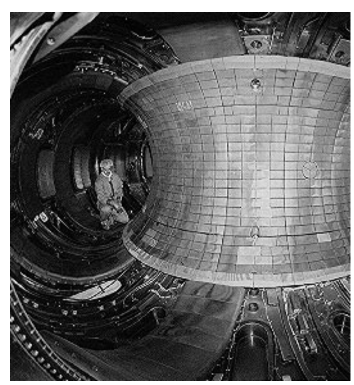
U.S. Experience in International Collaboration 3

The United States has a long history of collaboration in science dating back to the 1940s. Scientific cooperation is conducted primarily through informal agreements among scientists and institutions and through bilateral agreements between governments. High-energy physics, fusion, and space-related science activities are rich with examples of this type of cooperation. U.S. experience is more limited in large-scale collaborative projects where research efforts are highly interdependent and jointly funded and constructed. The International Thermonuclear Experimental Reactor (ITER) and U.S.-Russian activities associated with the space station are examples of large-scale collaborative efforts that involve close participation among nations. Although experience with this type of collaboration has been limited, valuable lessons have been learned.

National science goals influence whether the United States participates in scientific collaborative efforts; these goals provide the context for establishing national science programs and for developing government agency policy. In this chapter, our nation's overarching science goals are described briefly, followed by a discussion of the U.S. experience with collaborative projects in science and their implications for future activities. Several research areas are discussed: high-energy physics, fusion, scientific activities in space, and neutron sources and synchrotrons.



U.S. GOALS IN SCIENTIFIC COLLABORATION

A review of the literature suggests that since World War II, the overriding goal of U.S. megascience projects has been to establish and maintain leadership in as many scientific fields as possible. The view that maintaining scientific leadership is important has been reaffirmed in a recent White House report, *Science in the National Interest*.[1]

The significance assigned to this primary goal of leadership may have to be reevaluated, however, given the development of sophisticated science programs and facilities worldwide, the increasing costs of science, and the rapid diffusion of information. The United States is no longer the clear leader in all scientific disciplines. Other industrialized countries have developed comparable or competitive capabilities in many technical fields. Europe and Japan, for example, have leading-edge, high-energy physics and fusion programs and facilities. The ambiguous nature of the goal of maintaining scientific leadership also raises fundamental questions about what projects to fund and what level of commitment is most appropriate. Resolving these questions is the challenge that lies ahead for U.S. policymakers and for the scientific community.

Even so, leadership in science can be a source of national prestige. A classic illustration of the relation of megaprojects to national prestige is the Apollo mission to the Moon more than 25 years ago. The unexpected Soviet launching of two Sputnik satellites had rocked the foundations of the U.S. science community and its assumed technological superiority. Putting a man on the Moon was the culmination of a massive U.S. commitment to meet the Soviet challenge and win the space race. National prestige has also been cited as one of the reasons for justifying U.S. commitment to the space station.

Scientific leadership can also provide intellectual benefits to the United States by attracting top-notch foreign scientists to conduct research here. For decades, foreign scientists have made significant contributions to U.S. science efforts and have enriched its scientific community.

Other U.S. science goals are linked to economic productivity, foreign policy, national security imperatives, and environmental and social considerations. Scientific research can provide the foundation for innovation and technological development, which contributes to national economic well-being. Technological development in some fields, such as biotechnology and computers, relies on advances in basic science research. For example, research done on particle colliders and synchrotron radiation has stimulated the development of magnet technologies that have important medical and industrial applications. Likewise, basic research in solid-state physics in the 1950s laid the foundation for U.S. dominance in computer technologies today. These and other new products and processes fuel U.S. economic growth here and contribute to its competitiveness abroad.

As economic activities become more global, competition will continue to get tougher: new countries will join the competition, and new markets will emerge. It is in this context that the United States may rely even more on the results yielded by basic scientific research. In the words of Frank Press, former President of the National Academy of Sciences, "Basic research is our comparative advantage in the world. In time, a lot of countries will be able to manufacture as well as the Japanese. We're different in being able to create wealth with science."[2]

It is important to note, however, that other countries are leaders in technology development, yet they devote fewer relative resources to basic science research than the United States. Both Germany and Japan promote applications-oriented research with a view to developing products and processes for new markets. Based on the successes of the German and Japanese models, ensuring the proper mix of applied and basic research may be key to economic development.

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[1]William J. Clinton and Albert Gore, Jr., *Science in the National Interest* (Washington, DC: Executive Office of the President, Office of Science and Technology Policy, August 1994).

[2]Lee Smith, "What the U.S. Can Do About R&D," *Fortune*, Oct. 19, 1992, p. 75.

U.S. scientific preeminence and expertise have also contributed to foreign policy success and in the achievement of American goals around the world. Bilateral scientific research agreements, for example, have been used for years to build and strengthen alliances or signal displeasure. In the 1960s, bilateral science and technology (S&T) agreements between the United States and the Peoples Republic of China encouraged contact among scientists as well as government officials. As a symbolic message, the United States scaled back its S&T agreements with the Soviet Union after the Soviet invasion of Afghanistan.

Scientific agreements may also provide incentives to observe and maintain other treaties or agreements. For example, Russia's invitation to participate in the Space Station Project was, in part, contingent on its adherence to the Missile Technology Control Regime, an informal, voluntary agreement among suppliers of space technology to restrict the export of systems and components used for ballistic missiles. Moreover, bilateral scientific agreements may play a role in sustaining the science base of the former Soviet Union, promoting its stability, and preventing the proliferation of weapons-related expertise. With the end of the Cold War, however, S&T agreements may be less important as foreign policy tools.

Science has contributed in significant ways to national security goals as well. Our military technological superiority is the result of advances in fundamental science and engineering. As our national security goals are redefined by the end of the Cold War, basic science will continue to figure prominently. One of the most troublesome security challenges now facing the United States is the proliferation of nuclear weapons. New and improved technologies, particularly in arms monitoring and verification, will be required to meet this challenge.

Over the years, scientific research has enjoyed the strong support of different administrations and Congress. However, funding priorities have shifted in response to international events and domestic politics (see box 3-1).

Recently, complex and costly science projects, such as the Superconducting Super Collider (SSC), the Advanced Neutron Source, and the Tokamak Physics Experiment,[3] have motivated debate in the Administration and Congress about national research goals and the capacity of the U.S. government to fund basic research. In this context, there has been much discussion about the potential for international collaboration in large science projects. Collaborative efforts are now under way in space, fusion, and high-energy physics.

HIGH-ENERGY PHYSICS

High-energy physics is a field of basic scientific inquiry that explores the fundamental characteristics of matter and the basic forces that govern all physical phenomena. To gain insights about elementary particles and their interactions, physicists probe energy domains far removed from those encountered in daily life.[4] In its attempt to extend the frontiers of human knowledge about underlying natural processes and laws, and to answer questions about the origin of the universe, the high-energy physics field has especially defined itself by drawing on the intellectual resources of scientists throughout the world.

[3] The TPX is a fusion device proposed to be built at the Princeton Plasma Physics Laboratory. Congress has not yet authorized funds to begin construction of the approximately $700 million TPX. For an indepth discussion on the TPX, see the recent report, U.S. Congress, Office of Technology Assessment, *The Fusion Energy Program: The Role of TPX and Alternate Concepts,* OTA-BP-ETI-141 (Washington, DC: U.S. Government Printing Office, February 1995).

[4] Existing and new particle accelerators operate at energies in the billion electron volt (GeV) to trillion electron volt range (TeV). By comparison, the thermal combustion of a single carbon atom contained in coal releases about four electron volts. Thus, a single particle (e.g., a proton or electron) being accelerated to 1 TeV would have an energy about a trillion times greater than that associated with the burning of a carbon atom.

BOX 3–1: Funding Priorities

Broad-based federal support for scientific research has spanned five decades. During this period, the ability of the United States to conduct research has grown considerably and so, too, has the demand for funding. Today, there are far more opportunities for research than there are funds to support projects. Consequently, research funding decisions have been challenging and sometimes contentious for Congress, the Administration, and the scientific community.

Since federal support began in the mid-1940s, a key consideration in allocating federal funds has been the need to maintain a diverse portfolio of large and small science projects. Other considerations have included enhancing the U.S. science base in specific research areas, and training scientists and engineers In recent years, budgetary considerations have focused increased attention on the need for more explicit priority setting as a way to help allocate federal resources and strengthen the nation's portfolio. Currently, priority setting is distributed throughout the federal government at many different levels. At the highest level, scientific priorities are compared to other conscience needs. Priorities are also determined across research fields and within particular disciplines. The OTA report, *Federally Funded Research: Decisions for a Decade,* identified priority setting as a pressing challenge for the U.S. research system in the 1990s.[1]

A snapshot of historical funding priorities reveals that during World War II, federal investment focused on military and atomic energy-related projects. In the 1950s and 1960s, Soviet achievements in space and expanded military spending prompted the United States to increase funding for its own space initiatives and defense programs. By the late 1960s, however, research funding had declined due, in part, to the enormous costs of the Vietnam War and the expansion of domestic social programs. The decade of the 1970s brought renewed interest in space projects, the expansion of funding for energy and health research, and cuts in defense research and development (R&D). In the 1980s, during the Reagan Administration, defense projects regained top funding priority, and energy and health research funding declined. At the same time, basic science funding also increased Big science and technology projects, such as the space station, the Superconducting Super Collider, the Strategic Defense Initiative, and the Human Genome Project figured prominently on the national agenda. Finally, the belt-tightening of the early 1990s brought yet more changes, including termination of the SSC project, redesign of the space station, and the addition of Russia as a space station partner in 1994.

Despite the vicissitudes of funding during this period, megascience projects, including presidential science initiatives, have continued to command a noticeable portion (about 10 percent) of total federal R&D expenditures.[2] However, because of the disparate characteristics of large projects, comparisons and priority setting have proven difficult, resulting in a funding process for large projects that remains largely ad hoc.

[1] See U.S. Congress, Office of Technology Assessment, *Federally Funded Research: Decisions for a* Decade, OTA-SET-490 (Washington, DC: U.S. Government Printing Office, May 1991)

[2] Genevieve J Knezo, *Major Science and Technology P* *1996,* CRS Report for Congress, 95-490 SPR (Washington, DC: Congressional Research Service, Mar. 27, 1995

The principal scientific tool of this field of research is the particle accelerator. By accelerating particles to extremely high energies and bringing them together in collisions, researchers are able to develop greater understanding of the innermost structure of matter. This is done by observing the debris from collisions using extremely sophisticated detectors. Because energy and mass are interchangeable, high-energy particle collisions essentially redistribute mass and energy to create

TABLE 3-1: Elementary Particles and Force Carriers

First-generation family	Second-generation family	Third-generation family
Electron	Muon	Tau neutrino
Electron neutrino	Muon neutrino	Tau lepton
Up quark	Charm quark	Top quark
Down quark	Strange quark	Bottom quark
Force carriers	**Force**	
Photon	Electromagnetic force	
W boson	Weak nuclear force	
Z boson	Weak nuclear force	
Gluons	Strong nuclear force	

SOURCE: U S Department of Energy, Office of Energy Research, Division of High Energy Physics, *High Energy Physics Advisory Panel's Subpan. el on Vision for the Future of High Energy* Physics, DOE/ER-0614P (Washington, DC: May 1994).

new particles.[5] The higher the impact energy, the more massive these new particles can be, thus revealing hitherto unknown or *hidden* properties of matter. As a consequence of the need for higher energies, accelerators have increased considerably in size over the years. Accelerators and detectors are large, elaborate, expensive devices, and experiments typically involve the collaboration of hundreds of scientists and engineers.

Over the past 50 years, the experimental discoveries and theoretical insights of researchers worldwide have led to the construction of a remarkably successful model that describes the types of particles that exist in nature and how they interact with each other. This so-called Standard Model depicts all matter as consisting of only three families of fundamental particles. (See table 3-l.) Each family contains two types of *quarks*[6] and two types of *leptons.*[7] The protons and neutrons that form atomic nuclei are combinations of two different types of quarks, and the electrons that surround atomic nuclei are leptons. The remaining quarks and leptons are not found in ordinary matter and can only be studied in high-energy processes. The forces that operate among quarks and leptons are mediated by additional particles.[8]

Although the Standard Model has proved a successful predictive and explanatory tool, physicists believe that it cannot answer a number of questions. For example, why are there so many elementary particles and why do they appear as three

[5]This phenomenon is described by Einstein's formula $E = mc^2$. The process by which new heavy particles are created from the collisions of lighter particles is akin to a bowling ball emerging from the collision of two tennis balls. For example, the recently discovered *top quark, the* heaviest of known elementary particles, has a mass equivalent to that of a gold atom. Evidence for the existence of the top quark, the last quark to be identified, was announced in March 1995 by two independent teams of researchers at the Fermi National Accelerator Laboratory.

[6]The names given to these six quarks are up, down, strange, charm, bottom, and top. They each have different masses and charges. The proton consists of two up quarks and one down, while a neutron consists of two downs and one up. For further information see Daniel Morgan, *High-Energy Physics Accelerator Facilities,* CRS Report for Congress (Washington, DC: Congressional Research Service, Sept. 17, 1993), appendix, pp. CRS-22 to CRS-23.

[7]Each elementary particle also has a corresponding *antiparticle* with identical mass but opposite charge. For example, the antiparticle of the electron is the positron. Positrons are produced in accelerator collisions and have found important use as a medical diagnostic tool, a technique called positron emission tomography. Combinations of quarks and antiquarks can account for the roughly 200 known particles or *hadrons* that have been discovered.

[8]Quarks and leptons interact by exchanging particles known as force earners. The strong force that holds quarks together to form protons and neutrons is mediated by gluon particles; the weak force is mediated by W and Z bosons, and the electromagnetic force is mediated by photons. It is speculated that the force of gravity is also mediated by a particle earner, but no such carrier has been discovered.

families as opposed to any other number? What is the origin of mass and why do the fundamental particles exhibit no regularity in their masses?[9] Why is the universe made primarily of matter when the Big Bang theory would predict the creation of equal amounts of matter and antimatter?[10] Can the missing mass of the universe be explained by an as-yet undiscovered class of super-heavy particles?[11] The high-energy physics community believes that experimental clues to these questions could be provided by the next generation of high-energy particle accelerators. With the termination of the SSC, the Large Hadron Collider at CERN is the only currently approved project that will be capable of addressing most of these issues.[12]

U.S. Goals

Since World War II, the United States has been a global leader in both the experimental and the theoretical domains of high-energy physics. U.S. high-energy physics facilities are among the best in the world and have provided unique opportunities to conduct research and to advance scientific understanding.[13] In addition, these facilities have stimulated interest in science among the nation's young and have served as an important component of graduate-level education and training. Although establishing and maintaining a leadership position in high-energy physics research has been a major goal of U.S. programs, a policy of open access has also encouraged many researchers from Europe, Japan, and other parts of the world to participate in U.S. projects. Indeed, several prominent foreign scientists have received their training at U.S. facilities.

In recent years, U.S. leadership in high-energy physics has been challenged by scientific developments in Europe and Japan. Additionally, domestic budget constraints have limited various experimental endeavors, and some new or existing projects have been either deferred or canceled. The recent termination of the SSC project was a major blow to the U.S. program.[14] In the early 1980s, the U.S. high-energy physics community embraced the construction of the SSC as its top priority. The project was expected to open new windows of discovery and thereby solidify the leadership position of the United States well into the next century. Questions about its management, performance, and spiraling cost estimates,

[9]One theory suggests that particles acquire mass through interaction with a ubiquitous force field known as the Higgs field. Confirmation that such a field exists would come from the discovery of very heavy particles known as Higgs particles. Theory predicts that Higgs particles would have masses in the 1 TeV range, energies that cannot be produced by any existing accelerator. The Large Hadron Collider (LHC) device at CERN (as well as the canceled SSC) is designed to explore the energy range where Higgs particles might exist if the Standard Model is correct.

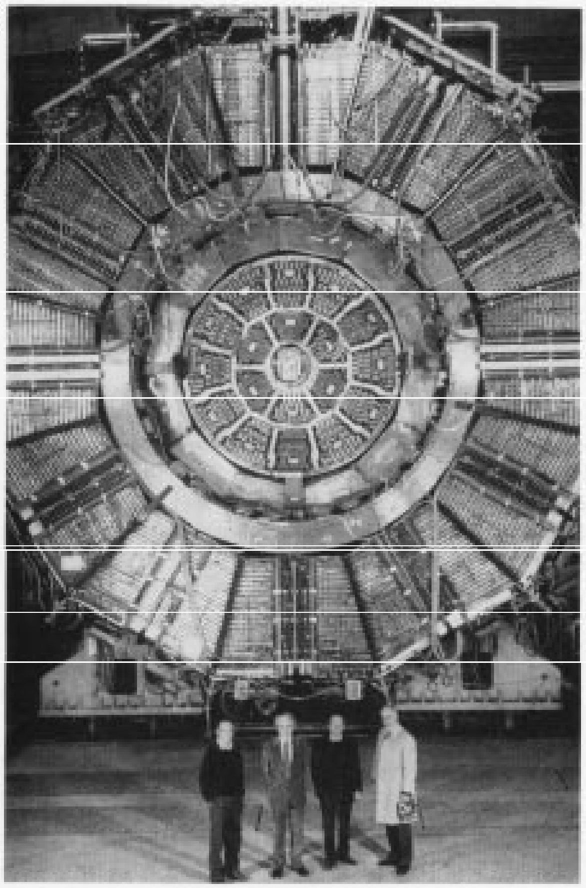
[10]This particular question is being addressed specifically by the *B-factory* projects being carried out at the Stanford Linear Accelerator Center and at the KEK facility in Japan.

[11]A central problem of modern astronomy is that most of the mass of the universe (90 percent) cannot be seen (so-called *dark* matter), but can be inferred from the gravitational behavior of galaxies. One possible theory accounts for this missing mass by positing the existence of neutral, stable particles that have not yet been detected. Such *supersymmetric* particles might be seen at the energies provided by the LHC facility now under construction at CERN.

[12]Although the LHC will have a combined beam energy roughly three times lower than the SSC, the luminosity or beam intensity of the LHC will be 10 times greater than that of the SSC. The LHC will be able to probe energies up to about 2 TeV. However, because of its higher luminosity, there will be a greater number of undesired collisions (so-called *noise*) that must be filtered by sophisticated detectors. The detector technologies that will be deployed at the LHC will be much more complex than those planned for the SSC.

