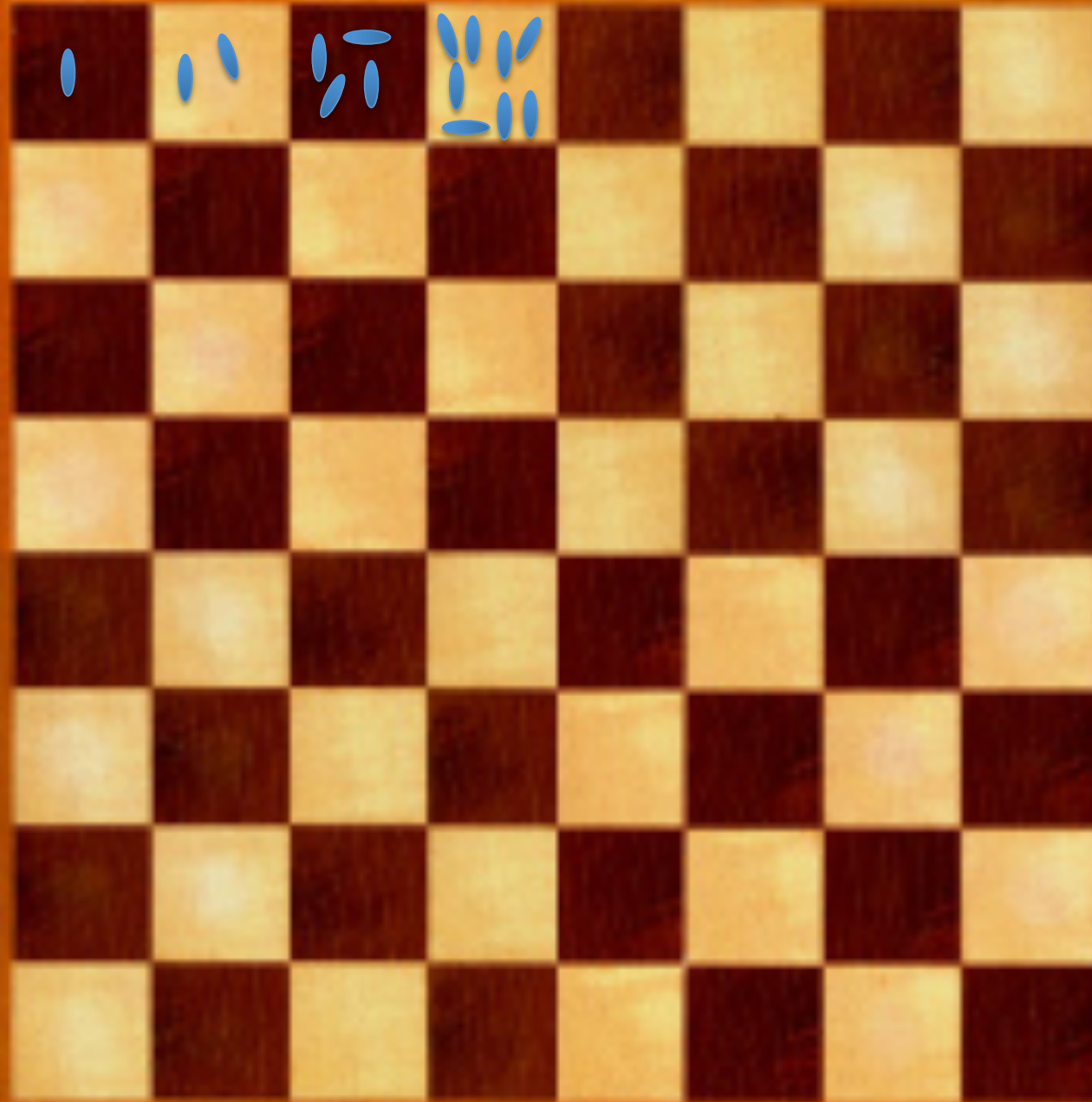
# Exponential growth in composites research

## All Composites



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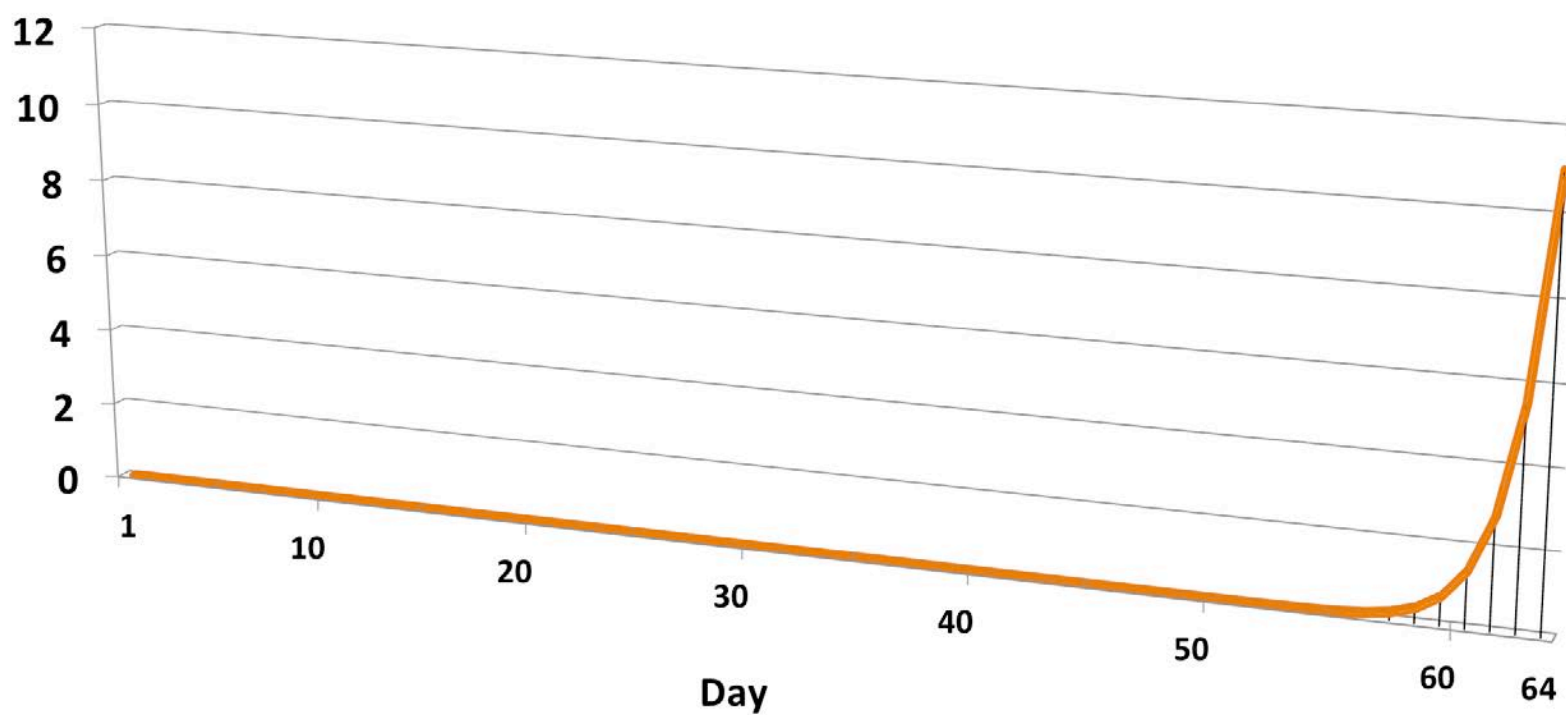
Day 4



