Committee on Natural Resources

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Testimony on "Helium Supply Shortages Impacting Our Economy, Defense and Manufacturing"
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1. Introduction

By way of introduction, I obtained my undergraduate degree at Columbia College (1971), and my PhD in Physics at UC Berkeley (1976). Following a faculty position at the University of Southern California, I joined Princeton University as Professor of Physics in 1985. In 2003, I was given a chaired professorship. I currently serve as the director of the Princeton Center for Complex Materials. I have coauthored ~250 publications in physics journals in the fields of superconductivity, magnetism and new quantum phenomena in solids, and have supervised 29 PhD candidates. In 1976, I co-discovered the phenomenon of "sliding charge density waves", a novel form of electrical conduction in solids. In 2006, I was awarded the Kamerlingh Onnes prize for research on high-temperature superconductivity. I became a member of the American Academy of Arts and Sciences in 2006, and the U.S. National Academy of Sciences in 2012. My research has been supported primarily by the National Science Foundation, DARPA, Office of Naval Research, and Army Research Office. I am a naturalized U.S. citizen.

2. The scope of liquid helium usage in scientific research

Liquid helium is vitally important for the two largest subfields of physics, condensed-matter physics and high-energy physics. I will confine my remarks to the former subfield (aside from a brief comment on the Higgs boson). Condensed-matter physicists are primarily interested in the quantum properties of solids and liquids. Today, they constitute the largest contingent of U.S. physicists (~40% of American Physical Society membership). Within this population, roughly a quarter ("experimentalists" including me) routinely use liquid helium to reach low temperatures. In my group at Princeton, we use roughly 10,000 to 15,000 liters of liquid helium each year. These numbers are typical of the 7-10 groups that are major liquid helium users at Princeton. Throughout the U.S., there are ~30 university campuses with annual usage comparable to Princeton's, and roughly 30 more with lower usage rates. In addition, the national user facilities -- primarily the National High Magnetic Field Labs in Tallahassee and Los Alamos, the Brookhaven National Lab., and Argonne National Lab. -- are very large users of liquid helium (720,000 liters per year at Tallahassee alone). This large research community, nurtured over the past 4-5 decades, has made the U.S. the dominant world leader in the important fields of condensed-matter physics, solid state chemistry, and materials science. Liquid helium nurtures the health of this community. The U.S. research community has been adversely affected by the dramatic helium shortages in the past 4 years and the steep increase in helium costs.

3. Liquid helium's role in enabling discovery and sustaining national scientific health

Liquid helium plays a critically important role in stimulating and enabling scientific discovery in condensed-matter and low-temperature physics. Since the 1950's, nearly all the discoveries pertaining to the electronic properties of solids have been enabled by liquid-helium cooling. The list includes all the several 1000's of known superconductors, including the high-Tc superconductors, the quantum Hall effect, and graphene physics. Of the 31 Nobel prizes awarded in physics since 1980, *roughly a third* recognized fundamental discoveries in condensed-matter physics or low-temperature physics (see Appendix). These discoveries were either directly related to liquid helium or enabled by it in an essential way.

The Higgs boson. Liquid helium is also crucial for high-energy physics (the next largest U.S. contingent in physics) in a supporting role. Intense public interest has been stimulated by the recent report of possible discovery of the "Higgs boson", a fundamental particle long predicted by the Standard Model of particle physics. In the Large Hadron Collider (LHC), where the experiments were carried out, charged particles are accelerated to extremely high energies and then allowed to collide. The evidence is obtained by examining the collision products. Because superconducting magnets are needed to force the particles to stay in a circular path, liquid helium has been essential for this historic discovery, and will be as well for future discoveries at the LHC.

The 2 main reasons why liquid helium is vital for research are:

1) Helium is the only fluid available for cooling samples to temperatures close to absolute zero. All objects follow the universal laws of quantum mechanics. However, at room temperature, large thermal agitations of molecules and atoms largely obscure or destroy the manifestations of quantum physics. Hence quantum behavior seems bizarre and unfamiliar to all of us. Cooling a sample suppresses the thermal agitations, allowing the quantum phenomena to become apparent. Put more directly, liquid helium is the "royal road" to discovery.