[13]The Department of Energy operates several high-energy physics and related nuclear physics facilities. They include the Alternating Gradient Synchrotron and the Relativistic Heavy Ion Collider at Brookhaven National Laboratory, the Tevatron at Fermilab, the electron linac at the Stanford Linear Accelerator Center, and the Continuous Beam Accelerator Facility (CEBAF) in Newport News, Virginia. The National Science Foundation funds the Cornell Electron Storage Ring.

[14]Murray Gell-Mann, a recipient of the Nobel Prize for his work in particle physics, described the termination of the SSC as a "conspicuous setback for human civilization." "Physicists Ponder Life After the Demise of the Supercollider," *New York Times*, Aug. 9, 1994, p. C5.



The ALEPH detector at CERN.

however, severely damaged support for the project.[15] Because of its cancellation, the United States is now exploring ways to maintain a presence at the high-energy frontier by utilizing and upgrading existing facilities and participating in international efforts.

In 1994, a subpanel of the Department of Energy High Energy Physics Advisory Panel (HEPAP) presented options for the future U.S. program. The HEPAP subpanel noted the importance of international collaboration in preserving U.S. scientific and technological capabilities. U.S. scientists already participate in experiments at several laboratories in Europe and Japan. For example, several hundred American physicists and engineers are now involved with various experiments at the DESY (Deutches Elektronen-Synchrotron) facility in Germany and at CERN in Switzerland. As a specific measure to ensure that U.S. scientists remain at the forefront of accelerator design and physics investigation, the subpanel recommended that the United States also join the LHC project at CERN.[16] However, the subpanel concluded that the long-term future of U.S. high-energy physics will depend on the research and development (R&D) foundation built here, not in Europe or Japan.

While many important technical innovations have resulted from high-energy physics research and related areas of nuclear physics research, these spinoffs have invariably been unanticipated, have occurred over a period of decades, and have often resulted from scientists from many countries working together.[17] In light of this history and the somewhat esoteric character of high-energy physics research, it is difficult to argue that participa-

[15] Initially, the project was estimated to cost about $4.4 billion (in 1988 dollars without an allowance for contingencies), but by 1993, cost estimates had escalated to more than $11 billion. At the time of termination, 15 miles (of a total of 54) of tunnel had been dug, magnets had been tested, and $2.2 billion spent, mostly on salaries. Some observers argue that the management of the SSC was politicized and taken out of the hands of Department of Energy technical managers who had a good record in overseeing the planning and execution of large projects. As a consequence, the various problems that developed over the course of the SSC endeavor might have been either avoided or addressed in a more effective manner.

[16] U.S. Department of Energy,Office of Energy Research, Division of High Energy Physics, *High Energy Physics Advisory Panel's Subpanel on Vision for the Future of High Energy Physics,* ***DOWER-0614P*** (Washington, DC: May 1994).

[17] Some examples of spinoffs from high-energy physics and nuclear physics research include ion implantation in the semiconductor industry, accelerate-based cancer therapy, computerized axial tomography (the CAT scanner), positron emission tomography, free electron lasers, synchrotrons generated x-ray beams, and large data-handling and transfer software. See Paul David et al., Stanford University, Center for Economic Policy Research, ''The Economic Analysis of Payoffs from Basic Research-An Examination of the Case of Particle Physics Research," CEPR Publication No. 122, January 1988.

TABLE 3-2: Escalation of Costs in High-Energy Physics and Related Areas of Nuclear Physics

Project	Decade	Nominal capital cost
Bevatron (U. S.)	1950s	$10 million
Stanford Linear Accelerator (U. S.)	1960s	$115 million
Fermilab Tevatron (U. S.)	1970s	$250 million
Continuous Electron Beam Accelerator Facility (U.S.)	1980s-1990s	$51 @million
Relativistic Heavy Ion Collider (U. S.)	1990s	$595 [a] million
Superconducting Super Collider (U. S.)	1980s-1990s[b]	$8 billion-$11 billion[a]
Large Hadron Collider (Europe)	1990s[c]	$2.3 billion[d]

[a]Estimated total project cost.

[b]project terminated, 1993.

[c]Completion planned 2005 to 2008.

[d]The estimated cost for the Large Hadron Collider would be roughly twice as large ($4 to $5 billion) if it were developed On the same accounting basis as U.S. cost estimates, Also this figure does not include the detectors, which may total as much as $2 billion.

SOURCE: Organization for Economic Cooperation and Development, *Megascience and Its Background* (Paris, France: 1993), p 19; Congressional Research Service, "Big Science and Technology Projects' Analysis of 30 Selected U.S. Government Projects, " August 24, 1994; and Harold Jaffe, Department of Energy, Office of High Energy and Nuclear Physics, personal communication, April 1995,

tion in multinational particle physics projects could undermine a country's technological competitiveness (see chapter 2).

■ Role of International Collaboration

High-energy physics research is a particularly good candidate for international collaboration for two reasons: 1) research in this field is essentially curiosity driven with little or no expectation of short-term commercial returns, and 2) the knowledge generated from particle physics experiments is more of a global than a national asset. Indeed, the most exciting advances in particle physics have resulted from the pooling of intellectual resources throughout the world. In light of the great expense required to build new accelerators (see table 3-2), collaboration among nations is likely to deepen in coming years.

The most recent accomplishment of researchers—the experimental verification of the existence of the top quark[18]—provides a compelling illustration of the universal character of the high-energy physics enterprise. More than 800 scientists from Brazil, Canada, Colombia, France, India, Italy, Japan, Korea, Mexico, Russia, Taiwan, and the United States collaborated on the two colliding beam experiments at Fermilab (CDF and DZero) that discovered the top quark. Moreover, about one-third of the funds for the 5,000-ton, $100 million CDF detector were provided by the Japanese and Italian governments. Over its entire history, 151 foreign institutions from 34 nations have been actively involved in research at Fermilab. Similar collaborative efforts have also occurred at Stanford Linear Accelerator Center (SLAC), the National Laboratory for High-Energy Physics (KEK) facility in Japan, and CERN. Because the high-energy physics community has evolved into a tightly linked network in which researchers from throughout the world communicate almost daily, collaboration has become an integral feature of nearly all empirical and theoretical undertakings.

Even with greater collaboration, innovation and competition in high-energy physics can be achieved by having multiple detectors at a single facility. For example, evidence for the discovery of the top quark was reinforced by the fact that two

18See S. Abachi et al. (The D0 Collaboration), "Observation of the Top Quark," Fermilab preprint, February 1995; and F. Abe et al. (The CDF Collaboration), "Observation of Top Quark Production in [proton-antiproton] Collisions," Fermilab preprint, February 1995.

TABLE 3-3: High-Energy Physics Facilities

Electron-positron collider			Hadron collider and fixed target machines		
Name	Institution	Country	Name	Institution	Country
LEP	CERN	European Consortium	Tevatron	FNAL	United States
SLC	SLAC	United States	SPS	CERN	European Consortium
CESR	Cornell University	United States	AGS	BNL	United States
TRISTAN	KEK	Japan	UNK 600		Russia
BEPC		China	PS	KEK	Japan
VEPP-4M		Russia	HERA	DESY	Germany
			LHC	CERN	European Consortium
			CEBAF		United States

KEY: AGS = Alternating Gradient Synchrotrons; BEPC = Beijing Electron-Positron Collider; BNL = Brookhaven National Laboratory, CEBAF = Continuous Electron Beam Accelerator Facility; CERN = European Laboratory for Particle Physics; CESR = Cornell Electron Storage Ring, DESY = Deutches Elektronen Synchrotrons; FNAL = Fermi National Accelerator Laboratory; HERA = Hadron Elektron Ring Anlage; KEK = National Laboratory for High Energy Physics; LEP = Large Electron-Positron Collider; LHC = Large Hadron Collider; PS = Proton Synchrotrons; SLAC = Stanford Linear Accelerator Center; SLC = Stanford Linear Collider; SPS = Super Proton Synchrotrons; TRISTAN = Transposable Ring Intersecting Storage Accelerator in Nippon; UNK 600 = Accelerating and Storage Complex; VEPP = Very Large Electron-Positron Project

SOURCE: OECD Megascience Forum

independent detector teams—the CDF and DZero groups—provided empirical findings. The LHC will also have two detector groups using different approaches—the ATLAS and CMS detectors.

In some cases, having parallel facilities—whether within a country or in different countries—is desirable. For example, both the United States and Japan are constructing *B-meson factories* as a means to understand the fundamental differences between matter and antimatter.[19] Even though the ultimate goals of the two projects are similar, they will employ different underlying technologies. This diversity of approach could lead to the development of new accelerator designs. In this particular case, construction of the B-factory in Japan was an integral component of its long-term strategy to develop expertise in the construction of advanced linear colliders.[20] As in the case of the top quark, having parallel efforts can provide important experimental verification of newly observed phenomena.

Although the design and management of future experimental facilities will likely involve many nations, existing high-energy physics facilities around the world (see table 3-3), with the exception of CERN, are currently funded and operated on a national basis. This is due principally to the fact that planning for most high-energy physics projects started 20 years ago or more. In addition, at various points in the past, high-energy physics research was regarded as a possible source of defense-related information. Even during the Cold War, however, scientists from Western countries

[19] A B-factory produces pairs of B mesons and anti-B mesons for the purpose of studying the phenomenon known as *charge-parity (CP)* violation. CP violation, which could explain why the universe appears to contain much more matter than antimatter, is an important concept in the Standard Model of particle physics. The U.S. B-factory is being built at the SLAC at a cost of $293 million. A similar factory is also being constructed at the KEK facility in Japan for about $350 million. Relative to other projects such as the LHC ($2.3 billion), the B-factory costs are low enough to be pursued on a noncollaborative basis. Some observers, however, argue that only one B-factory was necessary.

[20] Hirotaka Sugawara, Director, KEK National Laboratory for High Energy Physics, personal communication, Nov. 16, 1994.

were invited to work at the U.S.S.R.'s high-energy physics facilities on well-defined programs.[21]

Implications for the Future

In light of its many achievements over the past several decades, the U.S. high-energy physics program has been generally regarded as quite successful. U.S. capabilities are world class, and policies that encourage collaboration through open access arrangements have advanced the underlying science and strengthened ties with the international high-energy physics community. Because of the sophisticated nature of experimental work and the significant capital investments required, the level of this multinational interaction can be expected to intensify in coming years.

The history of the U.S. high-energy physics program, along with tightening budgets, suggests some important issues for consideration by policymakers and scientists alike:

- If it is determined that future high-energy physics projects should be carried out on an international basis, such initiatives will most likely fare better if they are truly collaborative from the outset: in planning, financing, construction, and operation. In the SSC project, the United States sought foreign partners as a way of sharing costs well after key engineering decisions had been made. This did not prove to be a good formula for successful development of an international venture.
- U.S. participation in the LHC project at CERN could lay the foundation for future cooperative efforts in high-energy physics. Regardless of the particular form of the U.S. contribution to the LHC—whether knowledge, dollars, or equipment—an important precedent is being set in the area of international collaboration.[22] Participation in the LHC could maintain and perhaps even extend American capabilities in the design of accelerator and detector systems and components (e.g., superconducting magnets). The HEPAP subpanel concluded that participation in the LHC project could also "strengthen our [U.S.] credibility as a capable host for such [large] projects in all fields of science."[23] The Department of Energy (DOE) is expected to recommend that U.S. contributions to the LHC project be roughly $40 million annually over the next decade.[24]
- Government decisionmakers from countries with major high-energy physics programs could benefit from the creation of mechanisms that facilitate multilateral planning of future large high-energy physics facilities. This would apply to hadron colliders that succeed the LHC[25] and to proposed electron-positron colliders such as the Next Linear Collider

[21]See Center for Science, Trade and Technology Policy, George Mason University, "Large Science Project Priorities of Selected Countries," report prepared for the Office of Technology Assessment, December 1994.

[22]CERN's member states contribute both to the infrastructure costs of the laboratory in proportion to their gross domestic product, and to the costs of their experimental teams who build and use detectors. Nonmember states, including the United States, need bear only the second of these financial burdens. However, because nearly 500 American physicists are involved with the two LHC detectors, the CERN Council is seeking U.S. contributions to the LHC accelerator project itself. John Krige, "ESA and CERN as International Collaborative Science Organizations," contractor report prepared for the Office of Technology Assessment, January 1995.

[23]U.S. Department of Energy, see footnote 16.

[24]See testimony of Martha Krebs, Director of DOE's Office of Energy Research, before the Subcommittee on Energy and Water Development, House Committee on Appropriations, Mar. 9, 1995. DOE, however, will not be in a position to recommend any specific level of LHC funding until overall Department cost reduction goals through 2001 are developed.

[25]The HEPAP subpanel (chaired by Sidney Drell) points out that "preliminary examination indicates that it may become practical to build a proton collider with beams of up to 10 times the energies of the LHC, using technology that could be developed in the next decade." Such a collider could be used to search for so-called *supersymmetric* or superheavy particles that may lie beyond the energy range of the LHC. U.S. Department of Energy, see footnote 16.

(NLC).[26] The NLC is already a multinational grass roots effort among scientists from more than 20 nations (preliminary experiments involve researchers from the United States, Japan, and Russia). Some scientists believe that the NLC should be set up as an international organization similar to CERN.[27] Even though it is only at an early concept stage, this embryonic collaboration could receive greater attention from relevant governments.

- Policymakers could explore opportunities for consolidation of high-energy physics research activities, as well as the possible elimination of duplicative programs and facilities. Strategies for efficiently utilizing existing high-energy physics facilities could also be developed. This could mean closing down some facilities and using the funds to extend operations at others. The DOE budget for fiscal year (FY) 1996 takes a step in this direction by providing funds to increase the effectiveness of high-energy physics facilities at Fermilab, SLAC, and Brookhaven. Cost-effectiveness can also be achieved by upgrading existing facilities. The construction of the new Main Injector[28] at Fermilab is one such undertaking. The United States could also examine where high-energy physics objectives might be met by using facilities in other nations. U.S. and foreign high-energy physics programs could be designed to take advantage of existing expertise and infrastructure throughout the world.
- Greater attention and possibly higher levels of funding could be given to nonconventional (e.g., nonaccelerator) approaches to high-energy physics. In light of the extraordinary costs of state-of-the-art accelerator facilities, support of novel approaches to particle acceleration could ultimately provide a fundamentally different and less costly means for probing the high-energy frontier. Although work in this area is now quite speculative, some interesting nonconventional approaches have emerged.[29]
- Given the success of the U.S. high-energy physics program over the past several decades, policies of *open* and *reciprocal* access for foreign scientists to national installations should be maintained. However, at a time of tightening budgets in virtually all industrial countries, strategies for ensuring equitable sharing of high-energy physics facility costs and benefits should also be explored.

FUSION ENERGY RESEARCH

For more than four decades, researchers in the United States and elsewhere have been working to understand and control nuclear fusion, the reac-

[26]Hadron colliders and electron-positron colliders are complementary experimental approaches. Hadron colliders provide great reach in energy, while electron-positron colliders provide a precise method to search for new phenomena in finer detail. The Large Hadron Collider at CERN and the Tevatron at Fermilab are designed to collide particles (hadrons) that are comprised of quarks. These collisions result in considerable debris, which makes it difficult to analyze data. In electron-positron collisions, however, the colliding particles (electrons and positrons, which are fundamental particles like quarks) annihilate each other; thus the only particles remaining after the collision are those created by the energy released. This makes it relatively easy to identify collision products. David Burke, Stanford Linear Accelerator Center, personal communication, Sept. 13, 1994.

[27]Japanese physicists are quite interested in taking a lead role in constructing the NLC facility. However, the Japanese government has taken no official position on this matter. Sugawara, see footnote 20; and Wataru Iwamoto, Ministry of Education, Science, and Culture, Research Institute Division, personal communication, Nov. 15, 1994.

[28]The new Main Injector at Fermilab, which is scheduled to begin operating in 1999, will greatly increase the number of high-energy collisions that experimenters can observe, and thus provide the opportunity for new discoveries. The Main Injector will be the most powerful proton accelerator in operation until the completion of the LHC in about 2004.

[29]For example, some researchers are exploring how particles can be accelerated by plasma waves. Some preliminary work suggests that in just one meter, plasma wave accelerators could reach energies around 30 GeV—about one-third of the energy that can be attained by the 27-kilometer circular electron-positron collider at CERN. A variety of serious technical hurdles must be surmounted before such a plasma wave scheme becomes workable. See Jonathan Wurtele, “Advanced Accelerator Concepts,” *Physics Today*, July 1994, pp. 33-40.

BOX 3–2: Fusion Re

A fusion reaction occurs when the nuclei of atoms of two light elements fuse to form an atom of a heavier element and additional particles, releasing energy. Scientists have found it easiest to produce fusion reactions using isotopes of hydrogen, the lightest element. The reaction illustrated in figure 3-1 shows the fusion of deuterium (D) and tritium (T) nuclei to produce a helium nucleus and a free neutron. The reaction releases a total of 17.6 million electron volts (MeV) of energy.[1] The neutron carries 14.1 MeV or four-fifths of the energy. In a fusion power reactor, the 14-MeV neutrons would be captured in the material surrounding the reaction chamber and converted into heat. The helium nuclei carrying 3.5 MeV would remain in the chamber, heating the fuel and making more reactions possible.

For the reaction to occur, certain conditions of temperature, density, and confinement time must be met simultaneously. Theoretically, there are a broad range of approaches that could be used to create fusion reactions.[2] In the laboratory, scientists have heated fusion fuels to over 100 million degrees Centigrade to form a *plasma,* a state in which individual atoms are broken down or ionized into their constituent electrons and nuclei. At these extremely high temperatures, the positively charged nuclei are able to overcome their natural repulsion and fuse. However, the plasma must be kept together long enough for enough of the nuclei to fuse to be a net producer of energy.

Several approaches to confining the plasma have been explored. In *magnetic confinement,* strong magnetic fields are used to control and shape the charged particles making up the plasma. These fields prevent the plasma from touching the reaction chamber walls, which would instantly cool and stop the reaction. The most technically successful magnetic confinement concept is the *tokamak,* which confines the plasma in a toroidal or donut-shaped vessel.