amos  
LABORATORY  
1943

NSA  
National Nuclear Security Administration  
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## Rice as fraction of world production (annual)

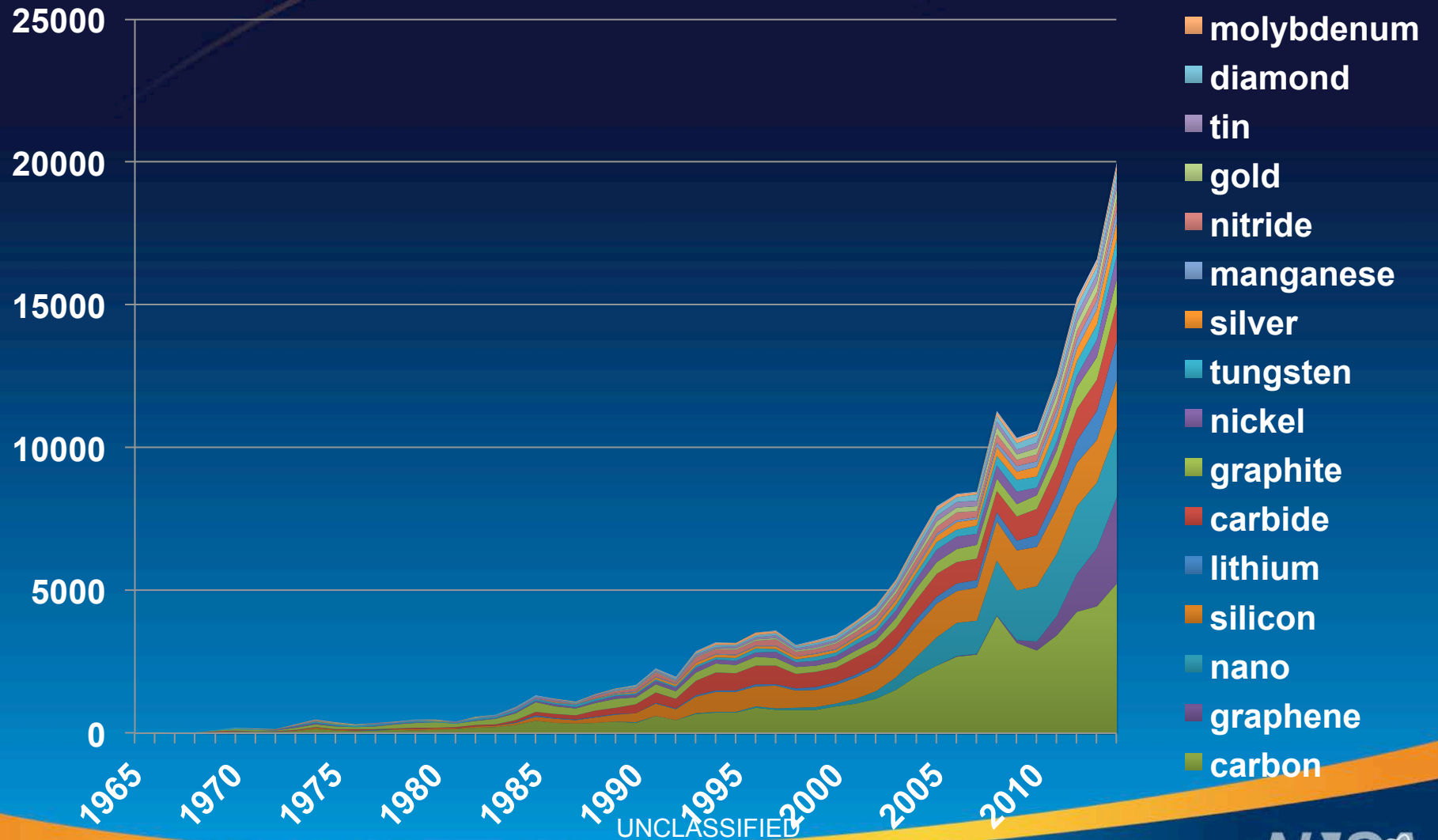


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$$y(t) = y_0 e^{rt}$$

## Number of papers involving composites



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# Faster, Sustainable and More Inclusive Growth

