Staff Paper P05-3 March 2005

Staff Paper Series

Military Procurement and Technology Development

by
Vernon W. Ruttan

DEPARTMENT OF APPLIED ECONOMICS
COLLEGE OF AGRICULTURAL, FOOD, AND ENVIRONMENTAL SCIENCES
UNIVERSITY OF MINNESOTA

Staff Paper P05-3 March 2005

Military Procurement and Technology Development[1]

Vernon W. Ruttan[2]

[1] In this paper I draw extensively on Vernon W. Ruttan (2001). *Technology, Growth and Development: An Induced Innovation Perspective.* Oxford University Press, New York, NY (ref. 1); and on Vernon W. Ruttan (in press). *Is War Necessary for Economic Growth? Military Procurement and Technology Development.* Oxford University Press, NY (ref. 2).

[2] To whom reprint request should be addressed - e-mail: vruttan@apec.umn.edu.

Abstract:

The purpose of this paper is to demonstrate that military and defense related research and procurement have been a major source of commercial technology development across a broad spectrum of industries that account for an important share of United States industrial production. I discuss the development of five general purpose technologies: (1) military and commercial aircraft, (2) nuclear energy and electric power, (3) computers and semiconductors, (4) the Internet, and (5) the space industries. The defense industrial base has become a smaller share of the industrial sector which is itself a declining sector in the U.S. economy. It is doubtful that military and defense related procurement will again become an important source of new general purpose technologies. When the history of U.S. technology development for the next half century is eventually written it will almost certainly be written within the context of slower productivity growth than the relatively high rates that prevailed in the U.S through the 1960's and during the information technology bubble that began in the early 1990's.

It is difficult to overemphasize the importance of the historical role of military procurement in technology development. Knowledge acquired in making weapons was an important source of the industrial revolution. To bore the condenser cylinders for his steam engines, "Watt had to turn to John Wilkinson, a cannon-borer, who had invented the one machine in all England that could drill through a block of cast iron with accuracy" (ref. 3, p. 435). In the U.S the American system of manufacturing emerged from the New England system of gun manufacture (ref. 4, pp. 87-116).

In a landmark book published in the mid-1980s Merritt Roe Smith (ref. 5, pp. 32-37), a leading historian of technology, complained that economic historians had largely neglected the contribution of military research, development and procurement to commercial technology development. This deficiency has largely been corrected (ref. 6).

The purpose of this article is to demonstrate that military and defense related research, development and procurement has been a major source of commercial technology development across a broad spectrum of the industries that account for an important share of U.S. industrial production, The focus on military procurement captures a much more inclusive range of research and technology development than defense R&D.

I discuss the development of five general purpose technologies: (1) military and commercial aircraft, (2) nuclear energy and electric power, (3) computers and semiconductors, (4) the Internet, and (5) the space industries. I focus primarily on the U.S because for much of the twentieth century the U.S. has played a leading role in initiating or implementing the general purpose technologies that have emerged from military and defense related research, technology development, and procurement.

MILITARY AND COMMERCIAL AIRCRAFT

The U.S. has employed two principle instruments to support the development of the aircraft industry--support for aeronautics R&D, and procurement of military aircraft. These efforts were remarkably successful. Between the late 1920's and the mid-1960's labor productivity growth in the air transport industry ran upwards of eight percent per year—more rapidly than any other industry during that period (ref. 7, p. 164).

The NACA Era. The aircraft industry "was unique among manufacturing industries in that a government research organization, the National Advisory Committee for Aeronautics (NACA) was established to support research on aircraft design for the industry" (ref. 7, p. 170). The first successful sustained flight of a heavier than air self powered flying machine was achieved by Orville and Wilbur Wright at Kitty Hawk, North Carolina on December 17, 2003. In the decade following the Wright brothers' first flight significant advances continued to be made by flight enthusiasts, mechanics and engineers. Through World War I advances in aircraft design, in the U.S. and Europe, were almost entirely evolutionary from the Wright brothers' models.

Well before the beginning of World War I there was substantial concern within the aviation community that the U.S. was lagging relative to the major European countries in institutionalizing aircraft R&D capacity. Concern about the imminence of U.S. participation in World War I precipitated sufficient convergence of scientific, military and commercial interest to mobilize a successful effort to pass legislation, as part of a Naval appropriation bill, to establish an Advisory Committee for Aeronautics--later the National Committee on Aeronautics (NACA) (ref. 8, pp. 1-25).[3]

Until well into the 1920's NACA primary efforts were directed to the development of research facilities and staff at the then relatively isolated Langley Field. Initial effort focused on the construction of state of the art wind tunnels to test propeller and airfoil design. By the mid-1920's research at Langley Field and contract research at Stanford University was beginning to have a major impact on aircraft design. In 1931 a wind tunnel was constructed that was able to test the performance of an entire aircraft. During the late 1920's and 1930's NACA received numerous awards for a series of important technical innovations. One of the more dramatic was the NACA cowling. In 1939 the 60 percent reduction in drag and the 14 percent increase in speed predicted by NACA wind tunnel tests were confirmed by a transcontinental speed record by a Lockheed Air Express equipped with a NACA cowling (ref. 8, p. 116).

Most of the advances in design and performance that resulted from NACA Research during the interwar period were "dual use"—applicable to both military and commercial aircraft. Every American airplane and every aircraft engine that was deployed in World War II had been tested and improved by NACA engineers (ref. 8, pp. 173-198). The advances introduced by NACA were achieved at remarkably low cost (ref. 7, p. 170).

On the eve of World War II the Douglas DC-3 was the worlds most advanced commercial airliner. When the DC-3 production line shut down at the end of World War II 10,926 had been produced—10,123 for the military and 803 for the commercial market. The DC-

[3] The organic legislation that established NACA specified a 14 member governing Committee consisting of seven government representatives—two each from the War and Navy Departments and one each from the Weather Bureau, and, the Bureau of Standards at the Smithsonian Institution—and no more than seven private members (ref. 8).

3 remained the workhorse for commercial airlines around the world until well into the 1960's (ref. 9, pp. 195-201; ref. 10, pp. 195-201).

The aircraft and airline industries were not, however, successful in achieving a stable economic structure. Many of the early firms in the industry were initially established by wealthy hobbyists, designers, and entrepreneurs "whose enthusiasm for aircraft defied rational business calculation (ref. 11, p. 57). Revenues were highly variable because of dependence on unstable military demand. The numerous firms were not in position to conduct substantial independent research in aeronautics or in aircraft design.

Military considerations were a primary motivation for the establishment and support of the NACA. Demand for military aircraft provided an inducement or advances in aircraft design by the aircraft industry. It remains an open question whether, in the absence of military demand, a mature propeller driven aircraft, epitomized by the DC-3, would have become available to the U.S. airline industry and the military before World War II.