2) Helium is used to cool the superconducting wires in superconducting magnets. At present, superconducting magnets using niobium-tin (and tentatively high-Tc cuprates) provide the only known means for producing intense magnetic fields over human-sized volumes. They have to be cooled to 4 Kelvin above absolute zero to remain superconducting. With increasing demands worldwide (in research, MRI machines and in future transport), the demand for liquid helium is expected to rise sharply.

To mix metaphors, we may say that liquid helium is the vital "oxygen" that nourishes the large, dynamic U.S. research community. Disrupting this vital flow will deliver a crippling body blow to a large segment of the community, and jeopardize the leadership role of the U.S. in the coming decades. Increasingly, the pre-eminence of the U.S. in this field of physics has come under stiff challenges from groups in Germany, Japan, Netherlands, China and S. Korea. These countries have steeply increased their investments in these areas and "grown" a new generation of physicists, mostly trained in the U.S. The investment stems from the universal consensus that, in contrast to many other fundamental scientific areas, the results here underpin important future technologies.

In an increasingly flat world, it is prudent for the U.S. to safeguard the availability of this valuable national resource. From the R&D viewpoint, strong fluctuations in the price of helium or in the supply would be very harmful to the U.S. national interest.

4. Benefits to Society

For brevity, I describe two current major areas of impact.

Superconductivity. Superconductors are metals that can carry a very large electrical current without producing heat when cooled below a certain "critical" temperature. This "magical" ability is exploited in MRI (magnetic resonance imaging) machines widely used in hospitals for whole-body scans. The magnetic field is produced by currents carried in superconducting wires cooled by liquid helium. In the U.S., this application currently accounts for ~30% of the national consumption. In addition, superconductors are also used as sensitive detectors of weak magnetic fields. Their exquisitely high sensitivities are ideal for the detection of weak seismic ground shifts, near active faults.

Solid-state electronics. Future historians may well identify the transistor as one of the most transformative products derived from physics in our era. Its rapid development led to the explosive growth of solid-state electronics, integrated chip technology, and the rapid miniaturization of transistors. These developments have altered every facet of society that relies on electronics and computers. Transformative inventions like the transistor do not happen in an intellectual vacuum. The ideas that led to the invention and continued improvement are intricately woven with research themes in low-temperature physics. While cryogenics played a minor role in the original invention of the transistor at Bell Labs, the continued growth of the field in the U.S. has been stimulated and driven by experiments carried out at cryogenic temperatures. For example, the rapid improvement in the performance of transistors based on the semiconductor gallium arsenide resulted directly from 20 years of fundamental research on the behavior of electrons at very low temperatures in intense magnetic fields (the "quantum Hall effect"). The synergistic and symbiotic relations between the fundamental research activities and engineering progress have led to transformative improvements in the performance of these devices (GaAs transistors outperform transistors based on silicon, for e.g. in sheer speed, and in harsh environments as "hardened transistors").

5. The Future

The following are possible future applications of discoveries enabled by research using liquid helium. In some cases, helium played an enabling role in the original discovery, but is unlikely to be used in the final implementation because of cost.

Superconductors. There is increasing concern that the national power grid is dangerously unstable to local fluctuations in demand. Large superconducting coils can be used to stabilize the grid by providing a large inductive response.

In many regions, power shortages arise because of severe bottlenecks for transmission cables. Recent "real-world" demonstrations have shown that high-Tc superconductors cables can triple power transmission through these bottlenecks.

The efficient distribution of electrical power between energy-rich regions (wind farms in Texas) and energy-hungry regions (New York) is increasingly problematical. An ambitious scheme to implement this using high-Tc superconductors, "The Tres Amigas Superstation," has been proposed for a site near Clovis, New Mexico, with construction to begin in 2013.

Superconductors have the potential for transforming transport. Magnetic levitation of trains, now restricted to a short line in Shanghai, may become more widespread in urban areas. The use of high-Tc superconductors has led to the development of light-weight, high-torque electrical motors which may find important applications in marine propulsion.