An Approach to the Twelfth Five Year Plan

## Faster, Sustainable and More Inclusive Growth

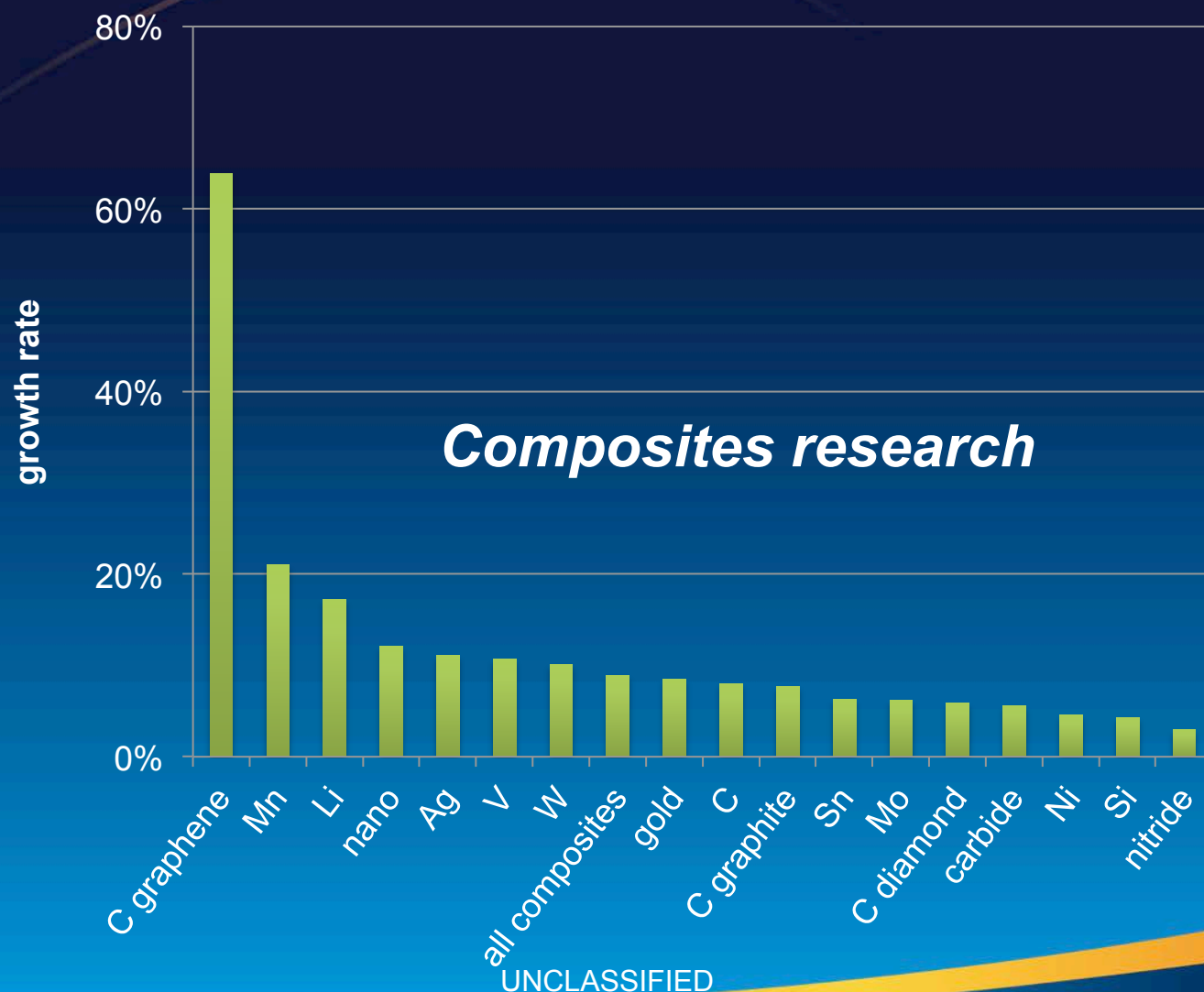
An Approach to the Twelfth Five Year Plan



Government of India  
Planning Commission  
October, 2011

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# publication growth (%/yr)





# The APS-MRS-ACS set of Energy Critical Elements: Helium Case Study

1 H Hydrogen 1.01																	2 He Helium 4.00						
3 Li Lithium 6.94	4 Be Beryllium 9.01																	5 B Boron 10.81	6 C Carbon 12.01	7 N Nitrogen 14.01	8 O Oxygen 16.00	9 F Fluorine 18.99	10 Ne Neon 20.18
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19 K Potassium 39.10	20 Ca Calcium 40.08	21 Sc Scandium 44.96	22 Ti Titanium 47.87	23 V Vanadium 50.94	24 Cr Chromium 52.00	25 Mn Manganese 54.94	26 Fe Iron 55.85	27 Co Cobalt 58.93	28 Ni Nickel 58.69	29 Cu Copper 63.55	30 Zn Zinc 65.39	31 Ga Gallium 69.72	32 Ge Germanium 72.61	33 As Arsenic 74.92	34 Se Selenium 78.96	35 Br Bromine 79.90	36 Kr Krypton 83.80						
37 Rb Rubidium 85.47	38 Sr Strontium 87.62	39 Y Yttrium 88.91	40 Zr Zirconium 91.22	41 Nb Niobium 92.91	42 Mo Molybdenum 95.94	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.91	46 Pd Palladium 106.42	47 Ag Silver 107.87	48 Cd Cadmium 112.41	49 In Indium 114.82	50 Sn Tin 118.71	51 Sb Antimony 121.76	52 Te Tellurium 127.60	53 I Iodine 126.90	54 Xe Xenon 131.29						
55 Cs Cesium 132.91	56 Ba Barium 137.33	57 La Lanthanum 138.91	72 Hf Hafnium 178.49	73 Ta Tantalum 180.95	74 W Tungsten 183.84	75 Re Rhenium 186.21	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.97	80 Hg Mercury 200.59	81 Tl Thallium 204.38	82 Pb Lead 207.2	83 Bi Bismuth 208.98	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)						
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			58 Ce Cerium 140.12	59 Pr Praseodymium 140.91	60 Nd Neodymium 144.24	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.96	64 Gd Gadolinium 157.25	65 Tb Terbium 158.93	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93	68 Er Erbium 167.26	69 Tm Thulium 168.93	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.97							
			90	91	92	93	94	95	96	97	98	99	100	101	102	103							

# Helium:

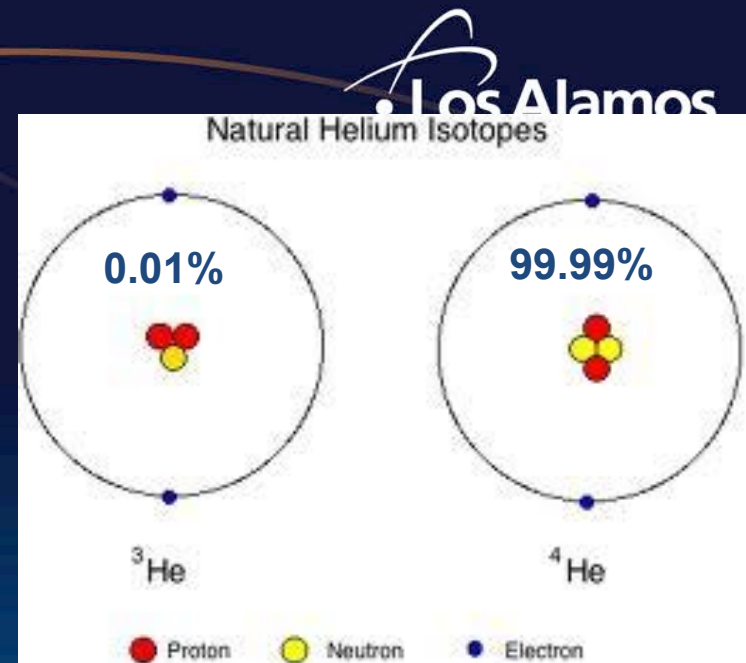
## A New APS-MRS-ACS Critical Materials Study (2016)