Jet Propulsion. During World War II the design of new aircraft was frozen. Major emphasis was on mass production of existing designs. During the 1930's, however, investigation of the aerodynamics of high speed convinced a small group of military aircraft engineers, led by Frank Whittle in the United Kingdom and Hans von Ohain in Germany, that a transition to a turbojet system of propulsion would enable aircraft to achieve higher levels of performance—to fly higher and at greater speed (ref. 12, pp. 97-114).

The production of the first jet engines in the U.S. during World War II was financed by the Army Air Force and drew on British technical assistance. Early military jets were inefficient in fuel consumption and required frequent engine replacement. It took more than a decade of learning by doing and using by manufacturers and the military before jet engines could be maintained and operated with sufficient efficiency to win a secure place in the U.S. airline industry (ref. 12). The first U.S. commercial jetliner, the Boeing 707, was delivered to Pan American Airlines in July of 1954 and initiate transatlantic service in October 1957.

The relationship between military procurement and commercial aircraft development is illustrated with particular force in the development of the Boeing 707. Boeing engineers began to consider the possibility of developing a commercial jet airliner in the late 1940's. It was considered doubtful that initial sales could justify development costs. The problem of financing development costs was solved by an Air Force contract to build a military jet tanker designed for the in flight refueling of the B-52 bomber.

The Boeing 707 set the design standard for the modern commercial jet airliner. It also confirmed the success of the Boeing policy of using military contracts to fund the development work that fed into the design of commercial airliners (ref 12). Development of the Boeing 747 followed a somewhat different pattern. In 1965 Boeing lost an Air Force competition to design a large military transport to Lockheed. Starting with the design they had developed for the military transport Boeing went on to design what became the Boeing 747 wide bodied commercial jet. By the 1970s the Boeing 747 had defined technological maturity in the commercial jet transport industry.

The NASA Era. The launching of the Sputnik satellites by the USSR in the fall of 1957 was followed by the establishment of the National Aeronautic and Space Administration (NASA). NACA research facilities and personnel were absorbed by the NASA or transferred to the Air Force. The incorporation of NACA into NASA was accompanied by a substantial shift in resources from aeronautic to space oriented R&D and from the practice of conducting R&D primarily in-house to contracting development to politically powerful aerospace contractors (ref. 13).

Throughout the 1960's and 1970's defense and defense related procurement continued to account for at least two-thirds of R&D directed to advancing aircraft performance. By the early 1970's, however, it was becoming increasingly clear that technology transfer from military and defense related procurement was no longer a dynamic source of new technology for the commercial aircraft industry. Since the early 1980's, government concern with the competitive position of the U.S. commercial aircraft industry led to substantial increase in the NASA budget for aeronautical R&D. By the early 1990's NASA and the Air Force were devoting upwards of $1.0 billion per year on R&D directed to large commercial aircraft development. By the early 2000's consolidation in the aircraft industry had left Boeing and Airbus as the only producers of wide bodied commercial aircraft and Boeing and Lockheed-Martin as the only significant players in the US military aircraft industry.

Perspective. It is hard to avoid a conclusion that during the interwar period commercial aircraft would have been developed and introduced much more slowly in the absence of defense related and R&D and military procurement. Defense related R&D and military procurement was primarily responsible to the transition from the piston-propeller to the jet system of propulsion. And military procurement provided the funding that facilitated the development of the wide bodied commercial jet. A generation ago Barry Bluestone and colleagues argued that "no aspect of the aircraft industry, including the commercial sector, could exist could exist without the R&D funds provides by the state or the states purchase of military equipment" (ref. 14). The more recent literature I have reviewed is fully consistent with the conclusions advanced by Bluestone and his colleagues.

NUCLEAR ENERGY AND ELECTRIC POWER

The initial development of electric power took place entirely within the private sector. A primary focus of the research team that Thomas A. Edison assembled at Menlo Park in 1876 was the development of a system for the generation and distribution of electric power. Over the next half century the electric power industry become a primary source of economic growth in the U.S. economy (ref. 15, pp. 172-217). Electric power largely displaced wood, coal, oil and gas in the lighting and powering of homes, offices and factories. The public sector became intimately involved in the regulation and pricing of electrical energy but was only marginally involved in technology development (ref. 3, pp. 83-85, 235-285).

By the late 1950's the eclectic power industry was no longer playing an important role as a source of economic growth in the U.S. Scale economies turned to diseconomies as engineers attempted to push the size of the largest coal fired generators beyond the 1,000 megawatt range. It was widely anticipated by some of its more extravagant proponents that nuclear power would make electricity "too cheap to meter."

Atoms for War. Demonstration of the feasibility of controlled nuclear fission by a team directed by the young Italian physicist Enric Fermi at the University of Chicago's Stagg Field in December 1942, set the stage for an active role of the U.S. and defense related institutions in technology development for the electric power industry. From its beginning it has not been possible to understand the development of the nuclear power industry apart from the military application of nuclear energy (ref. 16).

The steps that led to Fermi's demonstration of the possibility of controlled nuclear fission were set in motion in 1938 when two German chemists, Otto Hahn and Fritz Strassmanof, from the Kaiser Wilhelm Institute in Berlin, found that they could split atoms by bombarding their nuclei with neutrons. It was immediately recognized in the physics community, in both Europe and the U.S, that if the energy liberated by the splitting of the uranium atom could be controlled and directed it might be possible to construct a nuclear weapon more powerful than anything currently available (ref. 17, pp. 10-14).

Steps were taken to bring the implications of Hahn-Strassman discovery to the attention of President Roosevelt. After considerable delay responsibility for the construction of an atomic bomb was assigned to the Army which in turn assigned the project to the Army Corps of Engineers. In June 1942 the Corps formed the Manhattan District to oversee and construct an atomic bomb. Following a successful test in New Mexico in July a uranium bomb was detonated over Hiroshima on August 6 and a plutonium bomb over Nagasaki on August 9, 1945.

Atoms for Peace. In 1946 authority to promote and regulate the development of nuclear technology for both military and non-military purposes was transferred to the newly established Atomic Energy Commission (AEC). Initially neither the AEC nor the power industry evidenced a great deal of enthusiasm about the prospect for nuclear power development. President Eisenhower's "Atoms for Peace" speech before the United Nations in December 1953, committed the U.S. to a much more active role in commercial nuclear power development.

In December 1954 the Atomic Energy Commission, under considerable pressure from the Congress and the power industry announced a Power Demonstration Reactor Program. At the time the Power Demonstration Project was announced the Atomic Energy Commission had already made a decision to cooperate with Duqueesene Light and Power to build a pressurized water reactor at Shippingport, Pennsylvania. That decision was a direct consequence of a 1950 decision by the Navy to develop a light water nuclear reactor to propel its first nuclear powered submarine. By 1962 there were seven prototype commercial nuclear power plants using different coolant and moderator technologies in operation in the U.S.[4] By the mid 1960's, however, power reactor experimentation in the U.S. was over.