Inertial confinement fusion, the process used on a much larger scale in the hydrogen bomb, represents another approach under investigation. In this process (shown in figure 3-2), a pellet of fusion fuel is rapidly heated and compressed by intense lasers or heavy-ion drivers to such high densities that the fuel's own inertia is sufficient to contain it for the very short time necessary for the reaction to occur. Gravitational fields are sufficient to confine the fusion reactions in the Sun and other stars, but this approach cannot be duplicated on Earth.

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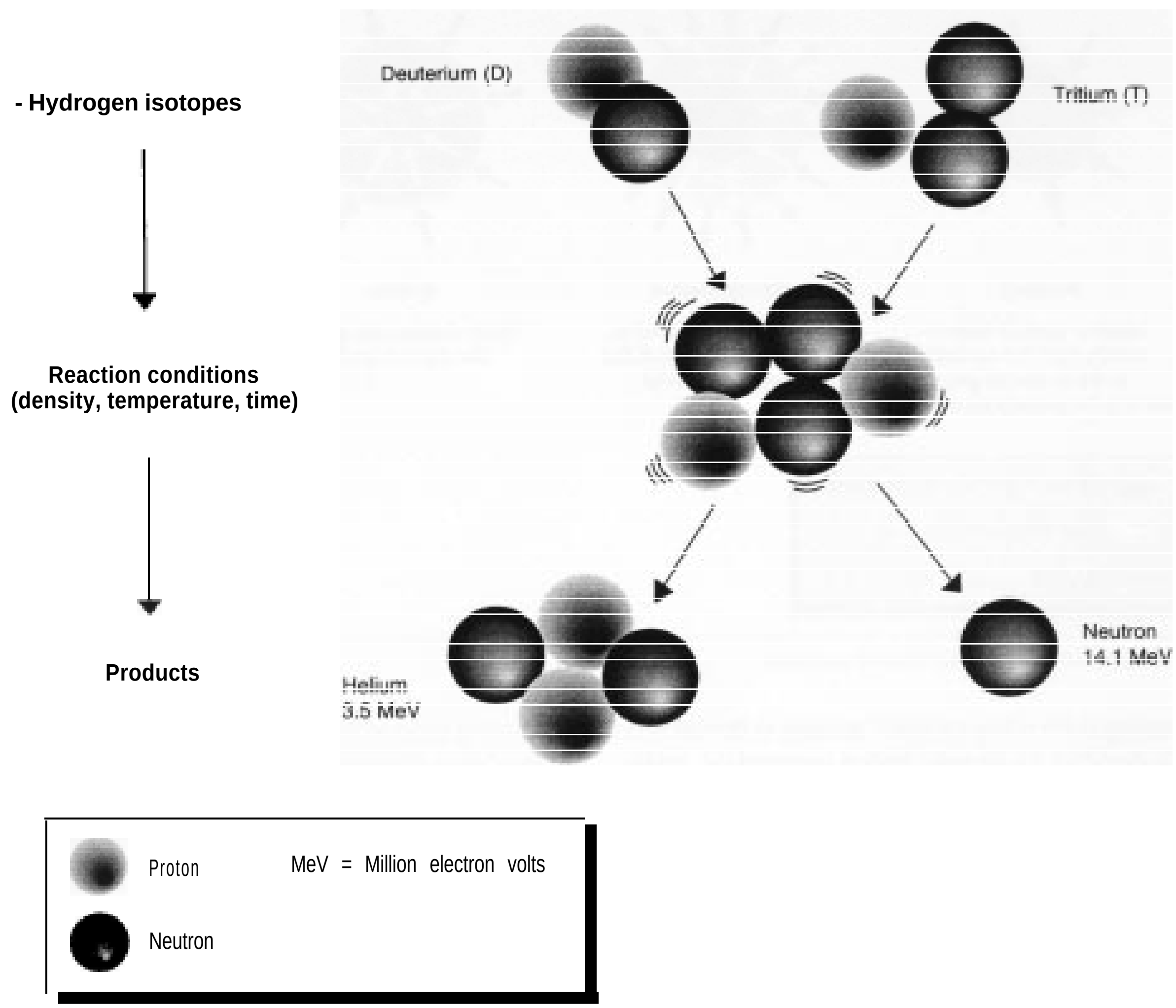
[1] For comparison, burning a single atom of the carbon contained in coal produces about 4 electron volts. A fusion reaction therefore releases more than 4 million times as much energy per atom as coal combustion. An electron volt is the amount of energy that a single electron can pickup from a 1 -volt battery One electron volt equals 1.52×10^{-22} Btu (British Thermal Unit), or 4.45×10^{-26} kilowatt-hours, or 1.6×10^{-19} joules.

[2] For more detail on fusion science and the history of magnetic fusion research, see U.S. Congress, Office Of Technology Assessment, *Starpower: The U.S. and the International Quest for Fusion Power,* OTA-E-338 (Washington, DC: U. S. Government Printing Office, October 1987). See also, U.S. Congress, Office of Technology Assessment, *The Fusion* Energy Program: *The Role of TPX and Alternate Concepts,* OTA-BP-ETI-141 (Washington, DC: U.S. Government Printing Office, February 1995), pp. 65-80, for recent developments and more on the state of research into other fusion concepts.

tion that powers our Sun, the stars, and the hydrogen bomb, in the hopes of one day tapping that process as a safe, environmentally attractive, and economical energy source. Fusion reactions occur when the nuclei of two lightweight atoms combine, or fuse, releasing energy (see box 3-2). Fusion research gave birth to and nourished the new field of plasma physics, which explores the behavior of plasmas, the fourth state of matter.

Among the advantages cited by fusion supporters are a virtually limitless fuel supply and potentially less serious environmental impacts than competing fossil or nuclear fission technologies. Developing fusion power requires first demonstrating its scientific and technical feasibility and then establishing it as a commercially attractive (i.e., economically competitive and publicly acceptable) power source. Significant domestic and

FIGURE 3-1: Deuterium-Tritium Fusion Reaction



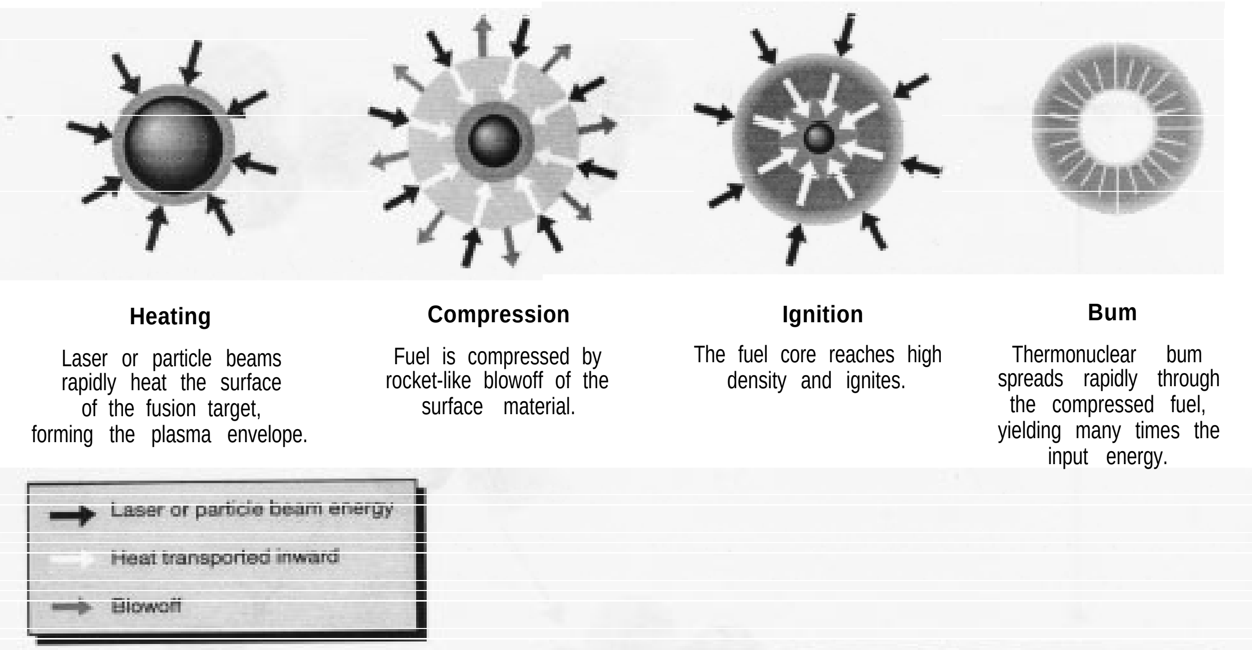
SOURCE: Office of TechnologyAssessment 1995, based on figure from U.S. Department of Energy, Office of Fusion Energy.

international resources have been devoted to achieving this goal, and substantial scientific and technical achievements have been realized to date. Most experts, however, readily concede the world is still several decades and several tens of billions of dollars away from realizing commercially relevant fusion-generated electricity.

Notable progress has been made in addressing the scientific and technical challenges to fusion power development. Researchers at the Princeton Plasma Physics Laboratory attained a world record in fusion energy production of 10.7 megawatts (MW) in experiments on the Tokamak Fusion Test Reactor (TFTR) in 1994. This marked an increase in fusion power production by a factor of about 100 million over that achievable 20 years ago. Fusion temperatures of 400 million degrees Centigrade have also been attained in experiments.

Among the scientific challenges remaining to be met in fusion research include achieving high-energy gain (energy output that is many times higher than energy input to create the reaction) and ignition (the point at which a reaction is self-sus-

FIGURE 3-2: Inertial Confinement Fusion Process



SOURCE: Lawrence Livermore National Laboratory.

taining even when external heating is turned off). To develop a magnetic fusion powerplant, scientists must also be able to achieve high-energy gain in a steady state (continuous, rather than intermittent, operation). Reaching the critical milestone of breakeven (the point at which the energy produced by fusion reactions equals the energy input to heat the plasma) remains beyond the reach of current facilities. The TFTR experiments reached just over one-quarter of breakeven for a few moments. The proposed ITER is being designed to reach ignition and to operate for long pulses of several hundred to more than 1,000 seconds. If successful, ITER would accomplish several critical milestones in the development of a fusion power reactor. Substantial engineering challenges in developing materials, components, and systems for operating fusion reactors also remain and will have to be met through a broad-based program of scientific, technical, and industrial R&D.

Under plans established a few years ago, tens of billions of dollars and about three decades of continued successful R&D are expected to be required before the science and technology are sufficiently advanced to enable construction of a demonstration commercial fusion power reactor. This facility (dubbed DEMO) is scheduled to follow ITER in about 2025. An actual commercial prototype is anticipated to be operational around 2040 under this schedule.

DOE sponsors two fusion research programs: the Magnetic Fusion Energy (MFE) program of the Office of Fusion Energy under the Office of Energy Research, and the Inertial Confinement Fusion (ICF) program in the Office of Defense Programs. The Office of Fusion Energy has responsibility for research on the energy aspects of both magnetic and inertial confinement fusion. Work on ICF science and technology in defense programs advances eventual energy applications of inertial fusion energy. DOE-sponsored fusion research activities are carried out at national laboratories, universities, private companies, and international research centers.

Program Goals and Funding

Fusion research program goals have been established by legislation and by presidential and secretarial decisions.[30] The overarching goal of the program is to demonstrate that fusion energy is a technically and economically viable energy source, specifically by developing an operating demonstration fusion power reactor by about 2025 to be followed by an operating commercial prototype reactor by about 2040. Other goals include the development of fusion technologies, the education and training of fusion scientists and engineers, and the encouragement of industrial participation and international collaboration. Budget realities, however, have tempered the expectations for achieving this optimistic development schedule.[31] Civilian energy goals for the ICF energy program are directed at the development of components for fusion energy systems that can take advantage of the target physics developed by the Defense Programs ICF research. Underlying both the MFE and the ICF research programs is a desire to maintain the U.S. position in the forefront of fusion research internationally and to preserve U.S. capability to participate in any future fusion technology advances.

Legislative authority for fusion energy research is found in the Atomic Energy Commission Act of 1954 (AEC Act);[32] the Magnetic Fusion Energy Engineering Act of 1980 (MFEEA);[33] and the Energy Policy Act of 1992 (EPACT).[34] Further legislative direction has been provided in committee reports accompanying the annual appropriations acts.[35]

EPACT calls for: support of a broad-based fusion energy program; participation in ITER engineering design activities and related efforts; development of fusion power technologies; industrial participation in technology; the development, design and construction of a major new U.S. machine for fusion research and technology development;[36] ICF energy R&D; and the development of a heavy-ion ICF experiment. EPACT builds on the framework established by MFEEA for a broad-based fusion research and technology development program, including support of research on alternative confinement concepts and fuel cycles. The 1980 act marked a shift in the program from a focus on fundamental fusion science and plasma physics to technology development.

The AEC Act is another source for DOE support for fusion-related nuclear physics (including plasma physics) and engineering education and training missions. Fusion research activities advance the general purposes of the AEC Act to: "encourage maximum scientific and industrial

[30]For more on the goals and structure of the DOE fusion energy programs see Office of Technology Assessment, *The Fusion Energy Program*, see footnote 3.

[31]DOE's FY 1995 budget request candidly admits that "budgetary constraints over the past few years may mean that the schedule for meeting such objectives is delayed." U.S. Department of Energy, Office of the Chief Financial Officer, *FY 1995 Congressional Budget Request: Energy, Vol. 2, Supply Research and Development,* DOE/CR-0021 (Washington, DC: February 1994), p. 425.

[32]Act of Aug. 30, 1954, ch. 1073, 60 Stat. 921, as amended, 42 U.S.C. 2011 et seq.

[33]Public Law 96-386, Oct. 7, 1980, 94 Stat. 1539, 42 U.S.C. 9301.

[34]Public Law 102-486, Oct. 24, 1992, sec. 2114, 106 Stat. 3073-3074 (codified at 42 U.S.C. 13474).

[35]See, for example, Conference Report on H.R. 2445, H. Rept 103-292, 103d Cong., 1st sess., at 139 Cong. Rec. H7948, Oct. 14, 1993 (daily ed.). The conferees directed DOE to give highest priority to participation in ITER and supporting TFTR experiments.

[36]The language in EPACT referring to a major new machine has been interpreted by some as authorization for the proposed TPX, and as others as referring to ITER, still others maintain that federal expenditures for construction of either facility have yet to be authorized specifically. In any case, the appropriations bills have deferred spending on TPX construction pending review, while allowing procurement for long leadtime component technologies to continue.

progress"; aid education and training; promote widespread participation in the development of peaceful uses for atomic energy;[37] and encourage international cooperation.[38] The act authorizes a broad range of research on nuclear processes, atomic energy theory and production, and the use of nuclear energy or materials for the generation of usable energy and for commercial and industrial applications.

Over the past two decades, fusion energy programs have been the subject of extensive reviews.[39] Most of these reviews have complimented the steady technical and scientific progress that has been achieved. Over the past decade, however, reviewers have expressed concern about increased risk to the success of the program from what many have seen as a premature narrowing of magnetic fusion research to a single focus on the tokamak path and curtailment of research on alternative confinement concepts in response to budget constraints. Even so, the reviewers strongly endorsed pursuit of further critical advances in fusion science relying on the tokamak as the most developed (and successful) concept available. Reviewers have also raised concerns that existing budget levels will not be adequate to carry out even the narrowed program objectives on the scales and schedules proposed.

Funding for the fusion programs in FY 1995 is $362 million for magnetic fusion energy and $177 million for inertial fusion. About $157 million of the MFE funds are allocated for activities that directly or indirectly support the ITER collaboration. Funds supporting ITER are spent on U.S. research activities designated as advancing ITER-related R&D. Only about $600,000 is for direct support of joint ITER administrative activities. The FY 1996 budget request for magnetic fusion is $366 million and includes support of the ongoing ITER collaboration and initial construction funds for the proposed new Tokamak Physics Experiment (TPX) at the Princeton Plasma Physics Laboratory. The $257 million, FY 1996 budget request for ICF activities includes construction funds for the National Ignition Facility (NIF)—the next major facility required for advancement of inertial confinement fusion.[40]

International Collaboration in Fusion Research

International cooperation and collaboration in fusion research date from the late 1950s, when much fusion research was declassified for the Second Geneva Convention on the Peaceful Uses of Atomic Energy. Since then, cooperation among researchers in the United States, the Soviet Union, Europe, and Japan has grown from informal exchanges between research laboratories, to formal bilateral collaborative agreements between gov-

[37] Atomic energy is defined as all forms of energy released in the course of nuclear fission or nuclear transformation. 42 U.S.C. 2014. Transformation is interpreted to include fusion.

[38] 42 U.S.C. 2013.

[39] See: U.S. Department of Energy, Fusion Policy Advisory Committee (FPAC), *Report of the Technical Panel on Magnetic Fusion of the Energy Research Advisory Board, Final Report,* DOE/S-0081 (Washington, DC: September 1990); Fusion Energy Advisory Committee, *Report on Program Strategy for U.S. Magnetic Fusion Energy Program*, DOE\ER-0572T (Washington, DC: U.S. Department of Energy, Office of Energy Research, September 1992); Fusion Energy Advisory Committee, *Advice and Recommendations to the U.S. Department of Energy in Response to the Charge Letter of September 18, 1992,* DOE/ER-0594T (Washington, DC: U.S. Department of Energy, Office of Energy Research, June 1993); Fusion Energy Advisory Committee, *Advice and Recommendations to the Department of Energy in Partial Response to the Charge Letter of September 24, 1991: Part D,* DOE\ER-0555T (Washington, DC: U.S. Department of Energy, Office of Energy Research, June 1992). For a more detailed summary of these reviews, see Office of Technology Assessment, *The Fusion Energy Program,* see footnote 3. For more on prior reviews, see U.S. Congress, Office of Technology Assessment, *Starpower: The U.S. and the International Quest for Fusion Power,* OTA-E-338 (Washington, DC: U.S. Government Printing Office, October 1987).

[40] NIF is primarily motivated by the desire to maintain technological expertise in areas of nuclear weapons design as a component of the DOE's *Stockpile Stewardship* program. NIF's contribution to the development of fusion energy and other scientific applications are adjunct functions of the project.

ernments, to the ongoing collaboration on the ITER design.