Moore's Law The explosive growth of semiconductor technology in the past 3 decades (doubling of chip capacity every two years) has led to serious concern that the end is in sight. Several federal agencies are sponsoring searches for the next generation of electronics to avert the dire consequences of Moore's law. These include graphene, topological insulators, Majorana electronics, oxide heterostructures. All of these frontier fields are critically dependent on research sustained by liquid helium.

Quantum Computing The biggest high-risk, high-payoff idea out there for transforming the way computing is carried out is quantum computing. Classical computers rely on bits that can store information in only one of two ways (0 or 1). A quantum qubit can store a continuum of information. Quantum computers based on qubits can in theory crack problems that are currently intractable. Because they exploit truly quantum phenomena, the research is largely carried out at very low temperatures. Liquid helium is a vital fluid in this enterprise.

Graphene. Geim and Novoselov shared the Nobel Prize in Physics in 2010 for discovering that single atomic layers of carbon (called graphene) can be peeled from graphite. In the presence of a strong magnetic field, graphene displays several spectacular electrical features that are not observed in ordinary metals (these experiments rely crucially on cooling with liquid helium). Researchers have proposed a host of interesting diverse applications for this atomic-layer Saran wrap, ranging from high-speed transistors to hypersensitive detectors, to water purification.

Functional MRI. In health-related areas, a potentially transformative invention is functional magnetic resonance imaging (fMRI). By tracking the oxygen signal using fMRI, scientists can now measure blood flow in local regions of a patient's brain. This allows the identification of regions of the brain showing enhanced metabolic activity when the patient is asked to respond to an image or command. fMRI may find important applications ranging from treatment of autism, brain disorders and injuries. In these machines the magnetic fields are produced by superconductors cooled by liquid helium.

Appendix: Nobel Prizes in Physics (1980-2011)

* denotes awards in condensed-matter physics or low-temperature physics

2011 Saul Perlmutter, Brian P. Schmidt, Adam G. Riess
*2010 Andre Geim, Konstantin Novoselov
2009 Charles Kuen Kao, Willard S. Boyle, George E. Smith
2008 Yoichiro Nambu, Makoto Kobayashi, Toshihide Maskawa
*2007 Albert Fert, Peter Grünberg
2006 John C. Mather, George F. Smoot
2005 Roy J. Glauber, John L. Hall, Theodor W. Hänsch
2004 David J. Gross, H. David Politzer, Frank Wilczek
*2003 Alexei A. Abrikosov, Vitaly L. Ginzburg, Anthony J. Leggett
2002 Raymond Davis Jr., Masatoshi Koshiba, Riccardo Giacconi
*2001 Eric A. Cornell, Wolfgang Ketterle, Carl E. Wieman
2000 Zhores I. Alferov, Herbert Kroemer, Jack S. Kilby
1999 Gerardus 't Hooft, Martinus J.G. Veltman
*1998 Robert B. Laughlin, Horst L. Störmer, Daniel C. Tsui
1997 Steven Chu, Claude Cohen-Tannoudji, William D. Phillips
*1996 David M. Lee, Douglas D. Osheroff, Robert C. Richardson
1995 Martin L. Perl, Frederick Reines
*1994 Bertram N. Brockhouse, Clifford G. Shull
1993 Russell A. Hulse, Joseph H. Taylor Jr.
1992 Georges Charpak
*1991 Pierre-Gilles de Gennes
1990 Jerome I. Friedman, Henry W. Kendall, Richard E. Taylor
1989 Norman F. Ramsey, Hans G. Dehmelt, Wolfgang Paul
1988 Leon M. Lederman, Melvin Schwartz, Jack Steinberger
*1987 J. Georg Bednorz, K. Alexander Müller
*1986 Ernst Ruska, Gerd Binnig, Heinrich Rohrer
*1985 Klaus von Klitzing
1984 Carlo Rubbia, Simon van der Meer
1983 Subramanyan Chandrasekhar, William Alfred Fowler
1982 Kenneth G. Wilson
1981 Nicolaas Bloembergen, Arthur Leonard Schawlow, Kai M. Siegbahn
1980 James Watson Cronin, Val Logsdon Fitch