The Westinghouse pressurized water reactor and the General Electric boiling water reactor become the industry standards (ref. 19, p. 30). Nowhere were electrical utility firms heavily involved in nuclear research. They assumed that replacing a fossil fuel fired boiler with a nuclear reactor to produce steam would be a relatively simple process—a nuclear reactor was just another way to boil water. By the mid 1960's all of the major industrial countries were making significant investments in nuclear power generation. Cowan (ref. 16) and Arthur (ref. 20) have characterized the history nuclear power development as an example of politically inspired "path dependence." Before alternative nuclear power technologies could become technically and economically viable it was too late.

Cost Inflation. By the mid-1970's the U.S. nuclear power industry seemed poised for rapid expansion. Government ownership of uranium enrichment facilities was the only major exception to private ownership of the nuclear energy supply chain. A petroleum supply crisis that began in the early 1970's was expected to increase demand for nuclear power. It was completely

[4] Nuclear reactors are classified by two of the materials used in their construction, the coolant used to transfer heat from the reactor core and the moderator used to control the energy level of the neutrons in the reactor core. In a light water reactor both the coolant and the moderator are light water—H_2O. In a heavy water reactor both are heavy water—D_2O. In a gas-graphite reactor the coolant is a gas, usually helium or carbon dioxide, the moderator is graphite (ref. 16).

unexpected that a combination of safety, health, and environmental concerns would bring expansion of nuclear power capacity to a halt by the end of the decade.

The light water reactors of the late 1960's were, partly due to engineering and cost consideration and partly due to safety concerns, no longer commercially viable (ref. 21). Construction costs for plants of comparable size, corrected for inflation, quadrupled in little more than a decade. In the U.S. no new nuclear power plant were ordered after 1978.

Since the late 1990's operational experience and advances in reactor technologies have led to renewed interest in nuclear power. Economic considerations have been reinforced by the potential role that nuclear power might play in reducing greenhouse gas emissions (ref. 22).[5]

Perspective. Nuclear power is a clear cut example of an important general purpose technology that, in the absence of military and defense related R&D and procurement, would not have been developed at all—it would not have developed "anyway." It is exceedingly difficult to imagine circumstances, in the absence of the threat that Germany might develop nuclear weapons capacity, that would have induced the U.S. federal government to mobilize the scientific, technical and fiscal resources devoted to the Manhattan Project. It is equally difficult to imagine circumstances other than the Cold War with the USSR that would have enabled the U.S. federal government to sustain its investment in nuclear energy into the 1980's.

What if there had been no Manhattan Project? Pool has argued that in the absence of an atomic weapons program the U.S. would not have built nuclear enrichment facilities. And without the enriched uranium it is unlikely that a nuclear Navy program would have been implemented or that a nuclear power program would have been developed (ref. 18, p. 43).

[5]The period from the mid-1970's to the mid -1990's was characterized by intense debates about energy futures (ref. 1, pp. 270-279).

Chauncey Starr, one of the more experienced and thoughtful observers of the nuclear power industry speculated in the mid-1990's that in the absence of the threat of war the Hahn-Strassman work would have been written up in the scientific literature and treated as a subject of mostly academic interest. Low power nuclear reactors would have been developed to produce isotopes primarily for medical and industrial applications (ref. 18, p. 41).

THE COMPUTER INDUSTRY

The development of the electronic digital computer was preceded by a long history of the invention of mechanical and electromechanical tabulating and calculating machines. During and immediately after World War II major efforts were made, with the support of the military, to develop fully electronic computing machines (refs. 23, 24, 25). The first fully automatic calculator, the Automatic Sequence Controlled Calculator (Mark I), was a product of collaboration between Harvard University and IBM. Early models were built for the Navy and the Air Force. In this section I focus primarily on mainframe computer and semiconductor development. I have discussed personal computer and software development in my book, *Technology, Growth and Development* (ref. 1).

Inventing the Computer. The first all-purpose electronic digital computer was developed by John W. Mauchly and J. Prosper Eckert and associates at the University of Pennsylvania's Moore School of Electrical Engineering in 1946. Development of the machine, the Electric Numerical Integrator and Calculator (ENIAC), was funded by the Army's Aberdeen Ballistics Missile Laboratory. The first program run on the ENIAC was a simulation of the hydrogen bomb ignition (ref. 23, p. 191). A second computer developed by the Moore School group, the

Electronic Discreet Variable Computer (EDVAC), incorporated a stored program and sequential processing. In what came to be referred to as the von Neuman architecture the processing unit of the computer fetches instructions from a central memory that stores both data and programs, operates on the data, and returns the results to a central memory (ref. 24, pp. 68-75).

In the early postwar period there was rapid consolidation of firms founded under the impetus of defense agency demand. Eckert and Mauchly formed the Electric Control Company in June 1946. A second pioneering company, Engineering Research Associates (ERA) was formed in 1946 by staff members of the Naval Communications Supplemental Activity, located in St. Paul, who had been involved in the development of computers in support of the Navy's work in cryptology (ref. 26). Both firms were acquired by Remington Rand in the early 1950's. They were both disappointed by the lack of enthusiasm by Remington for commercial computer development. This lack of enthusiasm was shared by other office equipment manufacturers (ref. 27, pp. 222-246). It was the Korean War that led to a decision by IBM to enter the market for commercial computers. The IBM Defense Calculator, renamed the 701, was formally dedicated in April 1953. The first machine to be externally installed was at the AEC Los Alamos Laboratory in March, 1953 (ref. 28, p. 114).

Air Defense. Intensification of the Cold War in the early 1950's played a critical role in the development of the capacity of IBM to manufacture a fully transistorized commercial computer. The impetus came from a decision by IBM to cooperate with the MIT Lincoln Laboratory in the design and development of a computerized air defense system, the Semi-Automatic Ground Environment (SAGE), funded by the U.S. Air Force. The SAGE task was to detect alien aircraft, select appropriate interceptor aircraft, and determine antiaircraft missile trajectories. The system would have to store and process large amounts of information and coordinate several computers in real time. By the time the project was completed IBM had built 54 computers for the SAGE system (ref. 29).

As work on the SAGE project was being completed IBM was producing six different computer lines, all of which had incompatible operating systems. Competitors were beginning to make inroads into IBM's market share. Software was accounting f or a greater proportion of the cost of computer systems. These problems were largely resolved with the introduction of the IBM 360 in 1965. The 360 family of computers used integrated circuits rather than transistors. They had large ferrite core memories with fast access times and multiprogramming which allowed many programs to run simultaneously, and an improved disk memory that allowed the machines to store more information in a secondary memory than had previously been thought possible. The 360 machines were designed for both commercial and defense applications. No matter what size, all contained the same solid state circuits and would respond to the same set of instructions. As it came on line the System 360 platform became the industry standard for the rest of the 1960's and 1970's (ref. 30). The decision by IBM to commit to the 360 line required enormous technical and financial commitment. "IBM literally bet the company on its 360 decision," (ref. 31, p. 218).