- He-4 second only to H in universe
- Created in Earth by radioactive decay
- Collected from natural gas wells
  - Usually just released
- Stockpiled in Texas mines for:
  - Military dirigibles (1925 et seq)
  - Liquid-fueled rockets flush (1957 et seq)
  - Welding, semiconductor manufacture
  - Cryogenics
  - Particle accelerators
  - Medical MRI
  - Future nuclear reactor coolant
  - Condensed matter research
  - Quantum fluids physics

■ **Not gravitationally bound to Earth**

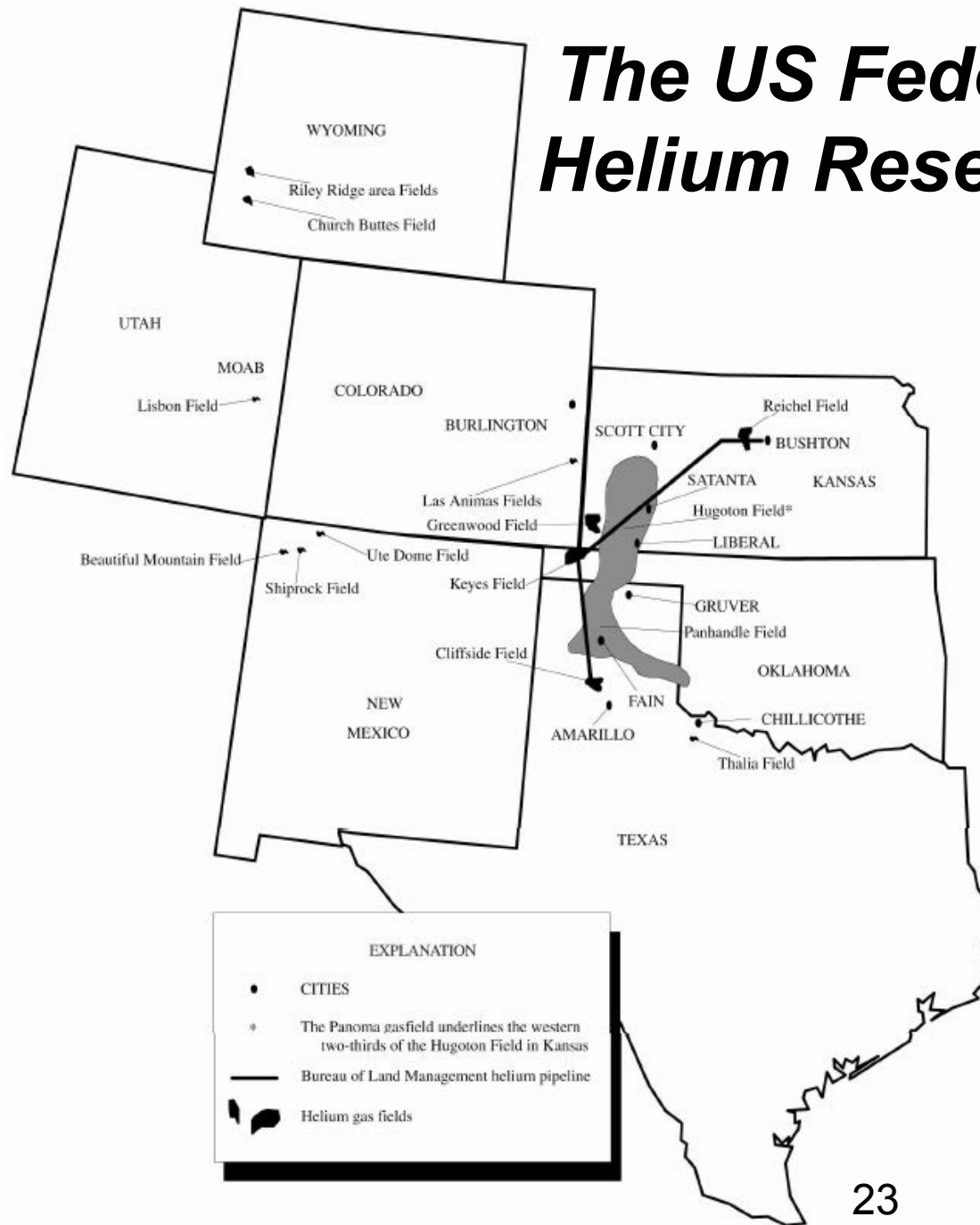
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# The US Federal Helium Reserve

**Lamos**  
LABORATORY  
1943



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# *Intermediate Policy Solutions*



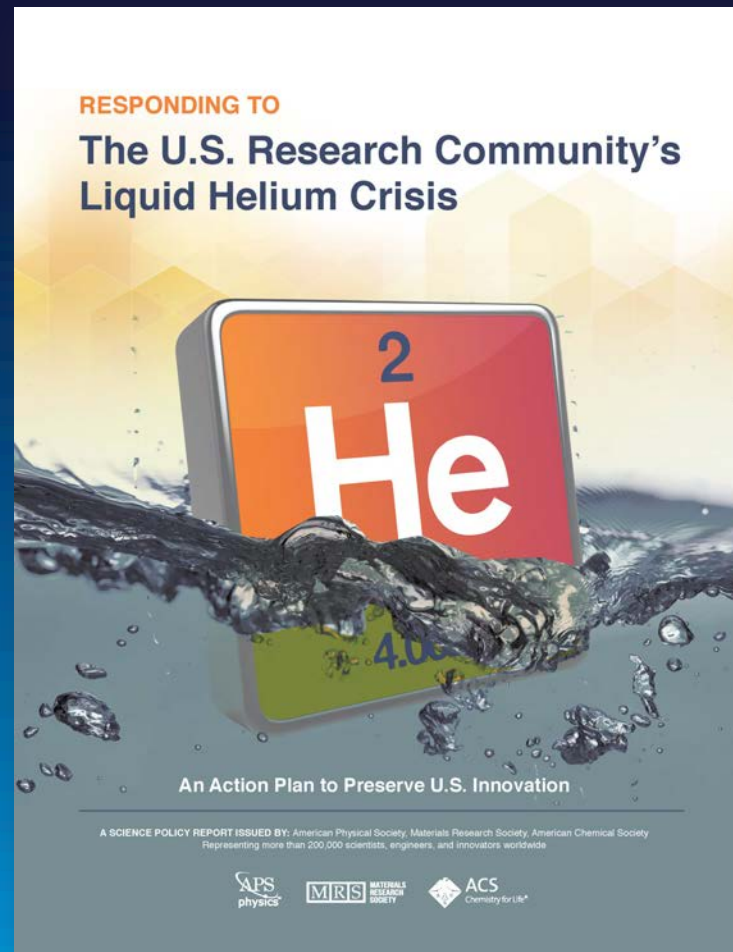
- In 1996, US Congress had determined to sell off the Federal Helium Reserve by 2020.
- Lawmakers woke up and passed the Helium Stewardship Act in 2013