The ITER Collaboration

The United States, the European Atomic Energy Community (Euratom), Japan, and the Russian Federation are engaged in an unprecedented collaboration on the engineering design of the proposed International Thermonuclear Experimental Reactor. This collaboration has its roots in discussions among the leaders of the European Community, Japan, the Soviet Union, and the United States in the mid-1980s. The impetus for the start of the ITER collaboration came from the discussions between President Ronald Reagan and Soviet General Secretary Mikhail Gorbachev at the 1985 Geneva Summit.

ITER's purpose is: 1) to establish the scientific and technological feasibility of magnetic fusion energy as a source of electric power by demonstrating controlled ignition and extended burn of deuterium-tritium (D-T) plasmas; and 2) to demonstrate and test technologies, materials, and nuclear components essential to development of fusion energy for practical purposes. It would not be equipped, however, to actually generate electricity. Demonstrating the production of electricity in a magnetic fusion energy powerplant would be left to the DEMO reactor, a device anticipated for construction no sooner than 2025.

If built, ITER would be by far the largest, most capable, and costliest fusion experiment in the world. ITER uses a tokamak design; it would be more than eight stories tall and 30 meters in diameter. The device is intended to sustain controlled fusion reactions in a pulsed mode for periods of at least 15 minutes. ITER is expected to be capable of producing more than 1,000 MW of thermal fusion power. Plasma temperatures inside the confinement chamber would be more than 150 million degrees Centigrade. Due to the radioactivity that will be generated, maintenance and monitoring of the reactor vessel will have to be carried out by remote methods. The impressive scale of ITER is dictated by the physical requirements of heating and containing a plasma to fusion conditions on a steady-state basis using available technology and materials.

ITER offers not only great scientific challenges, but practical technological challenges as well. For example, ITER's superconducting magnetic coils will be the largest ever manufactured. Each coil will weigh more than 400 tons. The amount of superconducting materials required to make them exceeds the currently available manufacturing capabilities of any one party; therefore, a cooperative effort is under way to coordinate the materials manufacture, fabrication, and assembly.

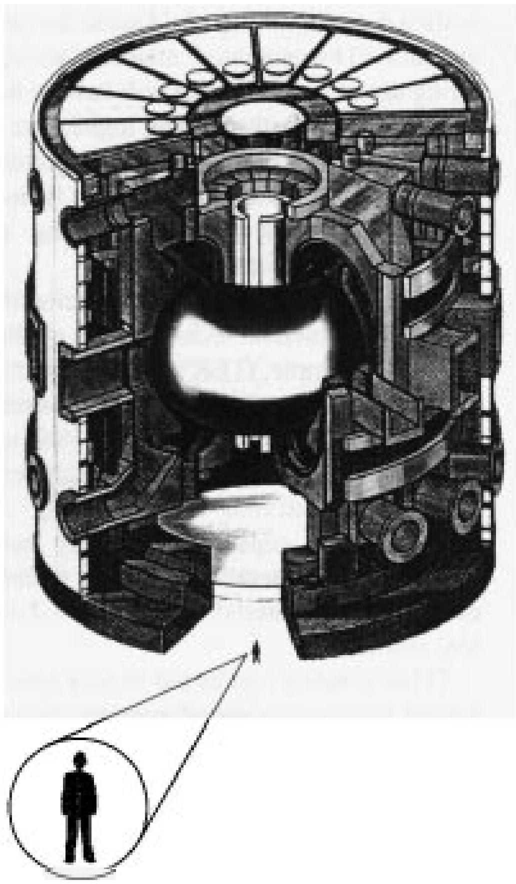
ITER is being conducted in four phases under formal intergovernmental agreements among the parties: 1) the now-completed conceptual design activities (CDA); 2) the ongoing engineering design activities (EDA); 3) the possible, future construction phase; and 4) the operations phase. Each phase is governed by a separate agreement among the parties. To date the costs of ITER activities have been shared equally among the four parties.

The CDA phase ran from January 1988 to December 1990 under the auspices of the International Atomic Energy Agency (IAEA).[41] All four parties contributed personnel and support to the ITER team for development of a conceptual design, scope, and mission for the project.

The EDA phase is being conducted under an intergovernmental agreement concluded in July 1992 and extending to July 1998.[42] Each of the parties has committed the equivalent of $300 million (1993 dollars) worth of personnel and equipment to the design effort over that period. The

[41]The CDA was conducted under a set of Terms of Reference developed by the ITER Parties, but formally transmitted by the IAEA Director General to the Parties for their individual acceptance. The ITER CDA agreement was in actuality a set of four acceptances of the same letter from the IAEA Director General.

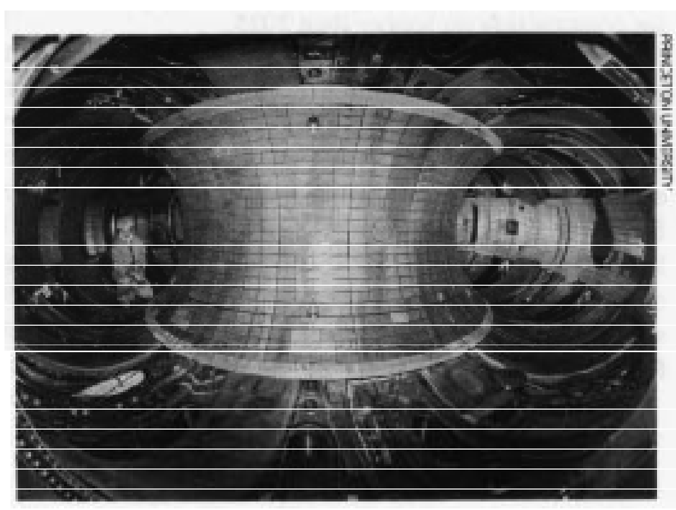
[42]The ITER EDA agreement was executed on behalf of the U.S. government by Secretary of Energy Admiral James Watkins.

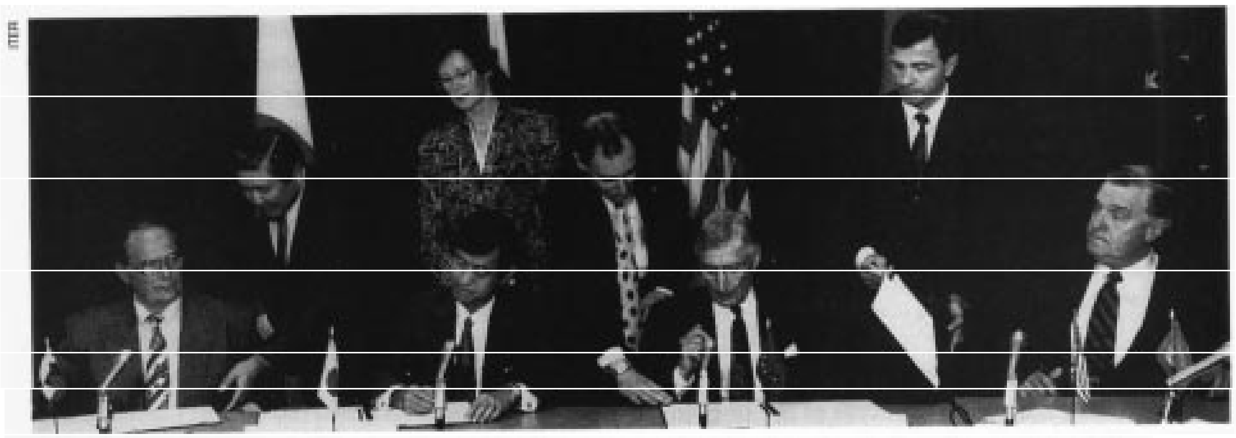


The Proposed International Thermonuclear Experimental Reactor

SOURCE: US. Departmentt of Energy.

Inside the vacuum vessel of the TFTR at the Princeton Plasma Physics Laboratory Graphite and graphite composite tiles protect the inner wall of the vessel.





The ITER Engineering Design Activities agreement was formally signed by the United States, Euratom, Japan, and the Russian Federation in July 1992.

purpose of the EDA phase is to produce a "detailed, complete, and fully integrated engineering design of ITER and all technical data necessary for future decisions on the construction of ITER." On completion, the design and technical data will be available for each of the parties to use either as part of an international collaborative program or in its own domestic program. Other objectives of the EDA phase are to conduct validating R&D supporting the engineering design of ITER, to establish siting requirements, to perform environmental and safety analyses related to the site, and to establish a program for ITER operation and decommissioning.

EDA activities are overseen by an ITER Council composed of two representatives of each party and the ITER Director who is responsible for coordinating the activities of the Joint Central Team (JCT) and other R&Din support of ITER. The JCT is an international design team composed of scientists, engineers, and other professionals assigned to the project by the parties. The formal seat of the Council is in Moscow. JCT activities are carried out by the parties and the four home teams at three joint work sites-Garching, Germany; Naka, Japan; and San Diego, California. Each work site is responsible for a different aspect of ITER design. In consultation with the ITER Council, the JCT, and each party's designated ***Home-Team*** Leader, the ITER Director assigns and coordinates R&D activities by the four home ***country*** fusion programs that support the JCT.

The next major step in ITER development will be the negotiation of a process for deciding on a host site. Exploratory discussions on a site selection process are currently under way. Site selection will have to be completed before specific site-related safety, environmental, and economic analyses and design work for the ITER facility can be finalized. A decision on a site and whether to proceed to ITER construction and operations phases is scheduled to be made before 1998. These subsequent phases would require anew international agreement. None of the parties is committed to proceed beyond the EDA phase.

The ITER construction phase is tentatively planned to start in 1998 and to be completed by 2005. Initial estimates of ITER construction costs were about $6.9 billion in 1993 dollars. More recently, some analysts have projected ITER costs of between $8 billion and $10 billion. Detailed cost estimates for this one-of-a kind research facility await completion of ITER engineering design work. Interim design and cost analyses are expected in rnid-1995. Final design and cost estimates are due in January 1998, if site selection has been completed.

The fourth or operating phase of ITER is proposed to begin in 2005 and run through approximately 2025. The early years would be dominated by a focus on the physics issues relating to achieving and sustaining an ignited plasma. A more intense engineering phase will follow. As an engineering test facility, ITER will be designed to allow researchers to install, test, and remove numerous ITER components, experimental packages, and test modules to examine materials properties, component characteristics, performance, and lifetimes in an environment approximating the conditions of an operating fusion powerplant. This experience will aid efforts in the design and development of a demonstration fusion powerplant.

Other Fusion Collaborations

Although they are not on the scale of the ongoing ITER collaboration, other precedents exist for cooperation in fusion research under various bilateral and international agreements. Among the most recent examples are the Large Coil Task (LCT) test facility at Oak Ridge National Laboratory, and collaboration on the DIII-D tokamak at General Atomics with the Japanese Atomic Energy Research Institute.[43] Positive experiences on the LCT experiments contributed to the confidence of the parties in entering into the ITER collaboration. Contributions from the Japanese in exchange for access to and operating time on the DIII-D helped pay for upgrades to the device. Efforts are ongoing to negotiate an agreement for collaboration among the ITER parties on a conceptual design for a 14-MeV (million electron volt) neutron materials test facility.

The 14 MeV neutron source would be an accelerator-based materials testing facility that would be used to expose fusion reactor materials to intense bombardment by high-energy 14 MeV neutron beams to approximate over a few short years the effects of a lifetime of exposure in an operating fusion reactor. The availability of a 14 MeV materials testing facility is considered by all world fusion programs to be essential to the development of low-activation alloys and other materials for use in fusion powerplants.

There is experience with international collaboration in the operation of a major fusion facility. The joint European fusion research program is carried out under the Euratom Treaty. The European fusion community consists of the magnetic fusion programs of member states of the Euratom Treaty plus Sweden and Switzerland. Research projects and funding levels are established under successive, but overlapping five-year research programs developed by the European Commission (EC) in consultation with fusion researchers and government ministers of member countries. The research programs are approved by the Council of the European Union (EU). Member-nation fusion programs carry out the research and receive contributions of up to 80 percent for projects included in the EC research program.

The Joint European Torus (JET), a large tokamak facility near Culham, England, is jointly funded and staffed by the Euratom fusion program and 14 European countries. JET was established as an independent collaborative undertaking that is separate from, but cooperates with, member-state fusion programs. The goal of JET is to confirm fusion's scientific theories and to demonstrate the scientific feasibility of nuclear fusion for power generation. JET is currently the world's largest tokamak; it hosts about 370 staff scientists and an equal number of contractors. In 1991, JET was the first tokamak to produce significant quantities of fusion power using a D-T fuel mix, reaching a record plasma current of 7.1 million amperes. JET researchers have been able to achieve, individually, all the required conditions (i.e., plasma temperature, density, and confinement time), for a fusion power reactor, but the JET is too small to achieve them all simultaneously. In 1996, JET is scheduled to begin a final phase of experiments involving fusion power production with D-T plasmas, using a recently installed pumped divertor. These experiments are intended to support ITER design activities.

Negotiations to establish JET were begun in 1973 and concluded in 1978. Several years of negotiation were necessary to concur on an appropriate site following completion of the design in

[43]These collaborations are discussed in Office of Technology Assessment, *Starpower*, see footnote 39.

1975. JET is operated under statutes adopted by the European Community (now the European Union) and governed by the JET Council, which includes representatives of the member countries. The EC fusion program provides 80 percent of JET funding; the 14 participating countries provide 20 percent, with the United Kingdom paying a 10-percent host premium on its share.

Implications for Future Collaborations

Early successes in international cooperation in fusion led to today's unprecedented ITER collaboration in which four equal parties are working together in an effort to design and construct the world's largest tokamak to achieve the critical goal of an ignited plasma. The earlier efforts created relationships among fusion researchers internationally and laid the groundwork for a more formal partnership in ITER. Budgetary strains facing science research also contributed to the desire for international collaborative efforts to continue progress in fusion and plasma science. The ITER team has been progressing in its design efforts supported by R&D and technology development activities in the parties' home-team fusion programs. The level of cooperation and success in ITER to date has led analysts to suggest that this collaboration could prove to be a model for future international efforts.

The ITER project and other international collaborative efforts in fusion, such as the proposed 14-MeV neutron source materials testing facility, still face a number of scientific, technical, political, and budgetary hurdles. Many difficult issues concerning funding, technology transfer, siting, intellectual property rights, project management, and allocation of benefits and costs remain to be negotiated before ITER can proceed to the next and considerably more expensive construction phase. The United States and its ITER partners are currently engaged in preliminary discussions concerning the form that such future negotiations will take.[44]

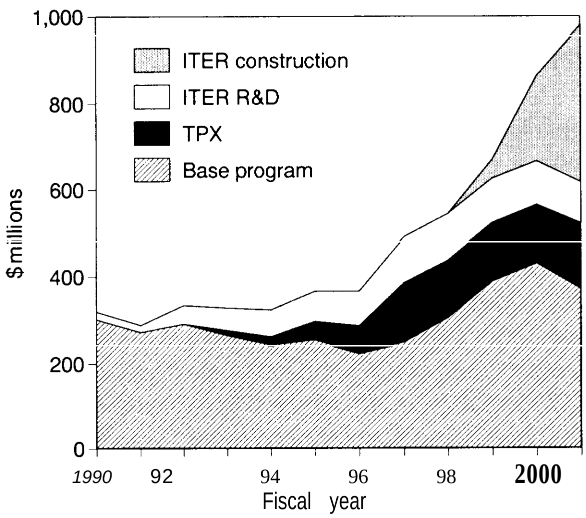
The U.S. fusion program faces substantial budgetary challenges and has come under increasing scrutiny as Congress is confronted by tough choices about the future of fusion energy research and other megascience activities. Carrying out the present development plan for a tokamak fusion reactor, currently the most technically advanced magnetic fusion concept, implies a doubling, or even tripling of the annual magnetic fusion budget ($373 million in FY 1995). This amount assumes that the United States will continue to pay an equal one-quarter share of the cost of ITER, with the other three parties international partners picking up the other shares (see figure 3-3). However, no agreements on ITER construction have yet been negotiated, including how much each of the participating parties will pay.[45]

The most immediate decision is whether to fund construction of the TPX, an approximately $700 million superconducting, steady-state advanced tokamak intended to replace the existing TFTR when the reactor is decommissioned after the current round of experiments. If the TPX is not built, the United States will soon be left without a new domestic leading-edge magnetic fusion device. In the view of many in the fusion research community, U.S. researchers and industry will also be deprived of vital experience that could

[44] On November 21, 1994, Secretary of Energy Hazel O' Leary transmitted the "Interim Report to the Congress on Planning for International Thermonuclear Experimental Reactor Siting and Construction Decisions," to several congressional committees in partial response to requests for a detailed ITER siting and development plan in the FY 1993 and FY 1994 Energy and Water Development Appropriations conference reports. The Secretary advised the committees that a more complete response could not be provided until the ITER Interim Design Report is completed and accepted by the parties.

[45] Some at DOE and in the fusion research community are exploring what role, if any, the U.S. fusion program could play in a future ITER collaboration if U.S. fusion program budgets remain flat as projected, or are reduced. Some have suggested that the United States might attempt to negotiate a role as a junior partner in ITER to preserve access to the facility and the technology for the U.S. fusion program. But it is not at all clear whether the other parties would react favorably to this approach.

FIGURE 3-3: Estimated Funding Levels Required for the U.S. Magnetic Fusion Energy Program for TPX, ITER, and 2025 DEMO in FY 1990-2001 ($ in millions as spent)



NOTE: This figure is based on internal Office of Fusion Energy planning estimates and the funding levels shown are not reflected in FY 1995 budget request documentation. The increase in base program funding in FY 1997-2001 reflects increased activity in support of TPX and ITER and for a proposed fusion materials test facility

SOURCE: Office of Technology Assessment 1995, based on information from the U.S. Department of Energy.

position them to compete for ITER contracts and take advantage of ITER technology.

If Congress or the executive branch decides not to increase fusion budgets to the extent that would be needed to pursue expensive new devices at this time, or even to reduce fusion budgets, a dramatic rethinking of the structure and priorities of the U.S. fusion effort will be required.[46] At a minimum, a flat or reduced budget will mean that continuing to support ITER collaboration at currently projected levels will cut even more deeply into the U.S. base program and constrain any efforts to expand investigation of alternative concepts.