Supercomputers. An alternative to the path followed by IBM was to design computers for military and space related applications that would be faster than any IBM machine at floating point arithmetic. The first machine that could properly be termed a supercomputer was the 1964 Control Data 6000. It was designed by Seymour Cray who would dominate supercomputer development for the next three decades.

In 1972 Cray and several colleagues left Control Data to form a new company, Cray Research, with the objective of producing the world's fastest computers specifically to meet the need of government agencies such as the Weather Bureau and of defense and defense related firms and agencies. The Cray 1, introduced in 1976, and a succession of even more powerful Cray machines, completely dominated the supercomputer field. The end the Cold War resulted in a decline in demand for supercomputer capacity. In 1995 the Cray Computer failed to find a market for its newest computer and declared bankruptcy (ref. 28, p. 157).

Semiconductors. It was understood, even in the late 1930's, that the speed, reliability, physical size, and heat generating properties of vacuum tubes would become a major technical constraint on electronic switching. After World War II Bell Telephone Laboratories formed a solid-state research group, directed by William Shockley, to develop new knowledge that might lead to the development of improved components for communications systems. In December 1947 Shockley and two colleagues, John Bardeen and Walter Brattain, produced the first working point contact transistor (ref. 32).

Until the late 1950's transistors were discreet devices. Each transistor had to be connected by hand to other transistors on a circuit board. In the mid-1950's Texas Instruments initiated a research program to repackage semiconductor products (transistors, resistors, and capacitors) as a single component. In 1958 the project, directed by Jack Kilby, produced the first crude integrated circuit. At about the same time Robert Noyce and Gordon Moore, then at Fairchild Semiconductor, independently invented an integrated circuit that incorporated transistors and resistors on a small sliver of silicon and added microscopic wires to interconnect adjacent components (the planar process). A third major semiconductor invention, the microprocessor, was developed at Intel in the late 1960's.[6]

The potential military applications of semiconductors were immediately apparent. The transition between the initial invention of the transistor and the development of military and commercial applications of semiconductors and integrated circuits was guided and substantially funded by the Army Signal Corps. By 1953 the Corps was funding approximately 50 percent of transistor research at Bell Laboratories. Its engineering laboratory developed the technology to replace hand soldering of components. By the mid-1950's the Signal Corps had underwritten the construction of a large Western Electric transistor plant and was subsidizing facility construction by General Electric, Ratheon, RCA, and Sylvania. Funding was also provided for engineering development (ref. 28).

Demand created by space exploration projects pushed semiconductors rapidly down the design and production learning curves. The diffusion of technical knowledge and the entry of new firms was encouraged by a military procurement policy of "second sourcing" to avoid dependency on a single supplier. "By subsidizing engineering development and the construction of manufacturing facilities … the military catalyzed the establishment of an industrial base," (ref. 34, p. 28). Demand for semiconductors continued to be dominated by direct procurement for military, nuclear power, and space applications until well into the 1970's (ref. 35, p. 13).

Perspective. The invention and early development of the electronic digital computer was supported almost entirely by Army and Navy contracts. Edwards (ref. 36, p. 52) and Flamm (ref. 27, p. 251) have argued that the support of military and defense related procurement advanced

[6] In 1965 Gordon Moore, co-founder of Intel, predicted that the number of transistors per integrated circuit would double every 18 months. This prediction, which turned out to be conservative, is known as Moore's Law (ref. 33).

the pace of modern computer development by at least a decade. The adoption of business and personal computers contributed importantly to the recovery of productivity growth in the U.S. economy beginning in the early 1990's (ref. 39). Without the impetus for development and commercialization associated with military support for R&D and defense and defense related procurement the major contributions of the computer and related information technology to the growth of the U.S. economy would have been delayed until at least the beginning of the twenty first century.

INVENTING THE INTERNET

The development of the internet involved the transformation of a computer network that had initially been established in the late 1960's by the Advanced Research Projects Agency (ARPA) of the Department of Defense (DoD).[7] The decision to support the development of and ARPANET followed several earlier successful efforts by the DoD, such as the Whirlwind computer that was developed in the early 1950's for the SAGE air defense system, in the field of computer communication. The decision also reflected the personal interest of Joseph Licklider, the first director of the ARPA Information Processing Techniques Office (IPTO) (refs. 38, 39).

Creating the Internet. Licklider initially visualized a system of "time sharing" in which a single computer located at a central location would be accessed by a number of users with individual terminals connoted to the central computer by long distance telephone lines. This would economize on the use of central terminals—the scarce resource in the system. The original concept for such a system had been developed Paul Baran, a young engineer working at RAND

[7] The Name of the Advanced Research Projects Agency (ARPA was changed to Defense Research Projects Agency (DARPA) in 1972 and then renamed ARPA in 1993. I have used ARPA throughout this paper.

(ref. 40). Messages would be broken into small "packets" and routed over the distrusted system automatically rather than manually. The concept appealed to ARPA administrators since it appeared to both open up a new area in computer science and to save ARPA money in computer facilities.

In 1966 ARPA secured the services of Lawrence Roberts, a MIT Lincoln Laboratory researcher, who had already connected a Lincoln computer to one at RAND in Santa Monica. Roberts was assigned responsibility to build a large multi-computer network that would interconnect the time-sharing computers at seventeen academic, industrial and government computer centers funded by ARPA. At a planning session at the University of Michigan in 1967 Roberts laid out his vision of a system in which the host computers would be interconnected by small interface computers thus enabling host computers with different characteristics to be able "to speak to each other." The proposal was initially resisted by several of the university based principle investigators but because all the centers were dependent on ARPA support Roberts was able to insist that the twelve sites link their computers to the network (ref. 41, p. 46).

ARPA awarded a contract for the development of a computer-interface message processor (IPM) that could route message packets along alternative routes to Bolt Beraek and Newman (BBN), a high-technology firm located in the Cambridge, Massachusetts area in early 1971. Nine month after the contract was awarded the basic elements of the system were in place. But several host system operators were slow in completing the special purpose hardware interface between their computer and its IPM. In order to galvanized the network community to get on line Roberts made a commitment to demonstrate the ARPANET at the First International Conference on Computer Communication to be held in October 1972 in Washington D.C. The demonstration convinced skeptics in the computer and telephone industries that packet switching could become a viable commercial technology (ref. 42, p. 78; ref. 43, pp. 275-282).

Although the potential capacity of the ARPANET as a communication tool was apparent, at least to those who had participated in its development neither the Defense Department sponsors of the research nor members of the design team anticipated that it would take a quarter century to resolve the technical and institutional problems necessary to release the potential of the INTERNET or that its primary use would be for personal and commercial e-mail rather than for transmitting data or research collaboration.

