lion electron volts. (By way of perspective, Tevatron I, currently the world's most powerful accelerator, has a mass reach of roughly 0.3 trillion electron volts.) Both the SSC and the Large Hadron Collider have more than enough energy to study these phenomena. All machines can reach that level, but the electron-positron linear collider may be unable to explore completely phenomena at the upper reaches of the energy range. However, an electron-positron linear collider, if built, stands a good chance of making substantial contributions to high-energy physics.

As a scientific instrument, the SSC seems to have the lowest level of risk of any of the alternatives, although the SSC is far from riskless. The Large Hadron Collider will require superconducting magnets of unusual design with strengths that have not yet been achieved. Similarly, electron-positron linear colliders need substantial additional research before they become a reality. On the other hand, the SSC has already benefited from $105 million in magnet and other research and development, and will need another $250 million. It is difficult to say that electron-positron linear collider technology would not make substantial progress with $250 million for R&D.

DEFER THE DECISION

The Congress has already postponed the decision to build the SSC for fiscal year 1989. Recently, Frank Press, President of the National Academy of Sciences, suggested that actual construction might be deferred while continuing magnet research until the current budget conflict is resolved.[2] If the Congress chooses this route, current research on alternative accelerator technology would presumably continue and might be increased. CERN would probably continue research on the Large Hadron Collider. If current research efforts come to fruition during the deferral period, the Congress might have more reliable information about the various options than at present. Delaying the funding for construction is not without cost, however.

2. Frank Press, "Dilemma of the Golden Age" (address to members, One Hundred and Twenty-Fifth Annual Meeting of the National Academy of Sciences, April 26, 1988). For additional comments, see Barbara Culliton, "Science Budget Squeeze and the Zero Sum Game," *Science* (May 6, 1988), p. 713.

This section discusses the risks and benefits of deferring the decision on whether to fund the SSC or one of the alternative projects.

Risks and Benefits to Science

The principal scientific benefit of deferring the decision is that the Congress can keep all its options open during this time of technological uncertainty about improvements in accelerator design: the technology for the Large Hadron Collider, and especially for the electron-positron linear collider, may make substantial progress during the next 18 to 36 months, lowering the design risk associated with these instruments. It might then be possible to advance high-energy physics with instruments that are less costly than the SSC while maintaining an acceptable level of risk.

Delaying the SSC, however, may disrupt other high-energy physics research, since the SSC will dominate the high-energy physics budget: no other major new projects can be undertaken while it is under construction. As discussed below, the advance of accelerator technology depends on being able to build new types of particle accelerators, which might be able to explore higher energy regions at lower costs. Decisions regarding these new projects could be made in the 1990s. If SSC construction is still absorbing a major portion of high-energy physics funds, these decisions may have to be postponed.

Lastly, in the event the Congress ultimately builds the SSC, deferral will have slowed the pace of advancement in high-energy physics by causing a later delivery date. Two new accelerators, however--the Stanford Linear Collider and Tevatron I--have enough scientific capacity to occupy physicists until the late 1990s. Even if the SSC is delayed for 18 to 36 months, it would be hard to argue that this delay would have a lasting impact on U.S. high-energy physics, especially if CERN is also slow in approving the Large Hadron Collider.

Risks and Benefits to Technology

One point in support of deferment is that benefits are already flowing from the SSC's superconducting magnet research program to industry. More research in this area is likely to produce additional advances for both the SSC and the superconducting magnet industry. At this point, only two of the eight prototype dipole magnets built by DOE have been even partially successful. Allowing more time to improve both the magnets and their manufacturing process is likely to both increase the possibility of industrial applications of the technology and decrease the design risk of the SSC.

On the other hand, DOE maintains that it already has an established technology-transfer program. Furthermore, full-scale manufacture of the magnets is scheduled to begin only after the process has been tested in an industrial setting, which should eliminate most of the design risk involved.

Budgetary Risks and Benefits

If the decision is postponed, short-term federal spending would be reduced; costly construction would be deferred until later. On the other hand, if the SSC is never to be built, it would be better to cancel it sooner rather than later: deferral, in this case, would only commit valuable resources to a wasted task.

Other Risks

The Executive and Legislative branches of government may not be able to agree on a solution for budget shortfalls in the near term. Delaying funding may leave the SSC unbuilt for years, during which time several factors could change. The SSC team could begin to drift apart as members commit themselves to projects with higher chances of being funded; technology could move forward, requiring the redesign of the SSC and further delays; and the costs of many components may rise, increasing total project costs.

BUILD THE SUPERCONDUCTING SUPER COLLIDER

Construction of the SSC would start within two years of a Congressional decision. The first two years would be spent largely on preconstruction planning. If everything went according to plan, the facility would become available for science six to seven years after that--sometime around 1997, if approved in 1989. The major risks and benefits involved in this project are scientific and technological; risks are also associated with the instrument's components, possible cost escalation, and the schedule itself.