A decision to reduce U.S. commitment to the ITER collaboration would pose difficult problems not only for us, but also for our partners. The United States has committed to provide resources to support its one-quarter share of the ITER EDA through 1998 in an international agreement signed on behalf of the Government by Energy Secretary James Watkins.[47] Changes to the EDA agreement require consent of all parties. The United States and any other party can freely elect not to participate in the next and more expensive ITER construction phase. Pulling back from the existing EDA commitment would certainly prove disruptive to the successful completion of ITER since the collaborative efforts of the parties are highly integrated and interdependent. The decision would have profound consequences not only for fusion research, but also for the future of U.S. involvement in international collaborative efforts on large science facilities. U.S. withdrawal from ITER would trigger an extensive reexamination of the U.S. fusion program, in which ITER participation has had a central role, backed by EPACT and directives from congressional appropriators. U.S. withdrawal from ITER would also require our partners to reexamine and possibly restructure their fusion research programs because ITER R&D activities now occupy a dominant role in those programs. It is by no means clear that the governments of the remaining parties would be willing to fund ITER design completion and construction on the scale and schedule currently envisioned.

The United States is not alone in pondering whether it is ready to take the next ambitious and highly expensive step in the development of fu-

[46] Office of Technology Assessment, *The Fusion Energy Research Program,* see footnote 3; and Robir Technology Assessment, testimony at hearings before the Subcommittee on Energy and Environment, House Committee on Science, Feb. 15, 1995.

[47] As is typical in such agreements, the ITER EDA Agreement and Protocol provides that the parties agree "subject to their laws and regulations" to carry out the collaboration. The agreement may be amended or terminated only by written agreement of the parties. International Atomic Energy Agency, "International Thermonuclear Experimental Reactor (ITER) Engineering Design Activities (EDA) Agreement and Protocol 2," ITER EDA Documentation Series No. 5, 1994.

sion as an energy source for the future. In 1990, a review panel for the EC fusion program also expressed some reservations about the pace of progress and, in calling for a reevaluation of the EC fusion program in 1995, noted:

> The Board wishes to advise the European fusion community that, while prospects and results may by then be so encouraging as to justify pressing ahead, either independently or in the ambit of a convincing international agreement, one possible outcome of such an evaluation would be to redirect the whole European Programme should the 1995 Report not favour immediately proceeding with construction of the Next Step device. Without prejudice to a possible increase in the fusion effort should conditions warrant, the Board wishes to make it clear that, in its view, the present scale of fusion spending cannot be considered an automatically assured expenditure floor unless there is clear evidence of progress toward the Programme's ultimate goal.[48]

The European review panel commented favorably on the benefits to be derived in reducing the technical and financial risks of proceeding with a next-step fusion machine by relying on an international collaboration. It also raised a suggestion that the ITER program be expanded into an extended and articulated international fusion program that would share all the main functions of fusion reactor development including the development of a neutron source for materials testing, and a major investigation of alternative fusion concepts.[49]

Japanese fusion research programs have been funded at levels comparable to U.S. and European fusion efforts and, like them, have devoted a significant share of current budgets to support of the ITER collaboration. The future of the Japanese fusion program also hinges on decisions to be made about construction of ITER. The Japanese government is deferring any decision on funding for a new large tokamak, the JT-60 Super Upgrade, proposed by the Japanese fusion research community as a successor to the Japanese JT-60U. According to OTA interviews, continued funding of the fusion program at current levels beyond the end of the existing research plan is by no means secure.

The significant integration of the major world fusion programs resulting from collaboration on ITER and other projects has created a situation in which, at present, no party supports a fully independent broadly based national fusion research program. The United States and its partners have heavily invested the future of their research programs on progress in ITER. Decisions on whether to proceed with ITER construction will mark a critical point both in the development of fusion power and in the success of international collaborations in big science. Proceeding with ITER as currently envisioned will demand an increase in the fusion budgets of all the partners and a long-term commitment to construction and operation of the facility in addition to maintaining the supporting infrastructure of domestic fusion programs. Should the United States (or any of the other partners) elect to delay or reduce its contribution, or withdraw entirely from the ITER collaboration, it would force a reevaluation and restructuring of all the partner's national fusion programs and would put the future of ITER in question. It would also heighten concerns about the risks of international collaboration and the reliability of commitments.

The U.S. fusion research program is currently facing a critical decision point on whether or not to build the TPX to explore advanced tokamak regimes in steady-state conditions as a replacement for the TFTR which is being shut down this year. TPX is intended as a national fusion research facility to be managed and used by scientists from laboratories and universities across the country. Without TFTR or a replacement such as TPX, the U.S. fusion program will not have any domestic

[48] Fusion Program Evaluation Board, "Report Prepared for the Commission of the European Community," July 1990, p. 56.

[49] Ibid.

large tokamaks to advance fusion research and will become even more focused on ITER.

Our ITER partners will face similar choices in a few years when their major national machines are scheduled for closure. Plans for new ambitious national fusion research devices in Europe and Japan have been deferred in favor of ITER. However, all parties eventually will have to define the appropriate roles and levels of support for domestic fusion programs in an era of expanded international collaboration.

Failure to pursue construction of ITER, or even a considerable delay in startup of construction and operations could prove disruptive to the partners' own fusion programs and could trigger a redefinition of fusion goals and priorities. One possible outcome could be that the partners might elect to build on past successful collaborations on the LCT, and ITER CDA and EDA to forge a new collaborative path on future fusion research facilities, perhaps at a less ambitious scale, schedule, and cost than originally envisioned for ITER.

SCIENTIFIC ACTIVITIES IN SPACE [50]

International collaboration has long been a vital part of U.S. scientific activities in space. The National Aeronautics and Space Administration (NASA) oversees most U.S. civilian international space activities. The National Oceanic and Atmospheric Administration, in coordination with NASA and non-U.S. partners, supports a smaller number of space-based Earth observation projects. Since its inception in 1958, NASA has concluded nearly 2,000 cooperative agreements. Virtually all of its science projects involve at least a minor international component, and collaboration has played a major role in several of NASA's largest science-related projects.[51]

NASA engages primarily in bilateral collaborations. Its most extensive collaborative relationships have been with Canada, the European Space Agency (ESA),[52] and Japan. In addition, NASA conducts major bilateral cooperative projects with individual European countries such as France, Germany, Italy, and Russia.

NASA is currently involved in 11 science-related programs that have a U.S. development cost of more than $400 million. Of these, six projects have costs more than $1 billion: the International Space Station, the Earth Observing System (EOS), the Advanced X-Ray Astrophysics Facility (AXAF), the Cassini mission to Saturn, the Hubble Space Telescope, and the Galileo mission to Jupiter. All of these projects involve significant international collaboration. Table 3-4 lists these projects, U.S. partners and their roles, the project status, and NASA's current estimates of development costs. Because of the complexity of accounting for all shuttle- and personnel-related expenses, these figures may not fully reflect each project's ultimate cost.[53]

[50] This discussion encompasses science and technology development activities that support NASA's Space Science program (astronomy, astrophysics, lunar and planetary exploration, solar physics, and space radiation), as well as other activities in geosciences, life sciences, and microgravity research.

[51] The National Aeronautics and Space Act of 1958 identified international collaboration as a fundamental goal. NASA's first international cooperative science project was the 1962 Alouette mission with Canada, a basic science project to investigate the ionosphere. For a list of more than 60 international cooperative ventures in space science between 1962 and 1985, many involving U.S. participation, see U.S. Congress, Office of Technology Assessment, *International Cooperation and Competition in Civilian Space Activities*, OTA-ISC-239 (Washington, DC: U.S. Government Printing Office, July 1985), pp. 379-380.

[52] ESA is a 14-member European space research organization. Its members are Austria, Belgium, Denmark, Finland, France, Germany, Ireland, Italy, the Netherlands, Norway, Spain, Sweden, Switzerland, and the United Kingdom.

[53] These figures also do not account for operations costs. Mission operations and data analysis (MO&DA) costs vary considerably and, when included in the analysis, can raise the costs for some projects significantly. For example, MO&DA costs for the Compton Gamma Ray Observatory (CGRO) through FY 1995 are $112 million, 20 percent of development costs. MO&DA costs for the Galileo program are $331 million, 37 percent of development. And MO&DA expenditures for the Hubble Space Telescope—$1.7 billion—have already reached 110 percent of the program's development costs.

TABLE 3-4: Current Large International U.S. Projects in Space (more than $400 million)

Project	Partners and project roles	status	Us. Costa (spent to FY 1995)
Space station	U. S.: Project leadership, overall design, construction, launch, operations Russia: Pressurized modules, fuel resupply, "lifeboats," launch, operational expertise Japan and ESA: Pressurized modules, launch, servicing equipment Canada: Robotics	Design currently under way. Assembly planned 1997-2002, followed by 10 years of operations	$38 billion ($14.4 billion)
Earth Observing System (EOS and EOSDIS)	U. S.: Spacecraft, instruments, launch, operations Canada, Japan, France, ESA, Eumetsat: Instruments, IEOS[b] spacecraft	EOS-AM1 launch planned for 1998 EOS-PM1 launch planned for 2000 Other launches planned for 2000 and beyond	Total program: $8 billion ($2.6 billion)
Advanced X-Ray Astrophysics Facility (AXAF)	U. S.: Spacecraft, instruments, launch, operations Germany, Netherlands, UK: Instruments	AXAF-I launch planned for 1998	$2,1 billion ($1.1 billion)
Cassini	U. S.: Spacecraft, instruments, launch, operations ESA: Titan probe (Huygens) Italy: Antenna	Launch planned for 1997	$1.9 billion ($1.3 billion)
Global Geospace Science (GGS)	U. S.: Spacecraft, instruments, operations, launch Russia, France: Instruments, science support	Wind launched in 1994 In operation Polar launch planned for 1995	$583 million
Collaborative Solar Terrestrial Research Program (COSTR)	U. S.: Instruments, operations, launch ESA: Spacecraft, instruments, launch Japan: Spacecraft, instruments, operations	Geotail launched in 1992 In operation SOHO launch planned for 1995 Cluster launch planned for 1995	$511 million
Ocean Topography Experiment (TOPEX)	U. S.: Spacecraft, instruments, operations France: Launch, instruments	Launched in 1992 In operation	$407 million
Compton Gamma Ray Observatory (CGRO)	U. S.: Spacecraft, instruments, launch, operations Germany: Instruments	Launched in 1991 In operation	$957 million
Ulysses	U. S.: Power unit, launch, tracking ESA: Spacecraft, instruments, operations	Launched in 1990 Mid-mission in solar orbit	$569 million
Hubble Space Telescope (HST)	U. S.: Spacecraft, instruments, launch, operations ESA: Instrument, solar arrays, operations	Launched in 1990 In operation	$2.3 billion
Galileo	U. S.: Spacecraft, probe, instruments, launch, operations Germany: Retro-propulsion module, instruments, tracking	Launched in 1989, arrival at Jupiter planned for 1995	$1.3 billion

[a]Capital costs include development, launch, orbital assembly, and construction of facilities. National Aeronautics and Space Administration (NASA) civil service, non-program facility, and administrative support expenses are not included. For Space Station (27 missions), CGRO, Ulysses, Hubble (two missions) and Galileo, NASA reports average shuttle launch costs of $400 million to $500 million. Figures represent dollars as spent or projected, unadjusted for inflation.

[b]The International Earth Observing System (IEOS) includes: NASA—EOS; NASA/Japan-Tropical Rainfall Measuring Mission (TRMM); NOAA--Polar-Orbiting Operational Environmental Satellite (POES); Japan: Advanced Earth Observing Satellite (ADEOS); European Space Agency (ESA) & Eumetsat—Polar-Orbit Earth Observation Mission (POEM).

SOURCE: National Aeronautics and Space Administration-Julie Baker, Resources Analysis Division, personal communication, May 1, 1995; Office of Legislative Affairs; and Space Station Program Office.

Nature of International Collaboration in Space

The character of international collaboration in space differs significantly from the nature of U.S. involvement in cooperative activities in other areas of science. Large collaborative ventures in other disciplines often rely on international scientific teams working interdependently at single facilities. These international teams work on both technology development and scientific investigations. In these collaborations, the level of information transfer about technical design and fundamental science is high. For example, several hundred researchers and accelerator experts are working closely at CERN to develop technical specifications for the LHC accelerator and particle detectors to ensure that the ultimate physics objectives of the project can be met.

Cooperative scientific projects in space have been more compartmentalized, with partners working more independently of one another in highly segmented projects. NASA often competitively selects the design of instruments proposed by internationally constituted scientific teams responding to competitive notices of opportunity. But space technology development-especially for the critical infrastructure elements that constitute a large portion of the cost of space projects (launchers, satellites and platforms, and so forth) —is typically conducted without any exchange of detailed design or manufacturing information.

Compartmentalization was originally a high priority because of the need to ensure the success of collaborative projects with partners whose technical capabilities fell below those of the United States and to prevent the transfer of potential dual-use civilian-military technologies. The heightened attention to preventing technology transfer has also been a reflection, in part, of both the much higher commercial potential of space technologies versus those in areas such as high-energy and nuclear physics, and the historical importance of maintaining U.S. leadership in space-related activities. Maintaining this leadership position is a fundamental consideration in guiding U.S. participation in international cooperative efforts.[54]

NASA long ago codified its approach to international collaboration in a set of guidelines. Among other provisions, these guidelines call for minimizing the transfer of technologies; the creation of "clean technical and managerial interfaces"; and collaboration on a project-by-project basis, rather than making the United States party to multiproject umbrella agreements (see box 3-3).

BOX 3-3: Selected NASA Guidelines for International Cooperation[1]

- Preference for project-specific agreements.
- Preference for agency-to-agency cooperation.
- Technical and scientific objectives that contribute to NASA program objectives.
- Distinct ("clean") technical and managerial interfaces.
- No or minimal exchange of funds between cooperating partners.
- No or minimal technology transfer.
- Open sharing of scientific results.

[1] These guidelines were developed during the 1960s and last revised in December 1991 in NASA Management instruction (NMI) 1362.1C. For a discussion of the guidelines, see Space Policy Institute and Association of Space Explorers, "International Cooperation in Space---New Opportunities, New Approaches," *Space Policy,* vol. 8, August 1992, p 199

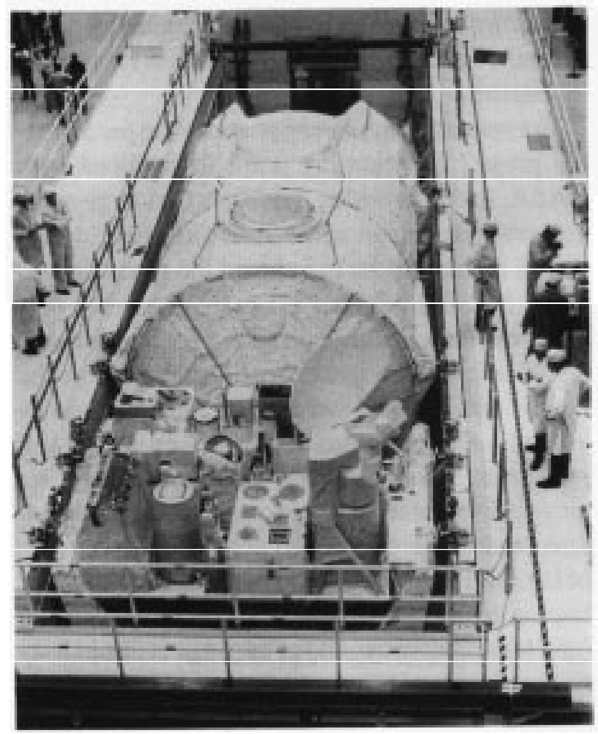
[54] The National Space Policy defines leadership as preeminence in areas critical to achieving national security, scientific, economic, and foreign policy objectives. But U.S. government agency efforts to pursue international projects are also guided by other broad goals, defined by the National Space Policy, which are to: 1) strengthen national security; 2) achieve scientific, technical, and economic benefits; 3) encourage private sector investment in space; 4) promote international collaboration; 5) maintain freedom of space for all activities; and 6) expand human activities beyond Earth. National Security Council, "National Space Policy," National Space Policy Directive 1, Nov. 2, 1989. This policy was formulated by the Bush Administration. The Clinton Administration, through the Office of Science and Technology Policy (OSTP), is currently undertaking a review and update of the policy.

An additional issue, NASA's dependence on other countries for technologies on a mission's critical path, has featured prominently in recent congressional debate on U.S. space policy.[55] Although NASA has no official policy on the issue of critical paths, dependence on other countries for critical-path items has been controversial because it raises questions about U.S. independence and control in collaborative space projects.

■ History of Space Collaboration

Despite NASA's longstanding and highly explicit guidelines for collaboration, its policies and approach to collaboration have changed over time. The agency's compartmentalized approach to collaboration was initially designed in the 1960s to foster space cooperation while preserving and enhancing U.S. leadership and independence in space-related science and technologies. World leadership was a primary, longstanding, and well-articulated U.S. space goal in the 1960s and 1970s. During this period, NASA was able to achieve this goal because its budget and technical capabilities far exceeded those of other Western industrialized nations. With Western partner countries eager to learn from the United States, NASA pursued collaboration largely on its own terms, creating what might be called a period of U.S. preeminence in international space cooperation. According to Vice President Quayle's Space Policy Advisory Board:

> [T]he United States . . . approached international cooperation from a position of strength, at its own initiative, largely on its own terms, and usually as a discretionary, "value-added" activity that complemented core U.S. elements of a particular mission or capability. The size of the U.S. space program and the preeminence of U.S. space capabilities made such an approach possible. International partners were willing to accept American dominance in cooperative undertakings as the price of associating themselves with the recognized leader in space.[56]



The European Spacelab module being loaded onto the space *shuttle Columbia.*

By the late 1970s and early 1980s, however, the situation had changed in important ways. Partly as a result of extensive cooperation with the United States, some partner nations had developed significant and sophisticated autonomous capabilities. Partner nations expressed increasing desires to participate more substantively in critical decisions about the development and operation of collaborative projects, and objected to playing junior partner to the United States. ESA, founded in 1975 to give European autonomous space launch

[55] The term critical path refers to an element essential to a project's operation and success, in contrast to technologies and services that am strictly value-added in nature. For an example of discussion of the subject see the 1994 floor debate on space station funding. Congressional Record, June 29,1994, pp. H5394-5395.