Designing the Internet. As early as 1972, following the demonstration of the technical feasibility of an ARPANET, the ARPA began exploring the possibility of transferring the ARPANET management to another government agency or a commercial carrier. Efforts to interest AT&T were unsuccessful. In 1975 a decision was made to transfer operational responsibility to the Defense Communication Agency (DCA). ARPA would continue to provide funding and technical direction. The DCA immediately began to reorient the network away from its research focus toward military operations. DCA managers were more concerned than ARPA had been about security implications of unauthorized used and was more serious than ARPA had been about preventing use of the network for “frivolous activities” (ref. 42, p. 136).

In the late 1970’s the DCA was confronted with a major decision that had a profound impact on the commercial development of the INTERNET. In 1979 an updated version of the Automatic Digital Network (AUTODIN), the message switching network that the DCA had developed for exclusive military use, was procured from Western Union. The DCA had initially planned to dismantle ARPANET once AUTODIN II became operational. After further consideration DCA was persuaded that there was an important role for a research oriented network and the ARPANET would be continued. In 1982 a decision was made to split ARPANET into a defense research network, still to be called ARPANET, and an operational military network to be called MILNET that would be equipped with encryption. Since it was transferred to civilian control, users of the INTERNET and other security devices. The DCA established a $20 million fund to support the transition and by 1990 the INNTERNET "was available for almost every computer in the American market (ref. 41, p. 43).

It was not until 1994 when the National Science Foundation established an Office of Advanced Scientific Computing, that ARPA was able to end all responsibility for ARPANET. The mandate of the Office was to organize a geographical diversifies set of new university based supercomputer centers. A NSFNET was established as a "backbone" for the system that eventually evolved into the INTERNET. It almost immediately became obvious, largely for ideological reasons, that the only way to fully accommodate commercial users on the INTERNET would be to remove it completely from government operation. The process of privatization was largely completed by the mid 1990s, thus opening the way for completion of a global "network of networks"—the World Wide Web (ref. 41, pp. 195-200).

Perspective. Since it was transferred to civilian control users have largely lost sight of the contribution of military procurement to the development of the INTERNET. From the perspective of the commercial or individual user it is surely correct to assert a critical date "by which to mark the explosion of the INTERNET onto the business and cultural scene is 1994, the year an easy-to-use INTERNET browser with secured transactions called Netscape was launched (ref. 43, p. 2).

In retrospect it is clear that no other organization, public or private, was prepared to provide the scientific, technical and financial resources to support the developments that became the Internet on the ARPA scale.

Latvin and Rivlan have estimated that the INTERNET may have added 0.25 to 0.5 percent to the annual rate of productivity growth in the U.S. economy during the early years of the 21st century (ref. 44, pp. 19-22). My own estimate, consistent with that of Latvin and Rivlin, is that in the absence of ARPA support and the earlier military and defense related support for the development of the computer and microprocessors, I would not yet have been able to transmit this manuscript to the publisher by e-mail.

THE SPACE INDUSTRIES

The launching of Sputnik, the first earth orbiting satellite on October 4, 1957 and a second satellite in May 1968 by the Soviet Union, challenged the assumption of U.S scientific and technical leadership. President Eisenhower and his immediate military and science advisors appeared not to be greatly alarmed about the apparent Soviet leadership. The U.S. had been flying spy planes (the U-2) over the USSR for more than a year and had previously initiated a program to develop satellite observation and communication capacity. Eisenhower saw Sputnik as a useful precedent for an international "freedom of space," policy (refs. 45, 46).

Missiles and Satellites. U.S. capacity in missile and satellite science and technology in the early post World War II period was based almost entirely on the acquisition of the scientific and technical resources of the German rocket team led by Werner Von Braun. The U.S. army was able to acquire most of the important German technical personnel and documents and almost all of the remaining V-2 rockets. After a brief stay for debriefing at Wright Field the team was transferred to Fort Bliss (Texas) and then, in 1949, to the Redstone Arsenal in Huntsville, Alabama. At Redstone Cold War concern dictated a shift from a space vehicle orientation to and emphasis on the development of intercontinental ballistic missiles (ICBMs). At Huntsville the team developed a variety of medium- and long-range ICBMs (ref. 46, pp. 62-75).

In April 1958, President Eisenhower approved plans to launch a satellite as part of the U.S. contribution to the scientific activities of the International Geophysical Year (IGY). Shortly later he signed a National Security Directive “which decreed that the U.S. The IGY program would not employ any launch vehicle currently intended for military purposes (ref. 46, p. 350). The IGY satellite program, Project Vanguard, was assigned to the Naval Research Laboratory which had no involvement in the missile program. After an initial Vanguard failure the Army Ballistics Missile Agency at Redstone was permitted to employ its Jupiter 3 ICBM to launch the Explorer I, the first successful U.S. satellite, on January 31, 1958. After a series of failures the Vanguard II satellite was successfully launched on February 17, 1959 (ref. 46, pp. 179-184).

At the time of the Sputnik crisis the Central Intelligence Agency, the Air Force and several defense contractors were already working on a surveillance satellite program, termed Corona. Corona was so secret that for several months after its imitation, “by order of CIA Chief Allen Dulles all details were to be passed along verbally and there were no documents or written records” (ref. 46, p. 187). Of the first 20 missions only 12 were productive. On August 18, 1960 the first fully successful Corona satellite, Discoverer XIV was launched. “This one satellite mission yielded photo coverage of a greater area than the total produced by all the U-2 missions over the Soviet Union,” (ref. 47, p. 24).

By the early 1960’s the potential strategic and economic contributions of the several space programs were beginning to become apparent. The program of the Army Ballistic Missile

Agency, motivated by the energetic bureaucratic entrepreneurship of Von Braun, had set in motion the technology that led to the NASA manned space flight program. Project Vanguard laid the groundwork for NASA initiatives in space science and space communications technology. The Air Force surveillance projects advanced the earth observing technology that let to advances in weather forecasting, space communications and earth observing systems.

Space Communications. The rapid development of communications satellites by the U.S. was an important unanticipated consequence of the space race. In 1961 President Kennedy issued a "Policy Statement on Communications Satellites." The statement recognized the potential economic value of satellites in providing communications services and recommended government policy for the conduct and coordination of space communication R&D; steps for policy implementation by the public sector; and an international effort in which all nations would be invited to participate. Kennedy's Statement was followed by passage of the Communications Satellite Act of 1963; by formation of the Communications Satellite Corporation (COMSAT) in 1963 and by organization of an International Telecommunications Satellite Consortium in 1964.

