IMPLICATIONS OF U.S. INVESTMENT IN THE ITER PROJECT:
Stimulation of Transformative Technologies

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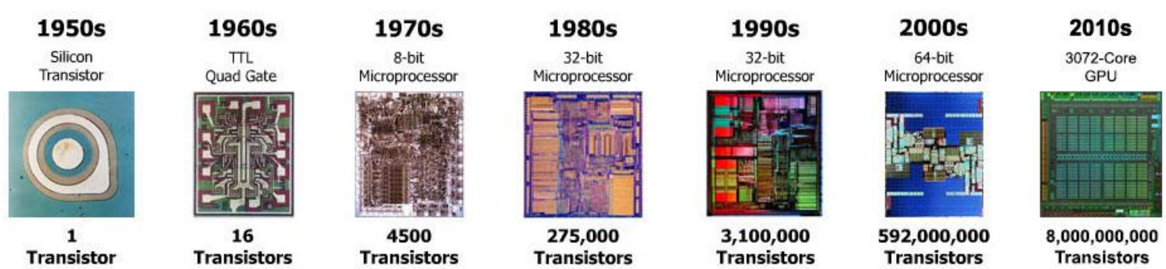
National pursuit of "big science" projects has long been among the most controversial of public policy decisions due to pragmatic considerations involving cost estimation, sustained commitment over extended timeframes, and the inevitable risks to success. Nevertheless, history has consistently proven that great socioeconomic payoffs can also result when national priorities are assigned and resources allocated in a stable and consistent manner. Among the most notable of U.S. examples is the *Apollo Project,* although numerous other cases of highly successful government investments also abound (e.g., air flight, radar, nuclear fission, lasers, satellite telecommunications, the internet, decoding the human genome, global positioning, etc).

Apollo Project Legacy

In the early 1960s, the newly-invented "integrated circuit" (IC) was largely untested and its reliability unknown. Working with the MIT Instrumentation Laboratory and Fairchild Semiconductor, the California company where the IC was invented and home to Gordon Moore of "Moore's Law" fame, NASA selected the "Type 'G' Micrologic Gate" for use in the Apollo Guidance Computer (AGC).[1] Consuming 200,000 units at $20-30 each, the AGC was the largest user of ICs through 1965.[2] By 1963, MIT had ordered and consumed some 60% of the world's available IC's. It was this early NASA/MIT Apollo requirement that helped spur the computer industry into further development, production and marketing of ICs.[3] Thus Santa Clara County, where Fairchild and its competitors were located, became known as *"Silicon Valley"*.

From the Fairchild Type 'G' Micrologic Gate…
(Credit: Philco-Ford Microelectronics and the Computer History Museum)



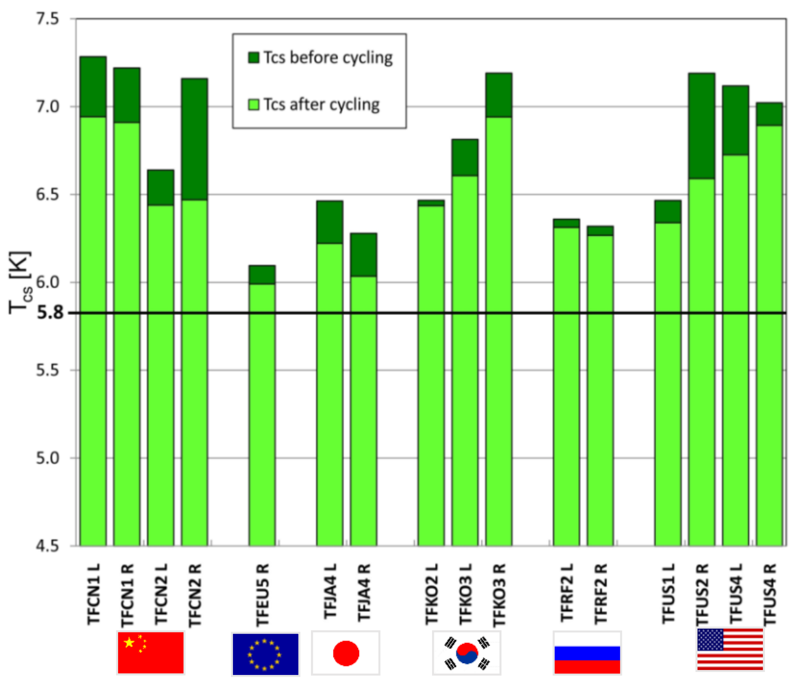
…to a Multitrillion Dollar Industrial Revolution in Microelectronic Devices
(Credits: Fairchild Camera and Instrument Corporation, Intel Corporation, Nvidia Corporation and the Computer History Museum)

[1] https://airandspace.si.edu/stories/editorial/apollo-guidance-computer-and-first-silicon-chips, accessed May 19, 2017.
[2] http://www.computerhistory.org/siliconengine/aerospace-systems-are-first-the-applications-for-ics-in-computers/, accessed May 19,2017.
[3] https://www.hq.nasa.gov/alsj/ic-pg5.html, accessed May 19, 2017.