Risks and Benefits to Science

The principal scientific benefit of building the SSC is that, barring schedule delays, it is the option that will set the most rapid pace of any of the alternatives in terms of providing access to high energy levels and hence to potential scientific discoveries. There are time and money trade-offs: how fast does the Congress want high-energy physics to proceed and how much is the Congress willing to pay to speed up discovery rates? The high-energy physics community is almost unanimous in its desire to set a rapid pace for construction. On the other hand, the U.S. high-energy physics community is unlikely to stagnate, and may indeed continue to flourish, even if the pace of construction is slower.

By the time the SSC is operational, the current generation of accelerators will have been in place for almost a decade and thus may have exhausted the major questions at the relevant energy levels. The SSC is also powerful enough to answer most of the "next step" questions in high-energy physics. Consequently, early use of the instrument means more time for high-energy physics. This continuity of effort may ensure that the expertise and scientific teamwork gained on other projects will not be dissipated by a gap in employment for the scientists involved.

There is, however, the risk that the large increases in the science budget needed to pay for the SSC may cause neglect in other basic science areas, either directly or by preempting growth. (This concern will be very large with regard to other physics research, especially in high-energy physics.) Proponents of the SSC, however, contend that the Congress rarely makes budgetary trade-offs among science projects, evaluating each on its own merits. They hold that science grows as one and that increases in one science agency's budget do not seem to preempt growth in other areas of science research.

Even if other sciences are provided for, the opportunity costs of this investment are quite high. As noted above, the SSC will cost U.S. taxpayers $3 billion to $4 billion more than collaborating with European countries on a joint accelerator or building a less powerful machine alone. Both of these instruments are more modest and may be more risky technically, but they are likely to accomplish many of the same objectives as the SSC. The issue is whether the experiments that can be performed only on the SSC justify the additional costs to U.S. taxpayers.

Risks and Benefits to Technology

Actual construction of the superconducting magnets may improve the low-temperature superconductor manufacturing technology enough to apply it to other uses. The SSC will encourage substantial automation and other techniques that enhance the production of superconducting cable and magnets. If there are new uses for low-temperature superconductors where cost is an issue, the industry may well move beyond its traditional markets in medical instruments and research. At present, there do not seem to be many new uses of this type.

At least part of the reason that low-temperature superconductors have not diffused throughout the economy is the lack of personnel trained to work with these low temperatures. The SSC will increase the size of the industry at least temporarily and trained personnel will carry their experience to other parts of the economy. On the other hand, given the growing experience of engineers and others in the business of magnetic resonance imaging equipment, which uses superconducting magnets, it is difficult to estimate how much the SSC will add to this experience.

A major technological risk is that the construction of the SSC will produce disruptive fluctuations in the low-temperature superconductor market. This effect would be magnified if no new sources of demand for superconducting magnets appeared and if SSC requirements had increased the cost of superconducting magnets to magnetic resonance imaging equipment and other users during its construction phase. The SSC may create mixed effects: it may mature production technology but provide excess demand and, in the short run, higher prices. Moreover, should the recently discovered high-temperature

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superconductors enjoy some technological breakthrough to ensure their early adoption, the low-temperature superconductors may not have a chance to move substantially beyond their current markets.

Budgetary Risks

As discussed in Chapter III, the SSC may cost more than estimated, even including contingency costs. Should there be a significant cost overrun, the SSC could consume more science resources than its proponents intend. While there is an allowance of 20 percent for contingency costs, many major conventional construction projects have exceeded their initial projected costs by more than 20 percent. Unexpected delays resulting from unforeseen factors--ranging from lengthy lawsuits by affected citizens to labor strikes--could add substantially to costs. Furthermore, it would be difficult to terminate such a large project should costs begin escalating out of control.

Once the SSC is built, it will raise other budgetary questions. If the SSC is located anywhere but Illinois, it will pose the question of what to do about the Fermi National Laboratory for Accelerator Research. Fermilab's budget for 1989 was $188 million and its central mission is high-energy physics. The advent of the SSC will mean that much of Fermilab's capabilities may no longer be at the frontier of high-energy physics, although other disciplines within physics might be able to make use of the facility.

Design Risks

Although the SSC is being built using mature accelerator technology, its design will test the limits of that technology. Accelerators require that all their parts work to the optimum and do so together, and the superconducting magnets or other components may not function together as designed. This risk is much lower, however, for the SSC than for any of the other accelerator designs discussed in the rest of this chapter.

So far, research for the SSC's superconducting magnets has been slow. The SSC Central Design Group has produced only eight full-size (17-meter) dipole magnets, of which only two worked. The first was a slightly modified version of the planned production magnet, calling into question its relevance to the final product, and the second did not achieve its design strength the first time it was powered up. At full power, the SSC would be running these magnets at 95 percent of their capacity. In addition, The SSC Central Design Group has yet to test how the magnets perform when they are linked. Nevertheless, DOE maintains that these two magnets, plus the many successful model magnets built to scale, constitute a "proof of principle" of their design.

Any persistent problems with the magnets could have two consequences. First, the installation of the magnets will be much lengthier as each dipole magnet will be have to be "trained" (cooled and brought up to power several times before the magnet attains its designed rating). If each of the 7,680 dipole magnets has just two such training sessions, it would add several thousand hours to the installation of the magnets. (This problem would not be unique: DOE had to train the Tevatron I magnets.)