During the late 1950's and early 1960's a number of communications satellite tests were conducted. The first labeled SCORE, launched into orbit on an Atlas rocket in December 1958, was designed to receive a message from earth, store it on tape, and transmit the message to the ground. "Score transmitted the first 'voice from space' when it was used to transmit a Christmas message to the world from President Eisenhower. The battery powered transmitter died on New Years Eve," (ref. 48, p. 45). In the early 1960's Bell Laboratories used its own resources to develop a more advanced communication satellite. It was launched on a Thor-Delta rocket in July 1962. It demonstrated the feasibility of a medium-altitude commercial satellite.

Beginning in the late 1950's NASA launched several passive satellites to resolve a series of technical problems such as voice delay. It also awarded a contract to Hughes Aircraft for the construction of a geostationary synchronous satellite. The Hughes series of SYNCOM satellites demonstrate substantial technical and economic advantages of the geostationary orbit for potential commercial applications (ref. 48, p. 18; ref. 49, p. 50).

As launching of the several communications satellites proceeded, the need for an operational implementation entity became increasingly apparent. After considerable debate an act establishing the Comsat Corporation in which ownership and governance would be divided among commercial carriers and the public was enacted in August 1964. While the Comsat legislation was being negotiated the Kennedy administration was also involved in negotiations with several European countries to establish an International Telecommunications Satellite Consortium.

In 1972 the Federal Communications Commission (FCC) authorized qualified private firms to launch and operate domestic satellite systems. In 1973 NASA announced that the private sector had reached a level of scientific and technical maturity that it could completely phase out its R&D on communications satellites. When the Reagan Administration took office in 1981 it attempted to move rapidly toward privatization of launch services. The only aerospace firm to respond to a NASA request for proposals was General Dynamics. Its bid assumed that it would be able to rent government launch services at a price that reflected incremental costs, and that NASA would continue to conduct research and development work on launch vehicles (ref. 50, pp. 128-131). Concerns about financial viability, most recently related to competition with the fiber-optical cable terrestrial systems, have continued to plague the satellite communications industry (refs. 51).

Earth Observing Systems. In this section I review the role of military and defense related R&D and procurement in the emergence of earth observing systems. Modern research on geographic information systems (GIS) owes its spectacular growth during the last quarter of the twentieth century to two technical developments: the computer and earth orbiting satellites. The computer brought about a transition from making maps by hand to the use of digital technology to produce three-dimensional maps (ref. 52). The CORONA program played an important role in both developments.

Cloud and Clarke have insisted that the impact of the CORONA program was so pervasive that it has been difficult to identify "any significant Geographic Information System technologies, applications, or data sets which do not have a primary or secondary origin in collaboration with the secret assets of the military and intelligence institutions" (ref. 53, p. 3).

Landsat. During the early 1960's NASA scientists and engineers were initiating studies to monitor earth resources from space. When NASA first initiated the Earth Resources Technology program in 1964 the program was viewed as a complement to other efforts to put more people into space rather than a program with specific earth monitoring or management objectives. Relatively little effort was made to serve the needs of agencies such as the Weather Bureau, the U.S. Geological Survey or the Department of Agriculture (ref. 54, pp. 45-55). It was not until the late 1960's that that NASA obtained enough funding to put out requests for proposals for the design of earth resource satellites that would meet the specifications of its own studies and those of potential users.

The first Landsat satellite, constructed by General Electric, was successfully launched on July 23 in 1972. Among the anticipated applications were identification of geological formations where petroleum and mineral deposits might be located and the location and quantity of water resources. By the time that Landsat 4 was launched in 1982 it had become the “workhorse” for environmental research dealing with earth surface monitoring and evaluation.

It quickly became apparent that the support for Landsat could no longer be rationalized as an experimental NASA program. Questions of ownership and management of the system had to be addressed. After substantial debate President Jimmy Carter transferred Landsat to the National Oceanic and Atmospheric Administration (NOAA) and instructed NOAA to develop a plan for the privatization of Landsat. In 1985 Landsat was acquired by the Earth Observing Satellite Corporation (EOSAT), a joint venture of Hughes Aircraft and RCA Astro-Electronics. EOSAT was charged with operating Landsat 4 and 5 under contract with NOAA, completing the privatization of Landsat services, and launching several more advanced satellites (Landsat 6and 7). EOSAT immediately raised the price of Landsat images tenfold—from $400 to $4000 (ref. 55, p.12). The effect was to preclude purchases of Landsat images by academic and independent users and to limit the market primarily to government and commercial users.

Even after privatization an ideologically burdened debate about government support for the Landsat system continued into the early 1990’s. It was increasingly recognized that full commercial viability would not be achieved until well into the next century. By the early 1990’s it was clear that the corporate owner of Landsat was not able, or willing, to devote the resources to the program that would be required to achieve technical of economic viability. The Land Remote Sensing Policy Act of 1992 repealed the Commercialization Act of 1984. After a series of rather convoluted interagency negotiations NASA was assigned responsibility for building and launching Landsat 7. As of late 2003 Landsat 7 was approaching the end of its operationally useful life. Negotiation over the launching of Landsat 8 remained unresolved. The academic and other public user communities had expressed great concern about the potential loss of continuity in more than 30 years of Landsat earth resources observations (ref. 56).

Global Positioning. The impact of advances in remote sensing on the development of civil technology and institutions was initially severely limited until well into the 1990's by the secrecy associated with earth observing technology and information. The situation changed rapidly, however. By the early 1990's the U.S. Air Force was supporting development of initial Navistar global positioning constellation of 24 orbiting satellites, at least four of which were above the local horizon anywhere on Earth for 24 hours a day. They emitted two sets of signals which allowed users to calculate their precise location anywhere on earth.[8]

The primary interest of the military services in what was to become GPS was to improve navigation for military aircraft and ships and to increase the accuracy of the weapons they carried. In 1972 several military programs involved in what was to become GPS coalesced when the Air Force was given responsibility for developing a navigation system for all military services as well as civilian users. Concurrently, technologies essential to GPS, including the CORONA satellite system and microelectronic instruments, were also being developed.

Experimental GPS satellites were first launched in 1978. Use of GPS for navigational purposes on commercial aircraft was approved in September 1983 following the Soviet downing of Korean Airlines Flight 007 over Soviet airspace (ref. 59). By the mid-1990's GPS civil applications included new systems for landing aircraft in bad weather, site-specific fertilizing and planting of fields, monitoring train and truck locations, cleaning up oil spills and location of industrial and commercial facilities.

[8] This section is adapted from (ref. 57). See also (ref. 58).

At the beginning of the new century, however, there remained considerable skepticism about the commitment of the DoD in making the necessary technical and financial investments necessary to enhance GPS capacity consistent with the growth of commercial demand. The European Union, motivated by strategic and commercial concerns, made an official decision in March 2003 to challenge the monopoly position of GPS by building the "Galileo," an independent European satellite constellation. The Galileo system of 30 state-of-the-art satellites was projected to be operational by 2008.