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# APS Helium Study

## October 2016



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# APS-MRS-ACS He Panel



- Simon R. Bare, Co-Chair, SLAC National Accelerator Laboratory
- Michael Lilly, Co-Chair, Sandia National Lab
- Janie Chermak, University of New Mexico
- Rod Eggert, Colorado School of Mines
- William Halperin, Northwestern University
- Scott Hannahs, National High Magnetic Field Lab
- Sophia Hayes, Washington University in St. Louis
- Michael Hendrich, Carnegie Mellon University
- Alan Hurd, Los Alamos National Laboratory
- Mike Osofsky, Naval Research Laboratory
- Cathy Tway, The Dow Chemical Company

## REPORT ADVISORS

*Damon Dozier, Materials Research Society*

*Ryan Davison, American Chemical Society*

## APS STAFF

*Francis Slakey, Associate Director of Public Affairs*

*Mark Elsesser, Senior Policy Analyst*

*Jeanette Russo, OPA Programs Manager*

*Ronald Lipscomb, Science Policy Intern*

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# He study recommendations

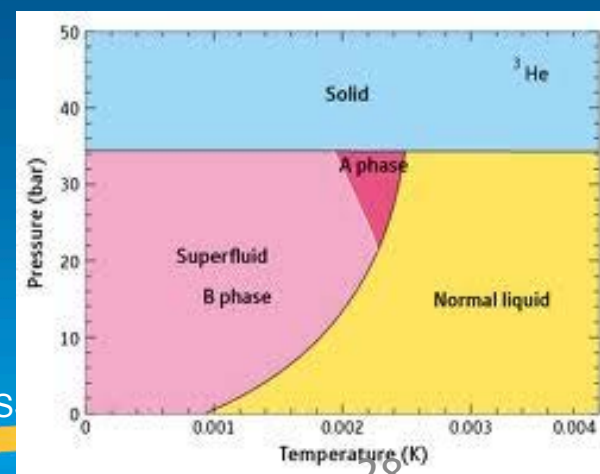
- 1. The **White House (OSTP) and OMB** together should develop guidance to federal **agencies**, which use or support the use of helium, on establishing plans to conserve helium without compromising their mission or the vitality of their research and development programs. The **National Science Foundation's DMR to fund small-scale liquefiers** for researchers...
- 2. **Congress** should mandate that a portion of the monies raised through the sales of crude helium from the Federal Helium Reserve be used to help finance the capital investment in equipment that reduces academic researchers' helium consumption. Executive Summary
- ✓ 3. The Bureau of Land Management (**BLM**) should clarify and then widely publicize its regulations regarding the in-kind helium program to explain that federal grantees are eligible for the program...
- ✓ 4. **BLM** should establish a royalty in-kind program for helium. A portion of the helium extracted from federal lands should be marked as in-kind and sold to vendors based on the current and established pricing methodology. Vendors would be required to refine and resell the helium to federal end-users.
- ✓ 5. The **professional scientific societies** should develop a methodology to help academic researchers determine if – given helium costs, scientific requirements and existing infrastructure – it is financially beneficial to make a capital investment in equipment to reduce their helium usage. The societies should facilitate contact between interested researchers worldwide and manufacturers of helium liquefiers and recyclers. **"Matchmaking website"**

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# He-3: A case study of colliding priorities

- Formed by decay of tritium
- **Only one practical global source:** the refurbishment and dismantlement of nuclear weapons (US and Russia)
- Applications
  - Cryogenics!
  - Quantum fluids research
  - Neutron detection
  - Medicine
  - Borehole logging for prospecting

**Tritium is used in nuclear stockpiles**  
**Also used in exit signs, gun sights.**



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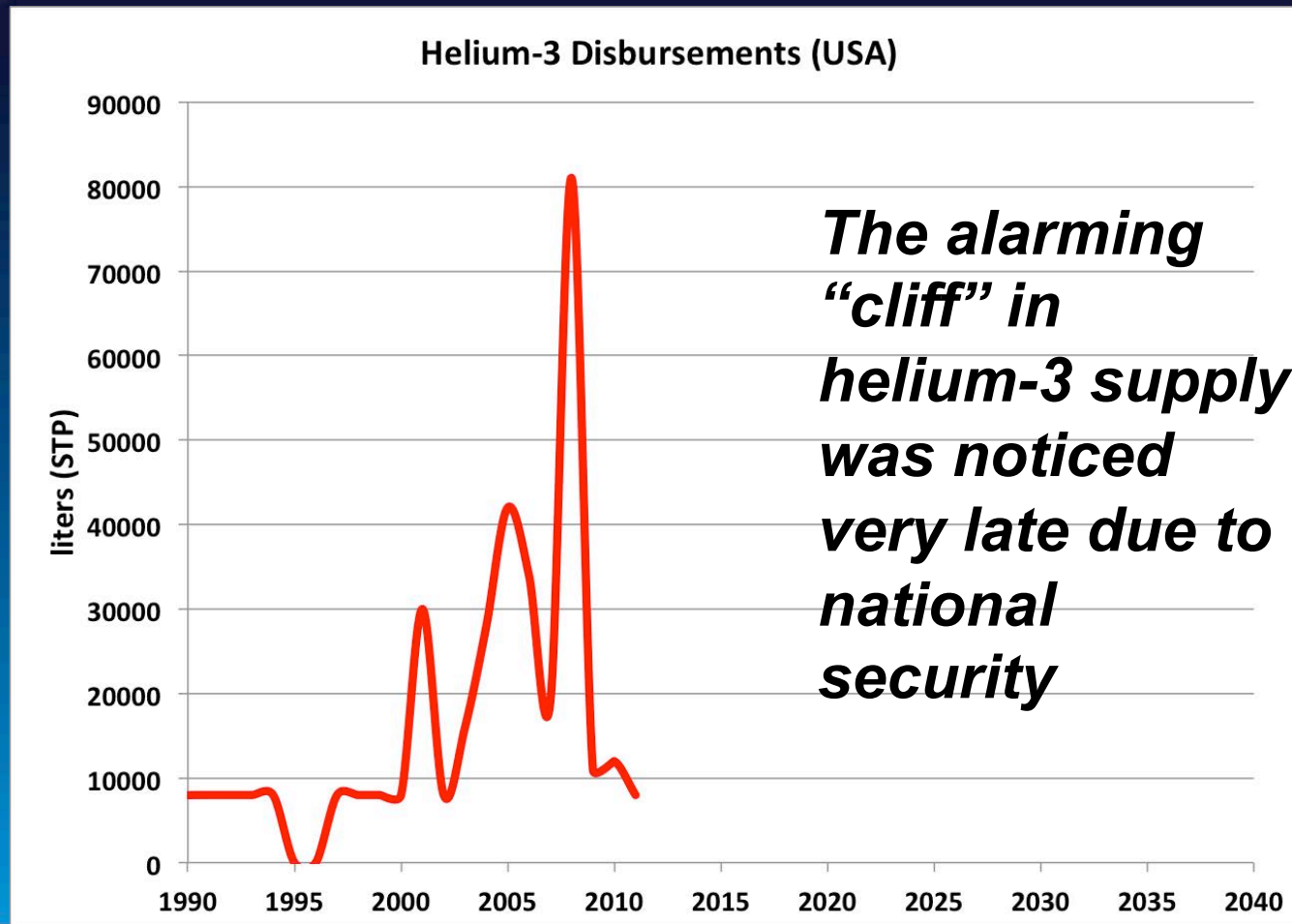
# Neutron Detectors for the US Department of Homeland Security (DHS)...