ITER Project Technology Investments

Analogous to the 1960's Apollo Project procurement of the first ICs, the ITER Project represents the largest procurement of superconductors in industrial history. Over 200 kilometers (2,800 tons) of low-temperature superconducting cable-in-conduit will be used in fabricating the massive electromagnets for the ITER tokamak.

Low-temperature superconducting technology is useful primarily in scientific research. So it is much like the first 8 bit microprocessors in the electronic device revolution – practical applications are limited. However as a direct result of the early technology investment made under the Apollo Project, the chip industry was able to advance R&D to 32 and eventually 64 bit microprocessors. Explosive growth in practical applications resulted. Adequately financed R&D in the low-temperature superconducting industry today is an essential precursor to a thriving high-temperature superconducting device market in the future. *This is the strategic benefit of many big science projects.*



Global Participation in Superconducting Cable Investment

T_{cs} [K] denotes transition temperature in degrees Kelvin

(Credit: The ITER Organization)

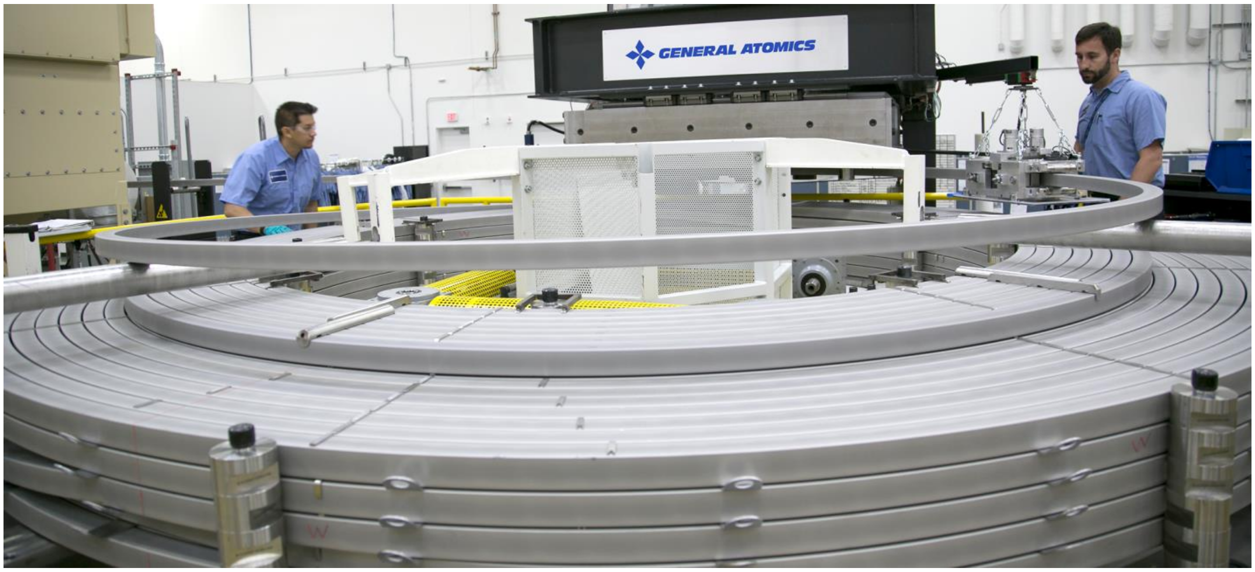
The U.S. share of this superconductor technology investment falls into three areas:

(a) provision of toroidal field cable-in-conduit employing state-of-the-art superconducting strand produced by two U.S. manufacturers -- Oxford Superconducting Technologies, Carteret, NJ and Luvata Special Products Division, Waterbury, CT[4];

(b) provision of the 1,000 ton Central Solenoid pulsed superconducting electromagnet (aka the "*heartbeat of ITER*" for its role in inducing and sustaining electric current in fusion plasma) – produced by General Atomics, La Jolla, CA, and;

(c) provision of project management and systems engineering & integration for all U.S. participation in the ITER Project – by Oak Ridge National Laboratory, Oak Ridge, TN.

[4] Both companies have since been acquired by foreign multinational holding companies -- OST by the Bruker Corporation of Germany and Luvata Special Products by the Mitsubishi Materials Corporation of Japan.



U.S. Winding of 2nd Central Solenoid Superconducting Magnet Production Module
(Credit: General Atomics, Inc)

The U.S. ITER investment in superconducting technologies does not stand alone. Similar investments are also underway for very-high-power (i.e., 20 Megawatt) microwave and radiofrequency power transmission systems; very high velocity and high speed (i.e., 500 m/s second at 60 Hz) fuel pellet injectors; very high throughput (i.e., 240 Pa*m^3/sec) tritium chemical processing, and; a variety of advanced microwave, laser, x-ray and optical diagnostic systems. Each of these technologies significantly advances the state-of-the-art in its respective domain and will represent new and unique domestic industrial capabilities and capacities.