At the time this paper was written it seemed clear that during the next several years additional countries and private firms would have high resolution remote sensing satellites in orbit. Many of these, particularly those operated by government agencies, will have dual military and civilian uses. And most will be selling an appreciable share of their imagery in the open market. It is doubtful that any government, or even a consortium of governments, will have the capacity to put meaningful constraints on access to the highest quality images (ref. 59).

Perspective. The initial decision by the U.S. to put a satellite into orbit was based entirely on military and strategic considerations. At the time the first satellites were launched neither the USSR or the U.S. had given significant attention to the potential dual use of satellites—for weather forecasting, communication, earth observing or global positioning.

Rapid development and diffusion of satellite communications technology was a response to demands that that could not be met efficiently, or in some cases at all, by existing land based technology. Latent commercial demand was reinforced by political motivation to demonstrate U.S. scientific and technical capacity for peaceful application of space technology.

In the case of earth-observing technology there was only a limited preexisting commercial market for the services that the new technology could provide. The initial demand for the data that could be provided by GPS was primarily for military application. The initial nonmilitary sources of demand for the data that could be provided by Landsat were primarily public sector resource-management and planning agencies. Furthermore, the development and diffusion of the most advanced earth-observing technology and data were constrained by national security considerations.

Development of civil applications was caught up in ideological debates that led to premature privatization and in concerns about the security implications of civil release of earth-observing data. It is also apparent, in retrospect, that reluctance to consider public good aspects and insistence on premature commercialization have been serious constraints on efforts to sustain the U.S. initial preeminence in earth observing systems.

In spite of the different motivations there was one essential common element that made the several systems possible. That element was the development, first by the military services and later by NASA of ICBM capacity, to place and maintain in orbit the "voice from the sky" and the "eye in the sky" satellites. The vehicles capable of launching and placing into orbit the satellites became available only because of the enormous prior investment by the military services and NASA.

A FUTURE FOR GENERAL PURPOSE TECHNOLOGY?

In this paper I have reviewed the role that military R&D and defense related procurement have played in the commercial development of five important general purpose technologies. In each case commercial development would have been substantially delayed without the stimulus from military R&D and defense related procurement.

I have not argued that the massive military and defense related R&D and procurement programs reviewed above can be adequately evaluated in terms of their impact on commercial technology development. With rare exceptions the benefit-cost calculations have not been carried out. I do insist, however, that the U.S. and the global technological landscape in which we live today would be vastly different in the absence of the military R&D and defense and defense related contributions to commercial technology development.

These findings suggest that it is necessary to ask whether a major war, or threat of a major war, is necessary to induce the U.S. to mobilize the scientific and technical resources to sustain the development of new general purpose technologies. In attempting to answer this question three additional questions must be asked.

The *first* is whether the private sector can be relied on as a source of new general purpose technologies. Each of the general purpose technologies I have reviewed have required at least several decades of public support, primarily in the form of military R&D and defense or defense related procurement, to reach the threshold of commercial viability. Decision makers in the private sector seldom have had access to the patient capital implied by upward of a twenty or thirty year time horizon. During the last several decades a number of the most research intensive U.S. firms have withdrawn from the conduct of basic research and are making very limited investments in early stage technology development (ref. 61).

The *second* issue is whether non-military or defense related public support for commercially oriented R&D might become an important source of general purpose technology development. In attempting to answer this question one must confront the historical fact that only agriculture and health have been able to achieve sustained public support for commercial technology development. Efforts to sustain public sector support for industrial technology development, such a the Advanced Technology Program of the National Institute of Standards and Technology (ATP/NIST) and to support public-private partnerships (CRADAs) with national energy laboratories., though productive, continue to have great difficulty in achieving political viability.

The *third* question that must be answered is whether military and defense related technology development can again become a major source for the development of major new general purpose technologies. As a result of the end of the Cold War and changes in the structure of the U.S. economy the defense industrial base has become a declining share of a sector of the U.S. economy that is itself accounting for a declining share of output and employment. The enthusiasm of the late 1980's and early 1990's on the part of defense intellectuals for the promise of development dual-purpose military-commercial technology as a focus for military procurement has eroded.

When the history of U.S. technology development for the nest half century is eventually written, my guess is that it will focus on incremental rather than revolutionary changes in both military and commercial technology. It will also be written within the context of slower productivity growth than the relatively high rates that prevailed in the U.S. through the 1960's and during the information technology bubble that began in the early 1990's.

References:

1. Ruttan, V. W. (2001). *Technology, Growth and Development: An Induced Innovation Perspective.* Oxford University Press, New York, NY.
2. Ruttan, V. W. (in press). *Is War Necessary for Economic Growth? Military Procurement and Technology Development.* Oxford University Press, New York. NY.
3. Kaenpffert, W. (1941). *Am. J. Soc.* 46, 431-444.
4. Rosenberg, N. (1972). *Technology and American Economic Growth* (Harper, New York).
5. Smith, M. (1985). *Military Enterprise and Technological Change.* MIT, Cambridge.
6. Hacker, B. C. (1994). *Technology and Culture* 35, 768-834.
7. Mowery, D. C. and N. Rosenberg (1983). In *Inside the Black Box: Technology and Economics*, ed. N. Rosenberg (Cambridge University Press, Cambridge, UK), pp. 63-177.
8. Roland, A. (1995). *Model Research: The National Advisory Committee for Aeronautics, 1915-58, Vol I and II. (*National Aeronautics and Space Administration, Washington, DC.
9. Constant, E. W. (1980). *Origins of the Turbojet Revolution.* Johns Hopkins, Baltimore, MD.
10. Anderson, J. D. (2002). *The Airplane: A History of its Technology.* American Institute of Aeronautics and Astronautics, Reston, VA.
11. Vander Meulen (1992). *Bus. and Econ. Hist.* 21, 56-64.
12. Cook, W. H. (1991). *The Road to the 707: the Inside Story of Designing the 707.* TYC Publishing Company, Bellview, WA.
13. Bromberg, J. L. (1999). *NASA and the Space Industry.* Johns Hopkins University Press, Baltimore, MD.
14. Bluestone, B., P. Jordan and M. Sullivan (1981). *Aircraft Industry Dynamics: An Analysis of Competition, Capital and Labor.* Auburn House, Boston, MA.
15. Gordon, R. J. (2004). *Productivity Growth, Inflation and Unemployment.* Cambridge University Press, Cambridge, UK.
16. Cowen, R. (1990). *J. Econ. Hist.* 50, 597-607.
17. Hewlett, R. G. and O. E. Anderson, Jr. (1962). *The New World: A History of the Atomic Energy Commission, Vol. I, 1939/1946.* U.S. Atomic Energy Commission. Washington, DC.