[56] Vice President's Special Policy Advisory Board, *A Post Cold War Assessment of U.S. Space Policy: A Task Group Report* (Washington, DC: Office of the Vice President December 1992), p. 9.

capability and to raise Europe's technical standard in space, has been particularly active in expressing this desire.[57]

Europeans cite their experience with the Spacelab project as a turning point in relations with NASA. In this program, Europe's first large-scale venture into human space activities, ESA developed a laboratory for use aboard the space shuttle. From NASA's point of view, the Spacelab program was successful. It provided a value-enhancing addition to the space shuttle at low cost to the United States[58] and gave the shuttle program an international dimension that increased its political prestige at home. Europe's gains from the project included valuable experience in building human-rated space equipment and access to the benefits of the shuttle program. However, ESA, which was hoping to recoup at least part of its investment (and large cost overruns) in the project through serial production of several laboratories, was disappointed that NASA bought only the two modules stipulated in the agreement. Moreover, many Europeans felt the project was a poor bargain. They asserted that Europe had built merely an accessory for the U.S. space shuttle with little practical return for European space-related science or industry. European scientists and engineers further complained that NASA treated Europe condescendingly, not as a partner.[59]

Questions about the stability of U.S. funding and periodic project redesigns also created challenges to collaboration by raising questions about U.S. reliability among potential partners. Foreign partners most frequently cite the 1981 cancellation of U.S. plans to build a spacecraft for the International Solar Polar Mission (ISPM), a joint project with ESA (see box 1-3). In 1979, NASA and ESA started a program to send two spacecraft out of the Earth's orbital plane to study the poles of the Sun. In 1981, NASA canceled plans to build the U.S. ISPM spacecraft, basing its decision on the need to close a $500 million budget shortfall in the fiscal 1982 budget. Europeans expressed surprise and dismay at the NASA decision but were unable to reverse the cancellation.

Although NASA kept its commitment to launch and track the European probe (renamed Ulysses), and provide its nuclear power source, Europeans have long cited the ISPM cancellation to illustrate their claims about the unreliability of U.S. commitments.[60] However, the real impact of the ISPM experience is less certain. Other countries may cite the ISPM example as part of a strategy to obtain more favorable terms in negotiations for joint space projects with the United States. Nevertheless, ISPM was an important milestone in the U.S.-European collaborative relationship.

As a result of these developments, in the 1980s, U.S. collaborative space policy entered an extended period of transition from the earlier era of U.S. preeminence to one in which the goal of leadership was less sustainable and more ambiguous. The ambiguity of the period was reflected in U.S. space policy documents, which moved from broad and unequivocal statements in the late 1970s and early 1980s about the need to maintain U.S. space leadership, to more opaque statements in the late 1980s and early 1990s that called for the United States to maintain leadership in certain

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[57] ESA was formed by the merger of the European Space Research Organization and the European Launcher Development Organization, both of which were founded in 1964.

[58] An earlier OTA report noted that "Spacelab cost (ESA) in excess of $1 billion. . . . For budgetary reasons, the alternative to an ESA Spacelab was not a less capable U.S. Spacelab, but rather no Spacelab at all." Office of Technology Assessment, *International Cooperation and Competition in Civilian Space Activities*, see footnote 51, p. 409.

[59] For a description and analysis of the Spacelab experience, see Joan Johnson-Freese, *Changing Patterns of International Cooperation in Space* (Malabar, FL: Orbit Book Co.), 1990, pp. 25-30.

[60] In virtually every interview conducted with U.S. space science partners in research for the present report, questions about U.S. stability were highlighted prominently by reference to the ISPM experience.

loosely defined critical areas (usually involving space transportation and human space flight).[61]

A final development in the late 1980s and early 1990s—constrictions in the space budgets of the United States and its foreign partners—spurred further changes in the U.S. and multilateral approaches to collaboration. The result of all these developments has been a significant change in NASA space policy: a greater willingness in several projects to accept foreign contributions as critical-path elements;[62] a more active program of flying U.S. instruments on foreign spacecraft; and a NASA strategic plan that speaks of keeping the United States at the forefront of space-related science and technology, rather than maintaining world leadership.[63] Although NASA policy still leaves much ambiguity about the role of U.S. space leadership, the agency's practices over the past few years have demonstrated greater flexibility in dealing with the issue. The continuing challenges to collaboration and the U.S. experience in the largest current international collaborative projects are discussed below.

Challenges to Collaboration

Although collaboration has worked well in several automated, small- and medium-scale science projects, NASA has encountered significantly more difficulty in structuring and executing collaborations in a few large programs, especially those involving human spaceflight. Instability in project financing and technical design (at NASA and, more recently, among U.S. partners) has also rendered collaboration more difficult.

The scale of large space projects—in terms of budgets and public profile—has made it difficult for NASA to structure stable, effective, and—when necessary—interdependent collaborations. This has been especially true in human space flight because of its enormous expense and its importance for U.S. leadership and prestige in space activities.

In large, high-profile projects (often involving human space flight), the pressures on the United States to maintain control over international collaborations have been greater than in smaller, automated missions. These pressures have come from NASA, as well as from outside, and were especially intense through the end of the Cold War. For example, in 1990, the Advisory Committee on

[61] The debate about space goals within and outside NASA was vigorous, but filled with ambiguity. Sally Ride's 1987 report, *Leadership and America's Future In Space*, strongly advocated the pursuit of space leadership. And President Reagan's February 1988 National Space Policy directive confirmed "leadership in space" as the basic goal of U.S. policy. But a new Bush Administration national space policy directive in November 1989 noted that although leadership would continue to be a fundamental objective, "Leadership in an increasingly competitive international environment does not require United States preeminence in all areas and disciplines of space enterprise. It does require United States preeminence in the key areas of space activity critical to achieving our national security, scientific, technical, economic, and foreign policy goals." Nevertheless, in 1992, Vice President Quayle's Space Advisory Board focused on the importance of international collaboration as a way "to influence the direction of future space undertakings around the world." The Clinton Administration has not yet issued a new space policy, but the first goal of the new 1994 U.S. science policy is to "maintain leadership." See National Security Council,"National Space Policy," see footnote 54; and Vice President's Space Policy Advisory Board, *A Post Cold War Assessment of U.S. Space Policy: A Task Group Report* (Washington, DC: Office of the Vice President, December 1992), p. 42; Clinton and Gore, see footnote 1, p. 7.

[62] Kenneth Pedersen notes that the U.S. preference for retaining control over critical path items will change because the increasing size and complexity of projects will produce "numerous critical paths whose upkeep costs alone will defeat U.S. efforts to control and supply them all." Moreover, Pederson argues, "It seems unrealistic today to believe that other nations possessing advanced technical capabilities and harbouring their own economic competitiveness objectives will be amenable to funding and developing only ancillary systems." Kenneth S. Pedersen, "Thoughts on International Space Cooperation and Interests in the Post-Cold War World," *Space Policy*, August 1992, p. 217.

[63] It must be noted that the United States is still the acknowledged leader in many areas. In a worldwide scientific consensus unique to space research, European and Japanese space officials acknowledge overall U.S. leadership. With a yearly space budget of $14 billion, the United States spends more than Europe and Japan combined on civilian space activities. Only the Soviet Union has pursued a space program of comparable scale and technical breadth. Since the disintegration of the U.S.S.R., Russia has continued the space program, but under severe financial constraints.

the Future of the U.S. Space Program (the Augustine Committee) recommended that international collaboration be used to demonstrate U.S. space leadership, but cautioned that the United States should retain operational control over critical-path elements in areas such as human space exploration.[64]

Pressures to maintain control have been especially strong in NASA's largest international human space project—the space station. The problems of international collaboration in the space station illustrate both the challenges of international cooperation in large projects and how the evolution of U.S. cooperative policy has affected ongoing projects. Although the space station program contained collaborative elements from the beginning, until very recently all critical aspects of the project remained firmly under U.S. control.[65] Consistent with the earlier U.S. approach to collaboration, the original station partners were not invited to assist in its basic design or construction; rather, they were invited to contribute supplementary elements. This approach to international collaboration had the advantage of adding elements to the station at no extra cost to the United States (see box 3-4.)

However, this approach to collaboration caused resentment among U.S. partners. According to one space policy analyst, the Europeans and Japanese saw the U.S. position as "arrogant and, particularly in Europe, insufficiently sensitive to a partner's ability to contribute significantly to the station program." It was further noted that the foreign partners were further dismayed by official NASA statements that the space station was critical to U.S. leadership and that international collaboration would "engage resources that otherwise might be used in support of programs competitive to the United States." This philosophy of collaboration conflicted with fundamental European and Japanese desires to achieve areas of autonomy in their space programs and more equal technical cooperation with the United States.[66] This made it more difficult to forge commitments among partners and to reach detailed agreements on management and utilization issues.[67] A 1989 NASA internal design review excluded the space station's foreign partners and caused further tension in the cooperative relationship. Since 1990, NASA has made a greater effort to include partners in station redesign activities. Despite these efforts, OTA has concluded that "the space station experience appears to have convinced the partners that they should not enter into such an asymmetrical arrangement [with the United States] again."[68]

However, with the addition of Russia as a station partner in 1993, the U.S. position on collaboration changed fundamentally. Under the new International Space Station program, the United States will rely on Russia for several critical elements, including: guidance, navigation, and con-

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[64] Advisory Committee on the Future of the U.S. Space Program, *Report of the Advisory Committee on the Future of the U.S. Space Program* (Washington, DC: U.S Government Printing Office, December 1990), p. 8.

[65] Although the Canadian Mobile Servicing System has been on the station's critical path from the beginning, the U.S. agreement with Canada provides for all Canadian hardware, plans, and materials to be turned over to NASA in the event Canada were to withdraw from the program. As in the agreement for the shuttle's Canadarm, this gives the agency *ultimate* control over the contribution and its underlying technology, in case of default.

[66] John M. Logsdon, "Together in Orbit: The Origins of International Participation in Space Station Freedom," December 1991, pp. 139-140.

[67] The desire (or need) to maintain U.S. control may also have reduced the potential financial savings offered by collaboration by excluding opportunities to take advantage of partners' expertise in critical areas of station design, construction, and operation. For example, NASA might have capitalized on Europe's experience in building Spacelab and satisfied the European desire to use this expertise by assigning construction of all (or most) pressurized station laboratories to ESA. Instead, the United States, ESA, and Japan will each build separate pressurized facilities.

[68] U.S. Congress, Office of Technology Assessment, *U.S.-Russian Cooperation in Space*, OTA-ISS-618 (Washington, DC: U.S. Government Printing Office, April 1995), p. 65.

BOX 3-4: The Space Station

The space station is a U.S.-led international effort to build and operate a permanently occupied Earth-orbiting research facility. The station is designed to play several roles: an orbital scientific laboratory for microgravity, Earth observation, and other experiments; a facility to study and develop skills for long-term human duration in space; and a model of international cooperation.

The program began officially in January 1984, when President Reagan announced the U.S. intention to build a space station and invited international participation in the endeavor. In 1988, after almost four years of discussions and negotiations, the European Space Agency (ESA), Canada, and Japan signed cooperative agreements to participate with the United States in building and operating the station. The original plan called for a station, named *Freedom,* to be built by the early 1990s. However, several program redesigns and funding reductions delayed station construction. In 1993, the United States invited Russia to participate in the station.[1] The new International Space Station project, based on the downsized *Alpha* design, is divided into three phases and calls for 34 construction-related space flights.

- Phase 1, 1994 to 1997—Joint Space Shuttle-Mir program.
- Phase 2, 1997 to 1998-Building of station "core" using: U.S. node, lab module, central truss and control moment gyros, and interface to Shuttle; Russian propulsion, initial power system, interface to Russian vehicles, and assured crew-return vehicle; Canadian remote manipulator arm.
- Phase 3, 1998 to 2002—Station completion. Addition of U.S. modules, power system, and attitude control; and Russian, Japanese, and ESA research modules and equipment.

Russian cooperation on the station is of a different nature than European and Japanese participation. Whereas Europe and Japan are making value-added contributions of pressurized research modules, the Russians are providing several critical space station components. These include the FGB module (for guidance, navigation, and control), reboost and refueling, a service module, a power mast, and a Soyuz/ACRV (emergency return vehicle).

Like Russia, Canada is also on the station's critical path. Based on its experience developing the Canadarm for the space shuttle, Canada is supplying robotic systems for station assembly and maintenance, However, unlike the U.S. agreement with Russia, the agreement with Canada would provide NASA with all Canadian hardware, plans, and materials should Canada withdraw from the program.

The United States is responsible for the vast majority of the station budget. It spent about $10 billion on *pre-Alpha* station work and will have spent an additional $28 billion on design, construction, launch, and assembly to complete the station. In a unique cooperative feature, the United States anticipates spending nearly $650 million in direct payments to Russia to pay for procurement of Russian equipment for the station. The Japanese anticipate spending $3 billion on the JEM (Japanese Experimental Module). ESA is considering a $3-billion station-related program. And Canada is spending about $1 billion.

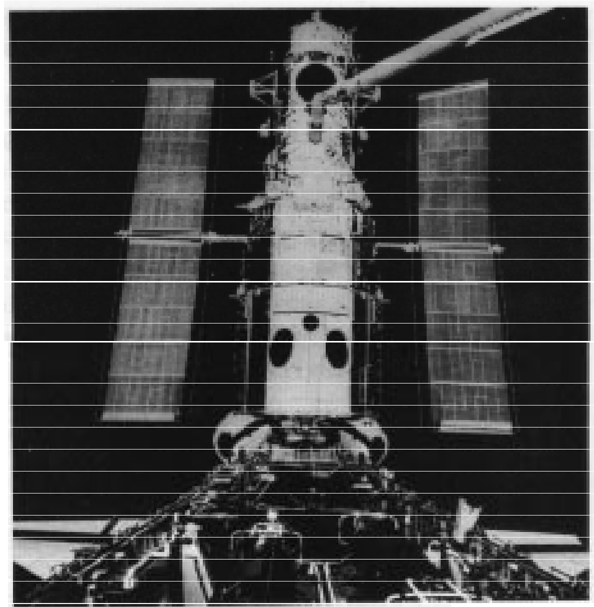
[1] A new intergovernmental agreement and revised Memoranda of Understanding are now being negotiated, bringing Russia into the program.

SOURCES. National Aeronautics and Space Administration; and Office of Technology Assessment, 1995.

trol in Phase 2; habitation until the U.S. habitation module is launched; crew-return ("lifeboat") modules through 2002; and reboost and fuel resupply. The Russian collaboration policy has evoked high levels of controversy in the United States and among the space station's foreign partners. Domestic objections to dependence on Russian technology are based on concerns about Russia's political and economic stability, questions about its technical reliability, the potential for loss of U.S. jobs, and traditional pressures to maintain U.S. control over critical mission elements.[69] Foreign partners expressed resentment over not having been consulted about Russia's sudden entry into the program.[70]

These concerns have been much less prominent in smaller and robotically operated science collaborations with Western Europe, Japan, and Russia. In these projects, NASA has for a longer time been receptive to new, more interdependent forms of collaboration. The agency has formed collaborations with European and Japanese space agencies, relying in some cases on partners for critical mission components. NASA has relied on ESA for critical solar power panels for the Hubble Space Telescope and on Germany for retro-propulsion systems and other critical components of the Galileo program. Although EOS has gone through several reorganizations and downsizings, it is extensively collaborative on both a mission and a programmatic level (see box 3-5). Out of the limelight of human space flight and without the huge price tag of the space station, these science projects have enjoyed greater flexibility and have not been burdened with carrying the full weight of U.S. leadership and prestige.

Another factor contributing to successful collaboration in science projects is financial and technical stability. This has affected both large- and medium-scale projects. Over the past decade, budgets for several NASA science projects were cut significantly while these projects were under development. Cuts have occurred both because of budget constraints and because funding requirements rose considerably above initial estimates.[71] For example, funding concerns prompted the restructuring of the space station in 1987, 1989, and 1991. The projected cost (originally $8 billion) rose considerably before it was downsized again in 1993. The program is now projected to cost $38 billion. As noted above, funding for EOS was also reduced several times within a few years, from $17 billion to $8 billion.[72] After large mid-program cost increases, AXAF and the CRAF/



EUROPEAN SPACE AGENCY

The NASA Hubble Space Telescope solar panels were built by the European Space Agency. Here the Canadian-built robot arm on the space shuttle Endeavors being used to inspect the telescope.

[69]NASA reports that it is "prudently developing contingency plans to allow the program to go forward in the event an international partner is unable to fulfill its obligations. Congressional representatives have endorsed the need for such planning in the case of Russia." Beth A. Masters, Director of International Relations, National Aeronautics and Space Administration letter to OTA, Apr. 26, 1995.

[70]The issue of Russian reliability, NASA contingency plans, the reactions of foreign partners to Rusaia's inclusion in the program, and the general risks and benefits of U.S.-Russian space cooperation are discussed in Office of Technology Assessment, *U.S.-Russian Cooperation in Space,* see footnote 68.

[71] For description of funding cuts in large science, see William C. Boesman, *Big Science and Technology Projects: Analysis of 30 Selected U.S. Government Projects* (Washington, DC: Congressional Research Service), Dec. 7, 1994.

[72] This figure accounts for EOS costs only through the year 2000.

BOX 3-5: The Earth Observing System

The Earth Observing System (EOS) is a multisatellite program to provide long-term, continuous data on global climate change, The program began in 1989, with National Aeronautics and Space Administration (NASA) plans to build three copies of two 15-ton polar-orbiting platforms, However, congressional concerns about cost and the risks of concentrating resources on two large spacecraft led NASA in 1991 to reduce the original program from $17 billion to $11 billion and to spread EOS instruments among several smaller orbiters, Since 1991, further funding cuts have reduced the program's budget to $8 billion (exclusive of EOS science costs) through the end of the century, The House Committee on Science has asked the National Academy of Sciences to review the EOS program with an eye to reducing its costs even further.

EOS is a highly collaborative project, involving instruments and spacecraft from the United States, Europe, Canada, and Japan. In exchange, these countries will fly several U.S. instruments on their own missions, EOS was originally coupled to the space station agreement in 1989, The two programs were later separated, and EOS is now NASA's contribution to the International Earth Observing System (IEOS), a joint project of the United States, Europe, Canada, and Japan. In addition to EOS, the IEOS includes a joint U, S.-Japanese project, the Tropical Rainfall Measuring Mission; data from the National Oceanic and Atmospheric Administration's Polar-Orbiting Operational Environmental Satellite program; Japan's Advanced Earth Observing System program; and the Polar-Orbiting Earth Observation Mission, a joint project of the European Space Agency and Eumetsat.