- ordered He-3-based neutron detectors for deployment at shipping centers to detect nuclear materials
- over-subscribed the He-3 supply by squeezing out research needs
  - Neutron scattering facilities around the world starved for detectors
  - Crash programs created for alternative detectors based on B-10 and Li-6.

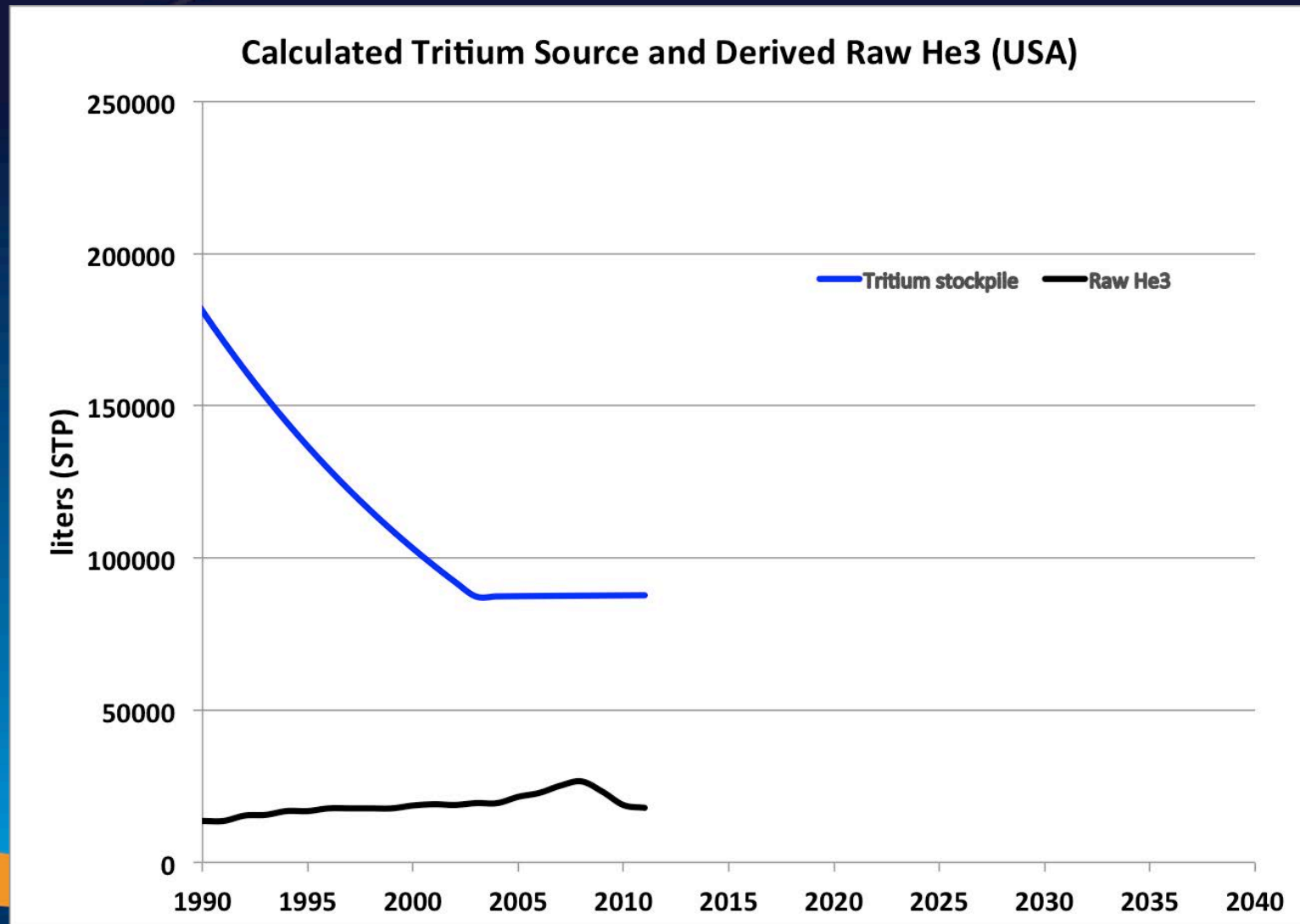


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# He-3 disbursements in US (from policy statements, usage)