18. Pool, R. (1997). *Beyond Engineering: How Society Shapes Technology.* Oxford University Press, Oxford, UK.

19. Cantelon. P. L., R. C. Hewlett, and R. C. Williams, eds. (1991). *The American Atom: A Documentary History of Nuclear Policies from the Discovery of Fission to the Present*. University of Pennsylvania Press, Philadelphia, PA.

20. Arthur, W. B. (1990). *Sci. Am.*, February, pp. 92-99.

21. MacKerron G. (1994). In *Handbook of Industrial Innovation,* ed. M. Dodgson and R. Rothwell. Edward Algar, Aldershot, UK, pp. 183-190.

22. MIT Nuclear Energy Study (2003). *The Future of Nuclear Power.* Massachusetts Institute of Technology, Cambridge, MA.

23. Seidel, R. W. (2002). In *From 0 to 1: An Authoritative History of Modern Computing,* eds, A. Akera and F, Nebeker, pp. 189-201. Oxford University Press, New York, NY.

24. Flamm, K. (1988) *Creating the Computer: Government, Industry and High Technology.* Brookings Institution, Washington, D.C.

25. Ceruzzi, P. E. (2003). *A History of the Modern Computer.* The MIT Press, Cambridge, MA.

26. Norberg, A. L. (2002). In *From O to 1: An Authoritative History of Modern Computing,* eds. A. Akera and F. Nebeker, pp. 163-176. Oxford University Press, New York, NY.

27. Cortada, J. W. (1993). *Before the Computer: IBM, NCR,Burroughs and Remington Rand and the Industry they Created, 1865-956.* Princeton University Press, Princeton, NJ.

28. MacKenzie, D. (1996). *Knowing Machines: Essays on Technical Change.* The MIT Press, Cambridge, MA.

29. Redmond, K. C. and T. M. Smith (2000). *From Whirlwind to MITRE: The R&D Story of the SAGE Air Defense Computer.* The MIT Press, Cambridge , MA.

30. Bresnahan, T. F. (1999). In *U.S. Industry in 2000. Studies in Comparative Performance.* D. C. Mowery, ed., pp. 215 244. National Academies Press, Washington, D.C.

31. Katz, B. G. and A. Philips (1982). In *Government and Technical Progress: A Cross Industry Analysis*, R. Nelson, ed., pp. 162-232. Pergamon Press, New York, NY.

32. Shockley, W. (1976). IEEE Trans. ED -23, 597-620.

33. (Moores Law Reference).

34. Misa, T. J. (1985). In *Military Enterprise and Technical Change: Perspectives on the American Experience.* M. R. Smithe, ed., pp. 253-298. The MIT Press, Cambridge, MA.

35. Wessner, C. W. (2003). *Securing the Future: Regional and National Programs to Support the Semiconductor Industry.* National Academies Press, Washington, D.C.

36. Edwards, P. N. (1996). *The Closed World: Computers and the Politics of Discourse in Cold War America.* The MIT Press, Cambridge, MA.

37. Jorgenson, D. W. and K. J. Stiroh (1999). *Am. Econ. Rev.* 89, 199 **199-115???**.

38. Norberg, A. L. and J. E. O'Neil (with K. J. Freedman) (1996). *Transforming Computer Technology: Information Processing for the Pentagon, 1962-1968.* Johns Hopkins University Press, Baltimore, MD.

39. Lickleider, J. C. R. (1960). *IRE Trans. on Human Factors in Electronics* 1, 4-11.

40. Baran, P. (1964). IEEE Trans. and Comm. (July), 1-9.

41. Abbate, J. (1999). *Inventing the Internet.* The MIT Press, Cambridge, MA.

42. Hughes, T. P. (1998). *Rescuing Prometheus.* Random House, New York, NY.

43. Kogut, B. (2003). *The Global Internet Economy*. The MIT Press, Cambridge, MA.

44. Latvan, R. E. and A. M. Rivlin (2001). *The Payoff from the Internet Revolution.* The Brookings Institution, Washington, D.C.

45. Burroughs, W. E. (1986). *Deep Black. Space Espionage and National Security.* Random House, New York, NY.

46. Dickson, P. (2001). *Sputnik: The Shock of the Century.* Walker Publishing Company, New York, NY.

47. Greer, K. E. (1995). "Corona" *Studies in Intelligence.* **S 17**???. pp. 1-37.

48. Edelson, B. I. (1984). "The Experimental Years," in *The Intelsat Global Satellite System.* J. Apter and J. N. Pelton, eds., pp. 39-53. American Institute of Aeronautics and Astronautics, New York, NY.

49. Cohen, R. L. and R. G. Noll (1991). *The Technology Pork Barrel.* Brookings Institution, Washington, D.C.

50. Bromberg, J. L. (1999). *NASA and the Space Industry.* Johns Hopkins University Press, Baltimore, MD.

51. Pasztor, A. (2003). "Satellited Bonanza Is a Fizzle." *Wall Street Journal.* September 9, p. B4.

52. Clarke, A. C. and J. G. Cloud (2000). "On the Origins of Analytical Cartography." *Geography and Geographic Information Science* 27: 195-204.

53. Cloud, J., and K. C. Clarke (1999). "The Fubini Hypothesis: the Other History of Geographic Information Science." Santa Barbara: University of California at Santa Barbara, Department of Geography (mimeo).

54. Mack, P. E. (1990). *Viewing the Earth: The Social Construction of the Landsat Satellite System,* Cambridge, MA: MIT Press.

55. David, P. A. (2004). "Can Open Science B Protected from the Evolving Regime of IPR Protections? *Journal of Institutional and Theoretical Economics* 160: 9-34.

56. Gower, S. N., A. F. H. Goetz, J. B. Schott, J. J. Thome, J. R. G. Townshend, S. L. Ustin and G. E. Woodcock (2003). Landsat Continuity Mission and Long-Term Landsat Mission: Open Letter to Science Community Landsat Data Users." Department of Geography, University of Maryland, College Park, MD (mimeo).

57. Committee on Criteria for Federal Support of Research ad Development (1995). *Allocating Federal Funds for Science and Technology.* Washington, D.C. National Academy Press: Box II.2, P. 49.

58. National Academy of Public Administration (1995). *The Global Positioning System: Charting the Future*. Washington, DCL National Academy of Public Administration.

59. Braunschvig, D., L. R. Garwin and J. C. Maxwell (2003). "Space Diplomacy." *Foreign Affairs* 82 (July/August), pp. 156-74.

60. Florini, A. M., and Y. A. Dehqanzada (2001). "The Global Politics of Commercial Observation Satellites." In *Commercial Observation Satellites: At the Leading Edge of Global Transparency.* Ed. J. C. Baker, M. O'Connell and R. A. Williamson, 433-448. Santa Monica, CA: RAN.

61. Branscomb, L. M. and P. E. Auerswald (2002). *Between Invention and Innovation.* National Institute of Standards and Technology, Washington, D.C. (NIST GCR 02-841).