NASA plans to launch the first two EOS satellites (EOS AM-1 and PM-1) in 1998 and 2000, NASA has spent about $2 billion to date on the program. Although EOS has a budget of $8 billion, this will finance the program only through the year 2000. NASA has designated $2.2 billion of the current EOS budget for EOSDIS, the system to manage and distribute the enormous amounts of data generated by the project.

SOURCE: Office of Technology Assessment, 1995.

Cassini program each eliminated a proposed spacecraft.[73]

In addition to these periodic downsizings for large projects, the congressional budget review has generated annual uncertainties about the stability of funding for virtually all space projects. Uncertainty about continued or stable yearly funding has been particularly acute for the space station. The program survived by only one vote in the House of Representatives in 1993. Uncertainty continues to affect other projects under analysis here, such as the Cassini mission to Saturn.

Periodic downsizings and the uncertainties of the annual appropriations process make collaboration difficult by generating questions among foreign partners about the reliability and stability of U.S. commitments. As noted earlier, cancellation of the U.S. ISPM spacecraft reverberates to this day. Yet, questions about funding stability can

[73] NASA originally planned the AXAF x-ray telescope as one large telescope. However, in 1992, the agency eliminated some instruments and divided the project into two telescopes--AXAF-I (x-ray imaging) and AXAF-S (x-ray spectroscopy)-to reduce costs. In 1994, further budget pressures resulted in cancellation of funding for AXAF-S. At that time, Congress instructed NASA to undertake discussions with Japan about the possibility of flying the AXAF-S spectrometer on a Japanese craft. These discussions are still underway. Cassini is a joint U.S.-ESA mission to investigate Saturn and its moon Titan. When it was initiated in 1990, the project called for two spacecraft: Cassini to fly to Saturn and a Comet Rendezvous Asteroid Flyby (CRAF) mission to rendezvous with and investigate a comet and asteroid. However, by 1992, estimated project capital costs had risen from $1.6 billion to $1.9 billion. Simultaneously, Congress reduced funding for the project. Under these constraints, CRAF was canceled the next year, leaving Cassini as the sole U.S. component of the project.

affect even projects that are successfully concluded.

In the past, analysts contrasted uncertainty about the funding of U.S. projects with the more stable budgets of its foreign partners, particularly ESA and the Japanese space agency (NASDA). During the 1970s and 1980s, funds for projects at ESA and NASDA—once approved—were less subject to the annual uncertainties of U.S budgets. However, over the past five years, ESA has experienced severe budget reductions (in its nonmandatory programs) that have necessitated the cancellation of its Hermes space plane program and Man-Tended Free Flyer (MTFF), reductions in Earth observation budgets, and substantial uncertainty about the agency's long-term plans. Like U.S. programs, ESA projects now face more rigorous and uncertain yearly budget reviews, with more frequent delays and downsizings than before. Of central concern to the United States, continued disagreements within ESA about the agency's proposed program to build a pressurized module, a Crew Rescue Vehicle (CRV), and an Autonomous Transfer Vehicle for cargo raise questions about ESA's commitment to the space station.[74] Recently, ESA dropped the CRV from its proposed contribution. France may seek to develop the CRV in a collaborative project with Russia.[75]

Canada's commitment to build the robotic Mobile Servicing System (MSS) for the station has also come into question. In early 1994, Canada decided to terminate its critical path contribution to the station, but was dissuaded from doing so by President Clinton. Instead, Canada reformulated its contribution, with the U.S. assuming financial responsibility for portions of the MSS. Canada also delayed for two years a decision on whether to build an auxiliary contribution to the MSS, the Special Purpose Dexterous Manipulator.[76] Thus, the reliability of its partners has now become a concern for the United States.

Finally, financial stability—in both U.S. and foreign projects—also depends on the clarity of science goals and changes in project specifications that affect collaborative relationships. In this area, there is a stark contrast between human space flight and robotic space projects. In smaller and robotic projects, scientific goals have often been much clearer and less subject to dispute than in ventures involving human space flight. For example, consensus among partners about the scientific goals of planetary missions has been much stronger than about the space station. Whereas planetary and astronomical projects tend to focus clearly on scientific questions, the enormous cost of building facilities for human space programs such as the space station renders them infrastructure projects designed to satisfy a variety of goals—scientific, technical, economic, and political. These multiple goals complicate the execution of larger space projects, whether domestic or international in character.

All of these factors—NASA's history of mid-project downsizing, the annual congressional budget cycle, the ISPM experience, and questions about scientific goals—make it more difficult for the United States to engage in large-scale cooperative ventures. Collaboration has been easier in smaller projects where funding has been more stable and the financial risks are lower. This greater financial stability makes it easier to build the relationships of mutual trust among partners that are crucial to effective collaboration.

Results of NASA Collaborations

NASA's collaborative efforts have produced significant successes for the U.S. space program and

[74] According to a NASA official, "There is a growing program downside to not knowing whether we can count on Europe in this program." See "ESA Accord Postponed," *Aviation Week and Space Technology*, Ap. 3, 1995, vol. 142, No.14, p. 29; and Craig Covault, "Station Partners Reassess ESA's Role," *Aviation Week and Space Technology*, Mar. 27, 1995, vol. 142, No. 13, pp. 27-28.

[75] See Declan Butler, "France May Break Ranks Over Space Station," *Nature*, vol. 374, Apr. 27, 1995, p. 756.

[76] For a discussion of this issue, see Marcia Smith, *Space Stations* (Washington, DC: Congressional Research Service, Apr. 6, 1995), p. 11.

served U.S. interests and goals well. NASA indicates that it has saved money and increased the scientific yield of many U.S. projects by adding instruments and expertise from partner countries without sacrificing operational control or space leadership. Spacelab and the Canadian arm for the space shuttle are good examples of this type of cooperation.[77] Collaboration in space activities has also strengthened relations with U.S. allies and served other foreign policy interests.

Yet, in part due to changes in U.S. and foreign space policy, the reduction in available resources, and monumental events in world politics, the results of space-science collaboration over the past decade, although mostly positive, have been uneven. Recent U.S. experience in collaboration on large science projects in space has been paradoxical: although NASA initially designed projects that for the most part preserved U.S. independence, leadership, and operational control, its two largest projects—the space station and EOS—have evolved into highly interdependent collaborations.

Although the current rescoped EOS program might be seen as a model of interdependence in collaboration, this was not NASA's original vision. Rather than planning an extensively integrated international project from the beginning, NASA significantly expanded the program's dependence on foreign instruments when funding restraints dictated a dramatic downsizing of the U.S. contribution to the program. The downsizing of the EOS budget was the prime motive for expanding the program's international aspect.

EOS began as a project to build three copies of two U.S. polar-orbiting platforms with contributions of instruments from Europe and Japan. Foreign instruments were intended in some cases to complement proposed U.S. instruments. For example, data from the Japanese Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) were originally intended to complement NASA's proposed High-Resolution Imaging Spectrometer (HIRIS). In one case, ESA's Multifrequency Imaging Microwave Radiometer, NASA chose to rely exclusively on a foreign instrument for critical measurements.

However, the original EOS plan was criticized for its cost, the long period of time before the system could provide policy-relevant data, and its dependence on two large platforms to carry all the program's instruments. As a result, it was reviewed, rescoped, and downsized several times (see table 1-2).

NASA accomplished the downsizing of EOS with little loss of capability. However, in doing so, NASA has now come to depend much more extensively on several foreign instruments as critical U.S. mission elements[78] or on foreign spacecraft for flying critical U.S. instruments.[79] NASA acknowledges that reduced funding has increased U.S. dependence on foreign instruments and flights:

> At $8 billion, EOS must depend increasingly on the international partners. Failure to accomplish planned international cooperation on [Japan's] Advanced Earth Observing System (ADEOS), [ESA's] Polar-Orbit Earth Observa-

[77] An earlier OTA report noted that "[C]anadian expenditures (over $100 million) for the Shuttle's highly successful remote manipulator arm freed the United States from this Shuttle expense." Office of Technology Assessment, *International Cooperation and Competition in Civilian Space Activities*, see footnote 51, p. 409.

[78] The cancellation of HIRIS, for example, left NASA much more dependent on Japan's ASTER. NASA also eliminated the planned EOS synthetic aperture radar (SAR) and will now rely instead on data from European, Japanese, and Canadian SARs.

[79] NASA originally planned to fly 30 instruments on two U.S. platforms with no involvement of foreign spacecraft. In the rescoped program, NASA will fly 24 U.S. instruments on 21 U.S. and 10 non-U.S. platforms. NASA has retained all six foreign instruments originally slated for the program. National Aeronautics and Space Administration, Office of International Relations, fax communication, Jan. 27, 1995.

tion Mission (POEM), [U.S.-Japanese] Tropical Rainfall Measuring Mission (TRMM), and their follow-on missions will leave gaping holes in IEOS [International Earth Observing System].[80]

For the space station—designed as the U.S. flagship for human activities in space—NASA also designed a U.S.-controlled project with international enhancement. Although the United States sought supplementary international contributions from the inception of the station program, NASA insisted that the United States would build the station, with or without foreign participation.[81] Originally, this vision of collaboration was consistent with the goals and technical capabilities of potential partners. Although negotiations with European partners proved difficult, the United States was able to maintain operational control and to use international contributions as supplementary enhancements for two reasons: 1) no partner country or organization had the resources to mount an independent station program, and 2) U.S. partners had different priorities for human space flight.

For example, ESA initially planned to use the space station as an adjunct to its plans for achieving an autonomous human space flight capability in low Earth orbit. Its original plan therefore called for free-flying elements (such as Hermes and the MTFF) that could dock with the station or operate independently of it. This fit well with NASA's desire for "enhancing" contributions. From the beginning of their involvement with the program, the Japanese have seen the JEM (Japanese Experimental Module) as a chance to develop technologies for human space flight. Canada's contribution (robotics for station assembly and maintenance) builds on expertise developed for the shuttle program.

However, throughout the late 1980s and early 1990s—under increasingly intense funding pressures—NASA's station plans changed several times and were the subject of considerable uncertainty. Financial constraints reached a pinnacle in 1993. Simultaneously, the United States had undertaken discussions with Russia about technical cooperation. Technical cooperation with Russia was seen as an important tool for supporting U.S. foreign policy goals, which included Russian adherence to the Missile Technology Control Regime and the general goal of supporting the transition to a market-oriented democracy in Russia. This conjunction of financial, domestic political, and foreign policy imperatives resulted in a U.S.-Russian agreement to cooperate in a broad range of station design, construction, and supply activities.

Russia's inclusion in the space station program parallels the internationalization of the EOS program. Both projects originally envisioned cooperation of a mostly value-added nature, but evolved into deeply collaborative enterprises. In the case of the station, Russia's inclusion as a critical-path partner was motivated originally by both financial[82] and foreign policy considerations. The process was similar, however: contrary to its original intentions, well into each project, NASA "backed into" highly interdependent foreign collaborations.

The EOS and space station experiences demonstrate the complexity and difficulty of planning long-term collaborations on a large scale. In both cases, the original U.S. goals for international col-

[80]National Aeronautics and Space Administration, *EOS Reference Handbook* (Washington, DC: 1993), p. 12.

[81]"[T]he U.S. position was that the United States would develop a fully capable space station on its own, but that potential partners were welcome to suggest enhancements to that core station which would increase its capability." Logsdon, "Together in Orbit," see footnote 66, p. 137.

[82] The General Accounting Office has since reported that Russian participation will provide no significant cost savings to the United States. See U.S. General Accounting Office, *Space Station: Update on the Expanded Russian Role*, GAO/NSIAD-94-248 (Washington, DC: U.S. Government Printing Office, July 1994).

laboration changed, as a result in large measure of financial pressures and project downsizings. Given the benefit of hindsight, NASA might have saved time and money, increased program technical sophistication, and avoided tensions with partners if it had planned more integrated collaborations from the beginning. This may very well have been possible in the EOS program. Rather than undertaking a very large $17 billion U.S. project, NASA might have planned a more coordinated, international effort with a much smaller U.S. contribution.[83]

However, it is doubtful that the United States could have pursued a similar course in planning the space station. In the early 1980s, the goals and financial and technical capabilities of partner space agencies in Europe and Japan would have made a mutually interdependent collaboration less likely. Also, collaboration with the then Soviet Union was completely out of the question. Although downsizing did play a large role in forcing NASA to alter the character of its space station collaboration, the political changes that made cooperation with Russia possible were sudden and unexpected.

Future of Space Collaboration

There is a consensus—inside and outside NASA—that reduced budgets will necessitate expanded international collaboration on future large science projects in space. With the end of the Cold War, and the lessening of competitive pressures vis-a-vis the former Soviet space program, there will also be new opportunities to collaborate on a broad range of space-related science activities. NASA's two largest current projects—EOS and the space station—already demonstrate levels of interdependence with both Western partners and Russia that would have been impossible a decade ago. NASA's future plans for astronomy and planetary exploration also include significant international components. The agency is already discussing joint work with Russia and/or ESA for missions to the Moon and Mars, as well as projects to study the opposite ends of the solar system: the Sun and Pluto.

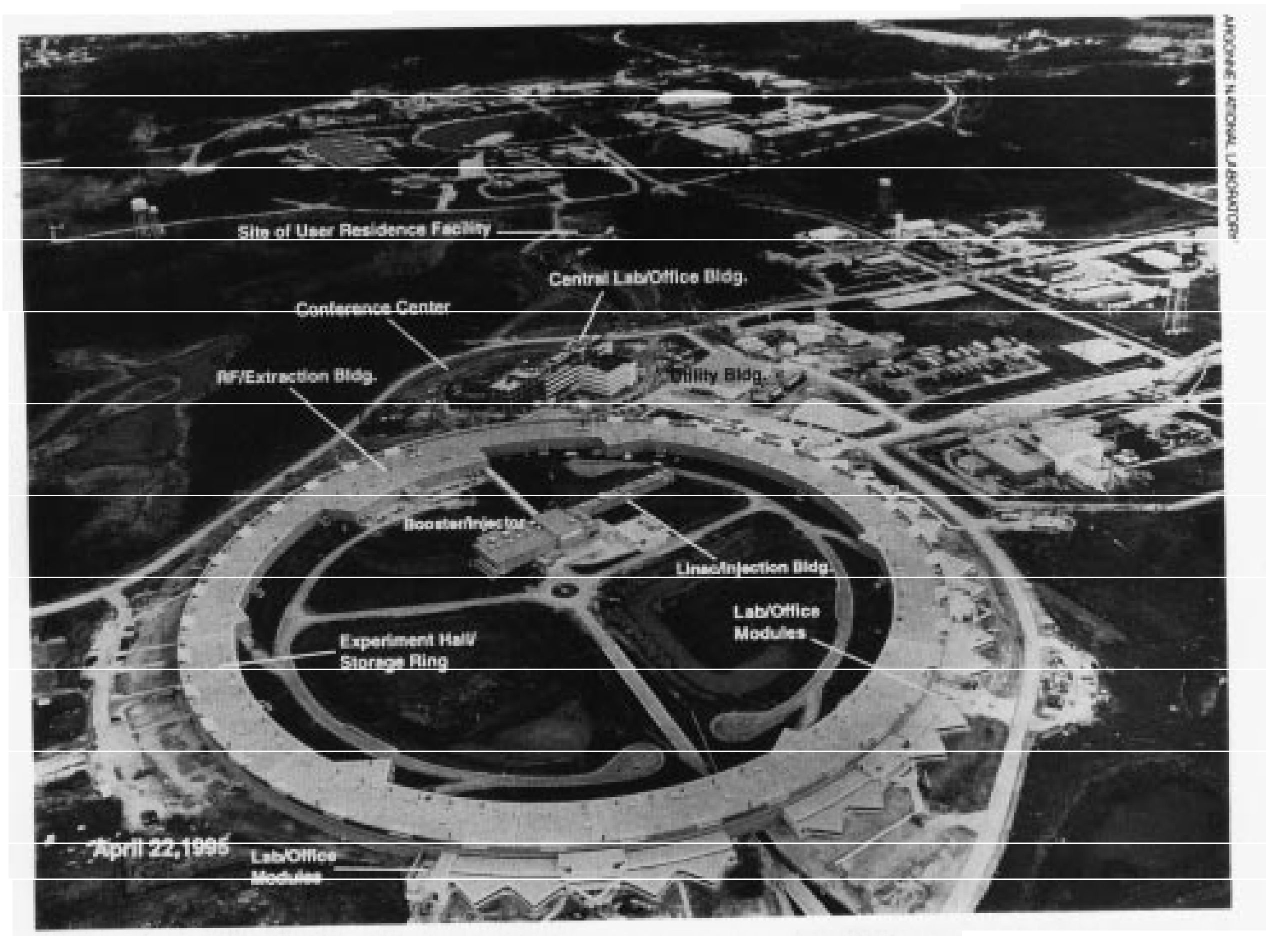
If collaboration is to be effective in these future cooperative activities, the United States must first decide on its goals for space. If leadership continues to be a paramount goal of U.S. space activities, this will complicate future, more integrated collaborative efforts because:

- No space agency, including NASA, has the financial resources to maintain the type of world leadership that the United States established in the past.
- The goal of maintaining U.S. leadership through collaboration creates fundamental tensions with partners who have developed sophisticated autonomous capabilities and are pursuing independence in some areas of space-related science. These partners are unlikely to accept future collaborations on past U.S. terms.
- The experience of the space station and EOS demonstrates that maintaining U.S. control over critical mission components has proved an elusive and perhaps unattainable goal in very large projects.
- The goal of U.S. leadership in space can be ambiguous and in some cases contradictory.

Moreover, as one space policy analyst notes, the end of the Cold War may devalue the traditional goal of leadership. In this scenario, "[T]he future scope, pace and vitality of the USA's approach to space cooperation would depend on other, less political interests—principally, economic, technological and scientific in nature."[84]

[83] A smaller EOS with greater international collaboration planned from the beginning may also have become a different program than the present EOS. Participants in an OTA workshop on EOS noted that had the project "initially been designed as an $8 billion program, it likely would be different than today's EOS." See U.S. Congress, Office of Technology Assessment, *Global Change Research and NASA's Earth Observing System,* OTA-BP-ISC-122 (Washington, DC: U.S. Government Printing Office, November 1993), p. 31.

[84] Pedersen, "Thoughts on International Space Cooperation," see footnote 62, p. 212.