# Assumed tritium mother reserve

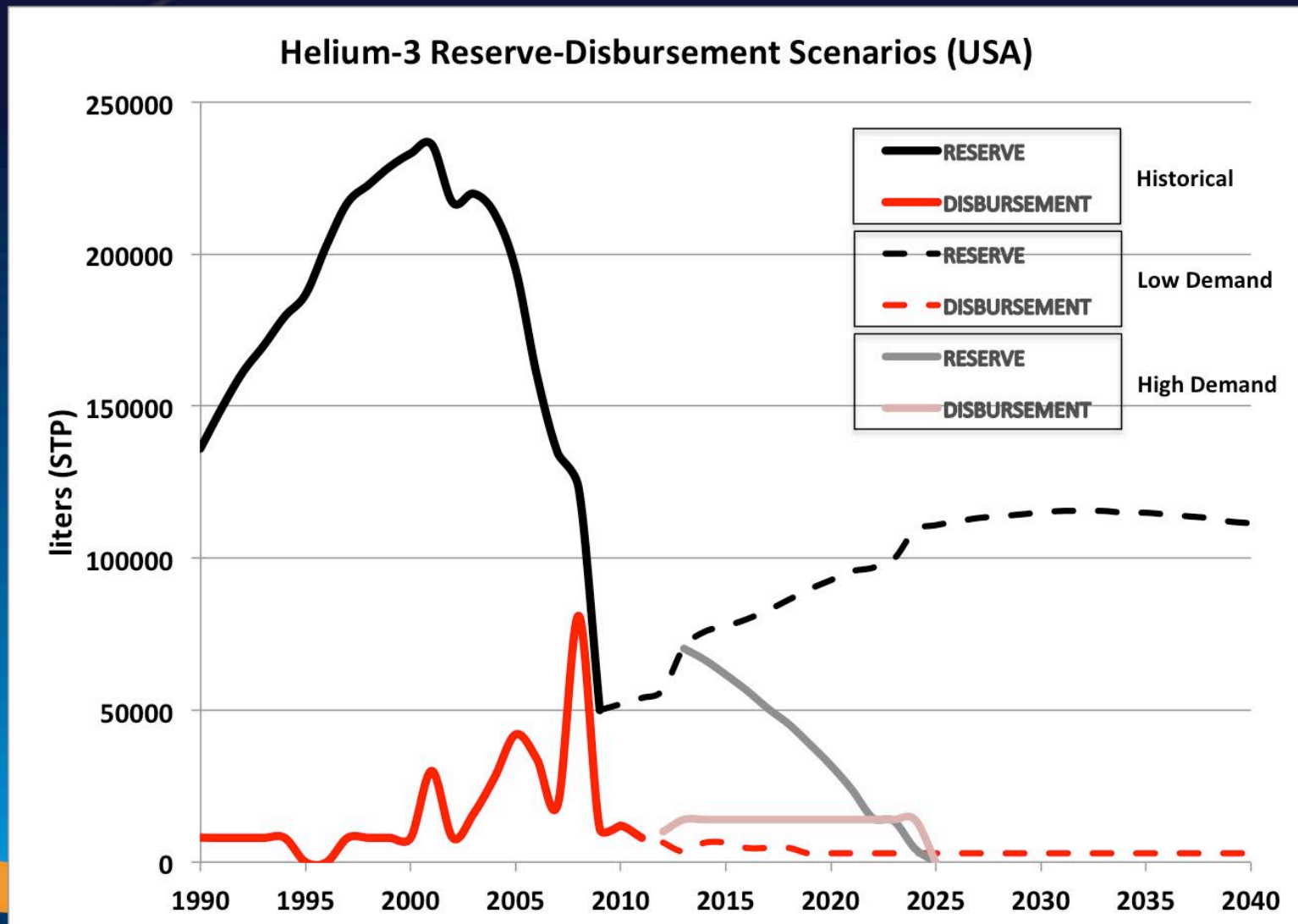


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# Low and High Demand He-3 Scenarios

[Hurd and Kouzes, Eur Phys J 2014]





# Materials Research

## A Network of International User Facilities



- x rays
- neutrons
- nanoscience
- microscopy & magnets

*~\$35B in capital facilities...*  
*only about half are shown...*

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# SESAME is a remarkable science diplomacy success



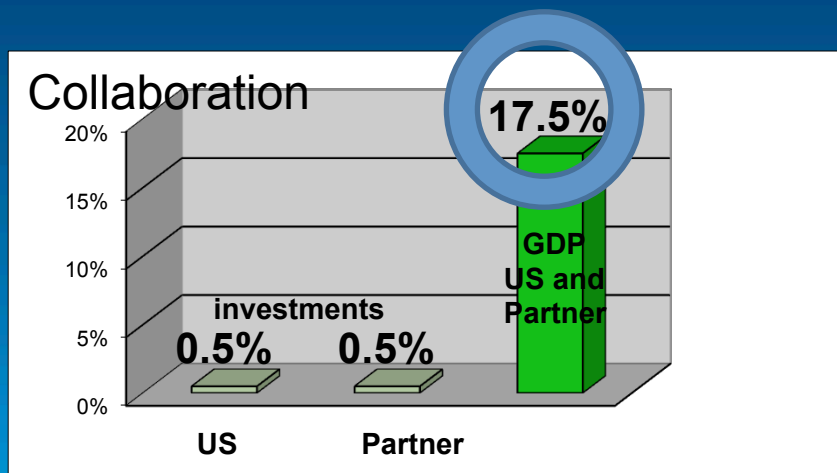
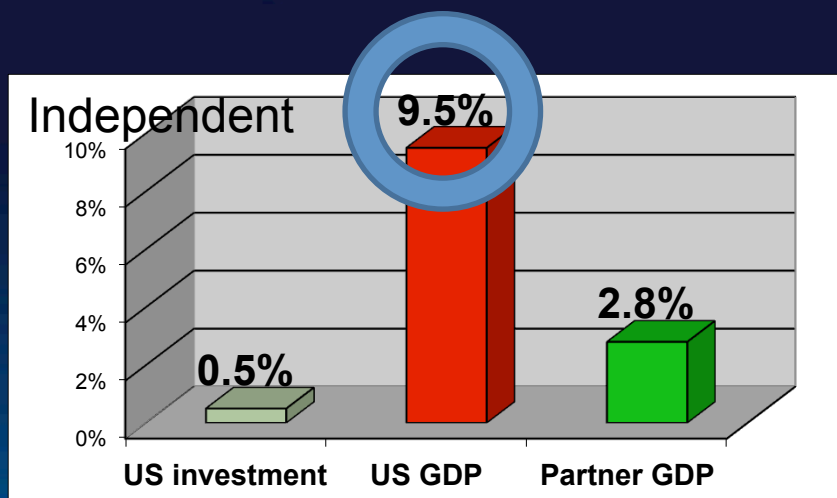
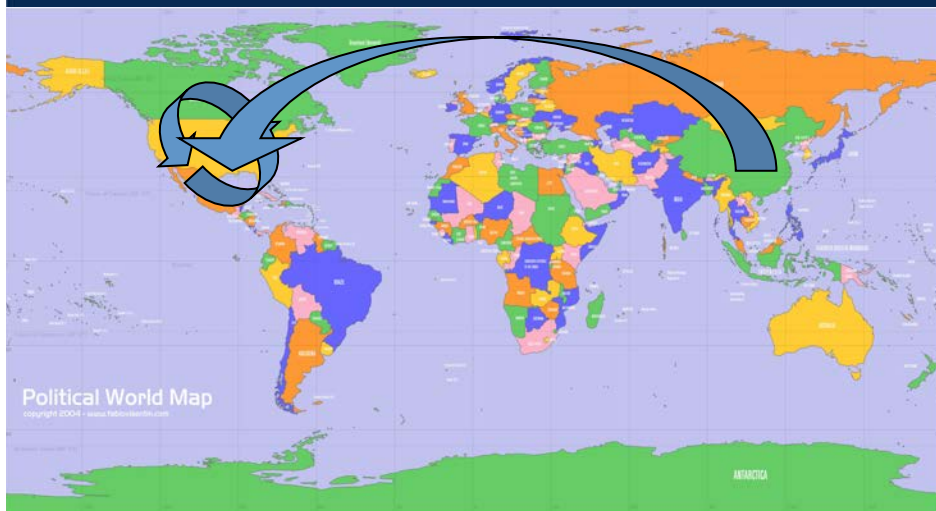
**SESAME Members**