Future Superconductor Applications[5]

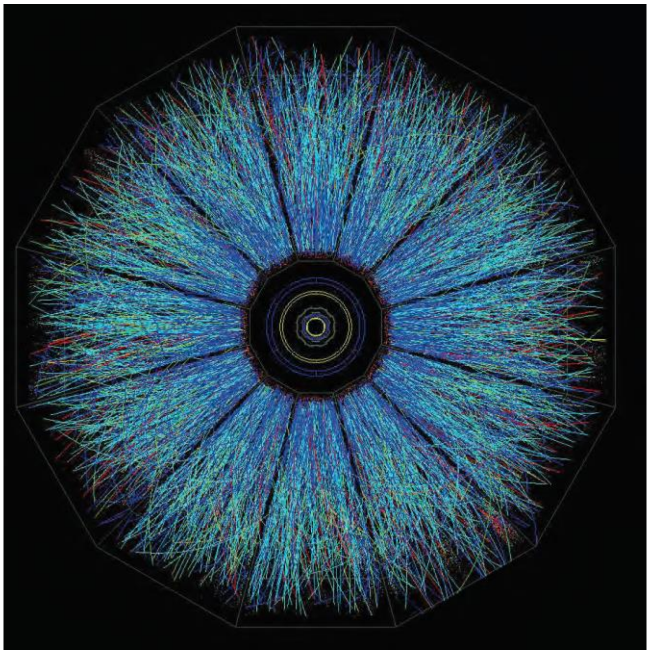
Superconductor-based products are extremely environmentally friendly compared to their conventional counterparts. They generate no greenhouse gases and are cooled by non-flammable liquid nitrogen (nitrogen comprises 80% of our atmosphere) as opposed to conventional oil coolants that are both flammable and toxic. They are also typically at least 50% smaller and lighter than equivalent conventional units which translates into economic incentives. These benefits have given rise to the ongoing development of many new applications in the following sectors:

- Electric Power | Superconductors enable a variety of applications to aid our aging and heavily burdened electric power infrastructure - for example, in generators, transformers, underground cables, synchronous condensers and fault current limiters. The high-power density and electrical efficiency of superconductor wire results in highly compact, powerful devices and systems that are more reliable, efficient, and environmentally benign.
- Transportation | The rapid and efficient movement of people and goods, by land and by sea, poses important logistical, environmental, land use and other challenges. Superconductors are enabling a new generation of transport technologies including ship propulsion systems, magnetically levitated trains, and railway traction transformers.
- Medicine | Advances in high temperature superconductors (HTS) promise more compact and less costly Magnetic Resonance Imaging (MRI) systems with superior imaging capabilities. In addition, Magneto-

[5] The statement below is by the Coalition for the Commercial Application of Superconductors, affiliated with the IEEE Council on Superconductivity. Full report available at: http://www.ccas-web.org/pdf/ccas_brochure_web.pdf

Encephalography (MEG), Magnetic Source Imaging (MSI) and Magneto-Cardiology (MCG) enable non-invasive diagnosis of brain and heart functionality.

- Industry | Large motors rated at 1000 HP and above consume 25% of all electricity generated in the United States. They offer a prime target for the use of HTS in substantially reducing electrical losses. Powerful magnets for water remediation, materials purification, and industrial processing are also in the demonstration stages.
- Communications | Over the past decade, HTS filters have come into widespread use in cellular communications systems. They enhance signal-to-noise ratios, enabling reliable service with fewer, more widely-spaced cell towers. As the world moves from analog to all digital communications, LTS (low-temperature superconductor) chips offer dramatic performance improvements in many commercial and military applications.
- Scientific Research | Using superconducting materials, today's leading-edge scientific research facilities are pushing the frontiers of human knowledge - and pursuing breakthroughs that could lead to new techniques ranging from the clean, abundant energy from nuclear fusion to computing at speeds much faster than the theoretical limit of silicon technology.



(Credit: Coalition for the Commercial Application of Superconductors)

Conclusion

While the mission of the ITER Project is to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes, an objective of profound global impact in and of itself if the project succeeds, the *implications for stimulating transformative technologies in parallel are still more compelling*. U.S. participation in ITER comes at an attractive investment-leveraging ratio; for less than 10% of the global investment in construction and 13% in operating expenses, the U.S. receives access to 100% of the scientific results, as well as *a highly competitive domestic industrial capacity for superconductor device production*.

Will 21st century superconducting devices one day match the socioeconomic impact of 20th century integrated circuits? As a nation, is it prudent to wager against superconducting technologies becoming transformative in the future? These and related science and technology policy questions require careful consideration if our nation is to remain a leader in the research & development of transformative technologies that sustain economic prosperity.