Aerial overview of the Advanced Photon Source facility under construction.

Instability and uncertainty in funding for U.S. space projects may also continue to complicate space collaboration efforts. Although the United States has thus far avoided direct harm from the ISPM cancellation, project downsizings, and the annual certainties of the budget process, continued lack of confidence among U.S. partners could impede future collaborative opportunities--especially those in which the United States would take a leading role. Likewise, new instabilities and uncertainties in funding for foreign space agencies pose challenges for U.S. collaboration with its traditional **partners.**

Nevertheless, the United States still dominates many areas of space research and has space resources matched by no other single country. This will continue to give the United States wider latitude in choosing projects and collaborative opportunities.

NEUTRON SOURCES AND SYNCHROTRONS

Over the past several decades, the use of neutron and synchrotron beams has led to fundamental advances in understanding the properties of matter. These tools have opened new areas of research and application in materials science, structural biology, polymer chemistry, and solid-state physics. Neutron sources and synchrotrons are large science facilities that essentially serve as platforms for small science. They could be regarded as infrastructure investments for several fields of science and technology. Thus, having access to state-of-the-art neutron-scattering and x-ray synchrotron[85] facilities could have long-term competitive implications. For this reason, many industrial nations have supported their own independent facilities. Although the cost and complexity of neutron and synchrotron installations have escalated with advances in the underlying science, international cooperation has been limited primarily to information sharing and joint experimental work by researchers, rather than the joint development of large international facilities.

Neutron scattering and x-ray scattering are complementary techniques that have been used to elucidate much of what we understand about the structure of many important materials. X-rays interact strongly with matter and thus can provide significant information about the surface and bulk properties of a given material. Due to their electrical neutrality, neutrons can penetrate deeply into compounds to provide information about the structural and nuclear properties of materials. Neutrons can pinpoint the location of light atoms such as hydrogen and carbon, which are difficult to locate with x-rays. The identification of such light atoms is particularly important in completing the structural blueprint of organic and biological substances. When used at low energies, neutrons can be employed to study the dynamic or vibrational characteristics of matter. The use of both neutron and x-ray beams has allowed researchers to develop extraordinary precision in understanding the basic behavior of both natural and synthetic substances.[86]

Neutron Sources

History

The use of neutron structural probes has provided the technical foundation for the successful development of many different types of polymers (plastics), novel alloys, ceramics, liquid crystals, pharmaceuticals, catalysts, and magnetic materials. For example, the introduction of magnetic recording heads in electronic equipment directly benefited from the understanding provided by neutron-scattering studies. The widespread introduction and use of plastic materials has also been greatly facilitated by the use of neutron scattering. Properties such as flexibility, hardness, and wear resistance are determined principally by the way in which long polymer chain molecules are packed together. Developing plastics that have a greater range of properties and improved performance depends directly on the structural analysis that neutron probing provides. In addition, neutron physics has provided the means to analyze residual stress and to identify defects in metals, ceramics, and advanced composites.[87] It has allowed us to better understand the structure of viruses, as well as to profile surface impurities and irregularities in semiconductors—materials that serve as the basis of virtually all electronic and computational products. Because neutron probing provides information on how atoms vibrate, greater understanding of the dynamic behavior of materials has also been achieved. For these and other reasons, neutron scattering will continue to be an

[85]Charged particles orbiting at a fixed rate through a magnetic field emit a form of electromagnetic radiation known as synchrotron radiation. Synchrotron sources are circular accelerators that can be tuned to emit radiation with a broad range of frequencies including soft and hard x-rays.

[86]See OECD Megascience Forum, *Synchrotron Radiation Sources and Neutron Beams* (Paris, France: Organization for Economic Cooperation and Development, summer 1994).

[87]Neutron radiography is used for quality control of aerospace and energy production components and to test weld seams on pipelines, ships, and offshore drilling platforms.

important technique for understanding both man-made and biological substances.[88]

Neutron beams can be produced in two different ways: from reactors in which neutrons are by-products of nuclear fission, or from spallation sources in which neutrons are generated by accelerating high-energy protons into heavy-metal targets. To some degree, reactors and spallation sources have overlapping capabilities, but each has different attributes. Reactors produce high integrated fluxes of neutrons across a broad spectrum of energies, but particularly at low energy,[89] whereas spallation sources can more readily provide pulsed high-energy neutrons. Reactors, however, can also be used to produce a variety of isotopes for medical applications[90] and for materials radiation studies.

Implications for the Future

The fact that the highest neutron flux reactors in the United States (at Oak Ridge and Brookhaven National Laboratories) are both 30 years old,[91] and that Europe and Japan have invested heavily in neutron facilities in recent years, have raised concerns that U.S. capabilities in neutron science may be lagging behind other nations. Because the most important breakthroughs in neutron research have depended on the availability of high neutron fluxes and nuclear reactors are more technologically mature than spallation sources, a 1993 DOE scientific panel recommended that a new reactor, the Advanced Neutron Source (ANS), be constructed to meet the growing needs of U.S. researchers and industry.[92]

The ANS design provides for neutron fluxes at least five times higher than those of the newly upgraded Institute Laue-Langevin (ILL) neutron facility in Europe. This ANS capability would be particularly important for studying small samples (e.g., biological crystals or material fragments) or where short exposure times are necessary. However, the proposed 1996 federal budget calls for discontinuation of the ANS project, principally because of its high cost (approximately $2.9 billion).[93] A secondary factor in the Clinton Administration decision to terminate the ANS program was that the use of enriched uranium in the ANS reactor came into conflict with U.S. nuclear nonproliferation policy. Although engineers had redesigned the reactor to use lower levels of enriched uranium, even these levels were not sufficiently low to completely resolve the underlying policy problem.

In recognition of the potential contributions that an advanced neutron-scattering capability could provide to a broad range of scientific disciplines, technological applications, and industries, DOE has proposed to undertake a conceptual de-

[88]In the past two decades four Nobel prizes have been awarded for work relating to neutron scattering. In addition, a host of other prestigious awards in condensed matter physics and chemistry have been given to researchers that have used neutron probes as an essential part of their work.

[89]Neutrons are often slowed down to produce low energy or so called “cold” neutrons. Cold neutron research is a rapidly developing area of inquiry that could lead to major commercial applications for new classes of polymers. The importance of cold neutrons is due to interatomic and intermolecular structure and dynamics. See U.S. Department of Energy, Office of Energy Research, “Neutron Sources for America’s Future,” Report of the Basic Energy Sciences Advisory Committee Panel on Neutron Sources, January 1993.

[90]While some types of radioisotopes can be produced by proton accelerators, the radioisotopes used for many essential medical and technological applications are primarily produced by reactors. For example, the element californium is increasingly used in cancer therapy. Ibid.

[91]The High Flux Beam Reactor run by Brookhaven National Laboratory and the High Flux Isotope Reactor at Oak Ridge National Laboratory were built in 1965 and 1966 respectively, and are nearing the end of their useful lives. A smaller, lower power reactor was built by the National Institute of Standards in 1969, and is expected to have a somewhat longer lifetime than the two DOE reactors.

[92]U.S. Department of Energy, see footnote 89.

[93]The ANS was deleted from the 1996 budget request after a decade of planning costing about $100 million. See *Budget of the United States Government, Fiscal Year 1996* (Washington, DC: U.S. Government Printing Office, 1995), appendix, p. 435.

sign study of a 1-MW pulsed spallation source as a replacement for the ANS.[94] Although such a spallation source would offer some technical advantages over the ANS (e.g., a higher *peak* neutron flux, which allows more complex physical phenomena to be investigated), it would be inferior in other respects (e.g., a lower *time-averaged* flux, which is key for small-sample analysis and reduced cold-neutron capabilities).[95] The proposed spallation source would not produce transuranic waste or hazardous fission products.[96] However, without the ANS, DOE might find it necessary to build a dedicated reactor to meet the growing radioisotope needs of the U.S. medical community and other industries. Although some preliminary estimates have placed the cost of a 1-MW spallation source at around $500 million, the technical uncertainties[97] associated with this technology led the 1993 DOE scientific panel on neutron sources to conclude that the cost "will increase considerably with more refined estimates."[98] Some observers believe that the costs will be in the $1-billion range.[99] A 1-MW spallation facility would surpass the neutron intensity of the world's most powerful existing spallation source (the ISIS source in the United Kingdom) by roughly a factor of six.[100]

If Congress concurs with the Clinton Administration decision to terminate the ANS program and if existing facilities are not upgraded,[101] U.S. researchers could well be compelled to rely on access to foreign facilities while a spallation source is being constructed. The ANS was not conceived as an international project. Since other countries have made substantial investments in developing their own neutron-source capabilities, it is not clear whether the ANS project could have become a multinational collaborative endeavor. Although U.S. scientists and industry would have been the primary beneficiaries of ANS, there most likely would have been many users from overseas.

Assuming the ANS is not built, the United States could still maintain critical capabilities in the field of neutron scattering by exploring the possibility of joining the European ILL facility, for example. The United States could also establish its own beam line and contribute to the development of new instrumentation at ILL.[102] This would be analogous to the proposed U.S. contribution to the Large Hadron Collider project at CERN. It could be done at a fraction of the cost of the ANS but would not substitute for the capabilities that the ANS would have provided. In addi-

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[94] Some in the neutron scattering community have called for the construction of a 5-MW spallation source, but this would be a much more challenging and expensive undertaking.

[95] It is estimated that the time averaged flux of a 1-MW spallation source would be roughly 100 times lower than that of the ANS. For cold neutron research in the areas of polymers, complex fluids, biomolecules, and magnetic materials, "the ANS would be decidedly superior compared to a 1-MW spallation source." To match the ANS flux, a 5-MW spallation source would be required, and would involve considerable technical uncertainty. U.S. Department of Energy, see footnote 89.

[96] The proposed spallation source would use a tungsten target that would produce low-level radioactive byproducts. However, if uranium is used as the target material, there would be more serious radioactive byproducts.

[97] The central technical challenge of spallation sources is cooling the target. Existing spallation sources are quite limited in the amount of heat that they can dissipate, and this problem is compounded as the power is increased.

[98] U.S. Department of Energy, see footnote 89.

[99] Colin West, Oak Ridge National Laboratory, personal communication, February 1995.

[100] See footnote 89.

[101] The Brookhaven neutron reactor, for example, could be upgraded for approximately $200 million. See "The Looming Neutron Gap," *Science*, vol. 267, Feb. 17, 1995.

[102] Developing new approaches and techniques for neutron instrumentation is a vital component of neutron scattering science. Upgrading of instrumentation at the European ILL facility has established ILL as the premier neutron center in the world. Organization for Economic Cooperation and Development, see footnote 86.

tion, the United States could also consider joining the ISIS spallation facility in the United Kingdom, which is capable of having its available beam time doubled with some modest additional investment ($60 million).[103]

Historically, use of both neutron and synchrotron facilities around the world has been based on the policy of open access to foreign scientists. Indeed, many advances in neutron scattering, particularly in instrumentation, have been brought about by multinational research teams. However, with increasing budget pressures on virtually all national science programs, this policy of open access is now being reviewed by various facilities.[104]

Since many facilities in different countries offer complementary approaches to neutron-scattering and synchrotron radiation research, there is an opportunity for improving international cooperation by having a more substantive global planning and coordination process among nations. This approach could facilitate more effective utilization of existing facilities. Paradoxically, there is a great demand for access to neutron and synchrotron facilities, but most facilities operate for limited time periods because of funding constraints. There is a need for greater international coordination in both the use of existing neutron facilities and the construction of new facilities. In particular, the European Union is now in the early stages of planning a 5-MW spallation source.[105] With the United States apparently also pursuing the development of a spallation facility, greater interaction between U.S. and European scientists and engineers could perhaps lead to innovative approaches to spallation source design and construction. At the most recent Organization for Economic Cooperation and Development Megascience Forum on neutron sources, several participants emphasized that investments should be directed to state-of-the-art multinational facilities that have high-flux capabilities, not to smaller national facilities.[106]

Synchrotron Facilities: A Bright Future

One of the most important and powerful tools available to scientific researchers in a broad number of disciplines is x-rays. X-ray beams generated from synchrotron sources have provided the means to study a wide array of physical and biological phenomena. An understanding of the underlying molecular structure of DNA (dioxyribonucleic acid), RNA (ribonucleic acid), and viruses has come principally from x-ray research. X-ray studies of ceramics, semiconductors, and other materials have directly aided the development of a host of commercially important technologies.[107] Because of their utility to a variety of scientific fields and industries, the number of synchrotron radiation sources operating throughout the world has grown rapidly. There are about 40 partially or fully operational synchrotron facilities worldwide, with nearly the same number either in the design stage or under construction.[108] The ex-

[103]"The Looming Neutron Gap," see footnote 101.

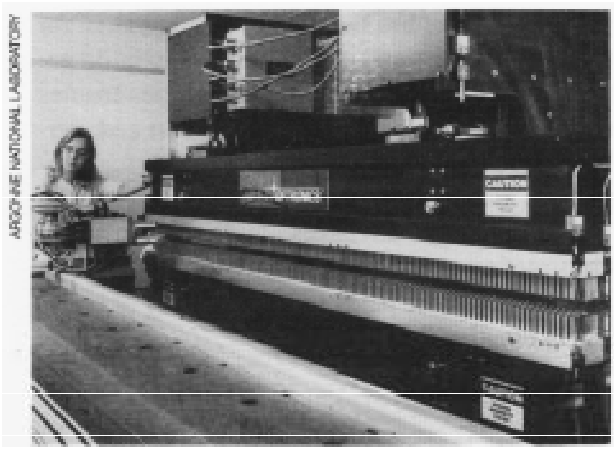
[104]For example, the ILL neutron facility in Europe has established new guidelines that partially restrict facility access to researchers who come from nonmember countries.

[105]The 5-MW European Spallation Source and the ANS were viewed by many neutron scientists as complementary programs. There was an expectation among some that researchers from Europe and the United States would have reciprocal access to these facilities. If Europe builds a 5-MW source and the U.S. proceeds with a 1-MW source, then in the eyes of many, Europe would have the leading international neutron facility.

[106]Other observers, however, pointed out that smaller facilities, particularly at the university level, have been responsible for some important advances in neutron scattering instrumentation. OECD Megascience Forum, Knoxville, TN, unpublished proceedings, Nov. 3-4, 1994.

[107]Another potentially important application of synchrotron radiation is x-ray lithography. The use of x-rays might offer the most viable means of improving the performance of microelectronic devices. As dimensions of these electronic chips shrink, visible light and ultraviolet light can no longer be used. Several companies including IBM, AT&T, and Motorola, as well as a number of Japanese and European companies, are developing x-ray lithography for chip manufacture.

[108]Organization for Economic Cooperation and Development, see footnote 86.



A closeup of a synchrotron insertion device called an undulator that generates super-intense x-ray beams.

pansion of synchrotrons light source capacity has been driven by a strong demand for x-ray beam time and by the desire to develop more intense sources to investigate a larger and more complex domain of problems.[10]

Three new major synchrotrons facilities—the European Synchrotrons Radiation Facility (ESRF), the U.S. Advanced Photon Source (APS), and the Japanese Super Photon Ring-8 (SPring-8)--will offer extremely intense x-ray beams that will allow researchers to study smaller samples, more complicated systems, and faster processes and reactions, as well as acquire data at unprecedented rates and levels of detail. *10 Researchers from industry, universities, medical schools, and national laboratories will exploit the capabilities of these machines.

At the APS at the Argonne National Laboratory, researchers will explore the following areas: structural biology, medical imaging, biophysics, chemical science, materials science, structural crystallography, time-resolved studies, basic energy science, tomography, topography, real-time studies, time-resolved scattering and spectroscopy, and geoscience. Collaborative teams from industry, national laboratories, and academia have been formed to explore new pharmaceutical products and polymer manufacturing techniques, as well as underlying processes associated with the formation of proteins.[111] The APS will be completed in 1996 at a cost of about $800 million, very close to the original estimate.[112] The ESRF and the SPring-8 have comparable construction and development costs.

Apart from the ESRF, which is a multinational effort of 12 European nations, there have not been any large international collaborative efforts in the planning and construction of new synchrotrons facilities. However, a cooperative exchange agreement has been established among ESRF, APS, and SPring-8 to address common problems of instrument development. These superbright light sources require sophisticated optical components, extremely tight mechanical tolerances, and novel detector systems.[113] The technical expertise for

[109] As an example of the demand for x-ray beamtime, the National Synchrotron Light Source at Brookhaven National Laboratory is used on an annual basis by more than 2,000 scientists representing 350 institutions, including researchers from more than 50 corporations.

ll0Each of these so-called "third-generation" synchrotron facilities will complement each other by providing a different range of synchrotron radiation frequencies and intensities. They each rely on “insertion devices” to produce x-rays of unprecedented brilliance. Insertion devices consist of alternating magnetic fields along the straight sections of the synchrotron ring. These alternating magnetic fields cause charged particles (electrons or positrons) to deviate in their trajectory giving off x-rays in the process. Insertion devices allow synchrotron radiation to be tuned over abroad spectrum of wavelengths from the infrared to hard x-rays.

111"Switching On a Brilliant Light," Science, vol. 267, Mar, 21, 1995, pp.. 1904-1906.

ll2The $800 million figure is a total project cost, which includes related R&D as well sd construction costs. Another synchrotron facility recently completed in the United States is the Advanced Light Source (ALS) at the Lawrence Berkeley National Laboratory. The ALS is a lower energy light source that provides the world’s brightest light in the ultraviolet and soft x-ray regions of the light spectrum. The ALS complements the hard x-ray capability of the APS. It is being used for basic materials science studies, the fabrication of microstructures, and structural biology.

113Organization for Economic Cooperation and Development, see footnote 86.

these areas is found in many different countries and many advances in x-ray instrumentation have resulted from multilateral collaboration. The coordination agreement among the three new synchrotron facilities will no doubt enhance the networks of cooperation that have developed in recent years.

Like neutron sources, synchrotron light sources essentially serve as vehicles for small science. Because of the wide range of uses for synchrotron radiation—in particular, its role in the development of new materials, processes, and products—there has been a strong imperative for the United States and other countries to build national facilities. Having multiple facilities ensures that demands for beam time can be met and, perhaps more importantly, provides a means for competition and thus greater innovation. However, as the technology advances and the costs of constructing new facilities increase, greater attention is likely to be paid to the possibility of building international facilities.