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**SESAME**  
SYNCHROTRON-LIGHT FOR EXPERIMENTAL  
SCIENCE AND APPLICATIONS IN THE MIDDLE EAST:



# Collaboration “spillover” benefits (Coe & Helpman 2007)



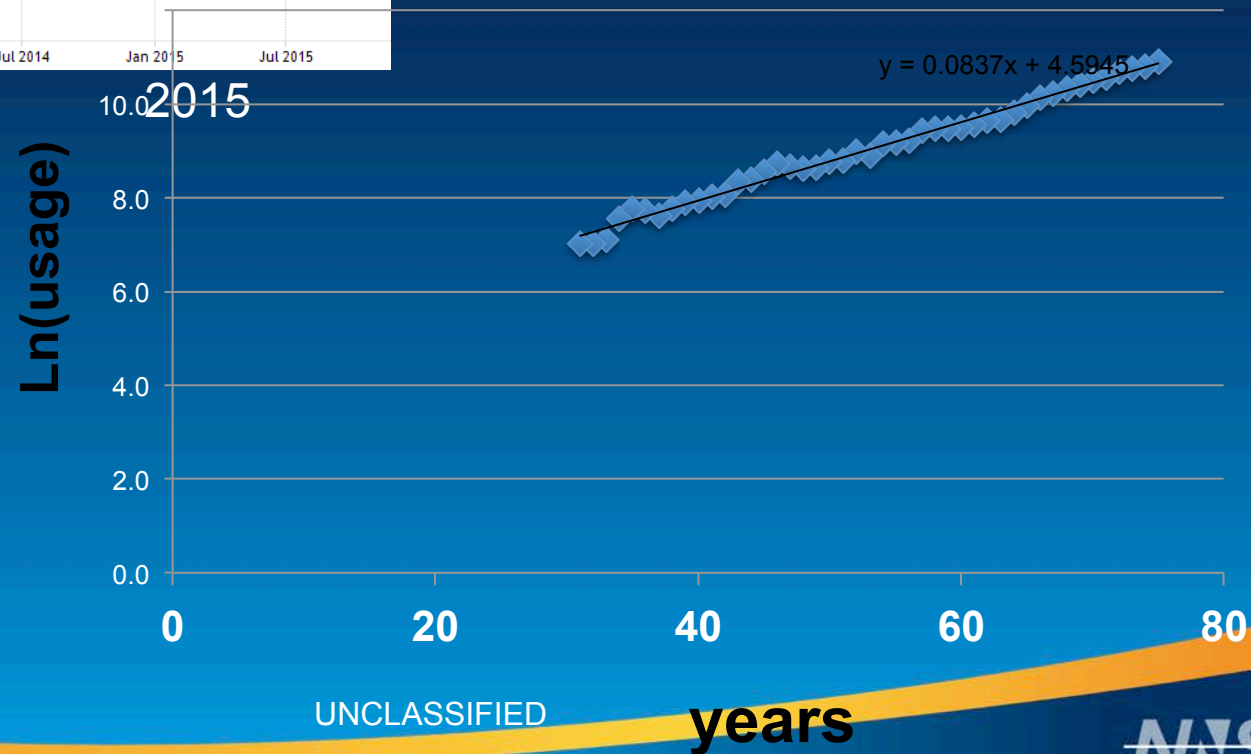
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# Can we beat the math?



All Composites



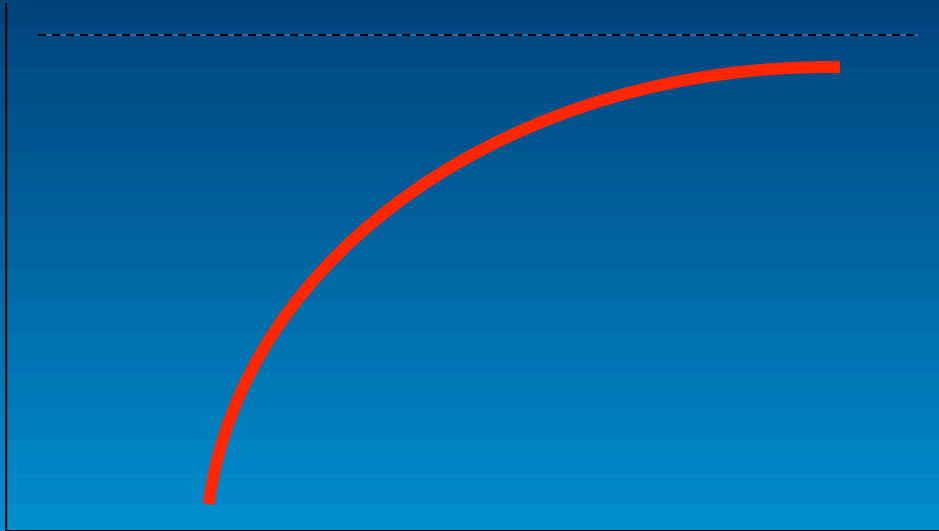
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# Sustained Availability (A. Bartlett)

$$P = P(0) \exp(-kt)$$

Supply  
TOTAL



- World petroleum will last 40 years at present rates of consumption, say
- Let  $k = 1/40 = 0.025$
- Global use of petroleum declines 2.5% per year
- **The petroleum will last forever!**
- Decay curve has a “half life” of 28 years.
- **At every point on the decaying production curve, the life expectancy of the then remaining resource will be 40 years at the then current rate of production.**

time

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# *Obligations*

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