The second consequence is more serious: with only a 5 percent margin in the capacity of its magnets, the SSC may be less powerful than originally thought. Despite the best efforts at precision in manufacture, the strength of superconducting magnets varies, and some magnets are likely to be below the specifications necessary to produce a proton beam of 20 trillion electron volts. The weaker magnets will reduce the overall energy and mass reach levels of the SSC. Tevatron I experienced similar problems: originally designed to produce beams of 1 trillion electron volts, Tevatron at first produced beams of only 800 billion electron volts. Only after many magnets had been replaced was the accelerator able to operate regularly with beams of 900 billion electron volts. The lack of spare capacity in the SSC's magnets may force DOE either to accept a less powerful machine, or to engage in an expensive magnet replacement program after the SSC is completed, or both.

JOIN CERN IN BUILDING THE LARGE HADRON COLLIDER

Herwig Schopper, the Director General of CERN, in his testimony before the U.S. Congress, invited the United States to join CERN in the process of planning and building the Large Hadron Collider

(LHC), which may become CERN's next-generation accelerator.[3] This would be a new step in international cooperation. While many countries often participate in individual experiments, international cooperation in the construction of accelerators is limited, except in the case of CERN, which is a multinational consortium. The LHC is not necessarily a replacement for the SSC: some view it as an intermediate step. The energy levels are roughly one-third of the magnitude of those intended for the SSC, meaning that fewer phenomena could be studied. But because it uses existing facilities, the cost is also estimated to be less than that of the SSC.

The LHC would be built by adding new equipment to CERN's Large Electron Positron collider, which will soon be completed.[4] The Large Electron Positron collider's designers provided for additional capacity for the day when higher energies would be desired. According to advocates of the LHC, if a ring of superconducting magnets is placed in the Large Electron Positron collider tunnel, it would have the capacity to accommodate proton-proton collisions at an energy level of 14 trillion to 16 trillion electron volts, providing a mass reach of 1 trillion to 1.5 trillion electron volts. Since the mass reach would be lower than that planned for the SSC, however, less scientific output would result.

The CERN strategy is to build an accelerator with the power of the LHC and discover the phenomena that are postulated to exist in the range of up to 1 trillion electron volts, including the Higgs Boson and other particles. After this level has been explored, larger instruments such as the SSC, or alternative technologies such as electron-positron linear colliders (see below), could be investigated. Joining CERN in building the LHC would be a way of postponing the decision on the SSC and waiting until either the budget atmosphere becomes more accommodating or until there is technological improvement. It

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3. This discussion is largely based on the testimonies of Herwig Schopper and Carlo Rubbia, both of the European Organization for Nuclear Research (CERN). See *Superconducting Super Collider*, Hearings before the House Committee on Science, Space, and Technology, 100:1 (April 7-9, 1987), pp. 288-293, and *Status and Plans of the United States and CERN High Energy Physics Programs and the Superconducting Super Collider*, Hearings before the Subcommittee on Energy Development and Applications of the House Committee on Science and Technology, 99:1 (October 29, 1985), pp. 30-51.

4. For technical details, see the European Organization for Nuclear Research, *Report of the Long Range Planning Committee to the CERN Council* (Geneva: CERN, 1987).

would have the advantage over simple postponement of the SSC decision that it would keep U.S. high-energy physicists productively employed, since the LHC is intended to take the same amount of time to build as the SSC.

There are disagreements over this strategy: some scientists connected with CERN have urged the rapid construction of the SSC. The CERN Committee of Council, however, has refrained from endorsing or planning accelerators of SSC energies, choosing to concentrate on the intermediate step. The CERN council and the member nations have not yet formally committed themselves to the LHC. The proposal is at a much earlier stage than that for the SSC, suggesting that the United States could have a substantial influence on the plans for the LHC, should the Congress choose to participate in that project.

Risks and Benefits to Science

The principal scientific benefit of the LHC will be to permit U.S. high-energy physics to explore high energy levels at a lower total cost than with the SSC. If built, the LHC would be a world-class instrument. Whether or not the U.S. government participates, U.S. high-energy physicists will have access to the facilities. Given the international nature of the high-energy physics community, high-energy physics in the United States would not suffer greatly from international participation. Federal government participation in the LHC would serve to acknowledge this international aspect of the science budgeting process.

Although the phenomena of current scientific interest should be visible to both the LHC and the SSC, the lower energy levels of the LHC may preclude observation of some other interesting phenomena. In addition, building only the LHC means that physicists will be competing for limited experiment time. The LHC might also have fewer detectors than the SSC and will be competing with the Large Electron Positron collider, which could still be running, for experiment time. As a consequence, fewer experiments may be performed, and the cost per experiment could rise.

If just the LHC were built, there would be only one instrument worldwide capable of investigating phenomena in these high energy ranges. If it were shut down, either because of an accident or other mishap, work in whole areas of high-energy physics would stop, because there would be no other instrument to match its energy.

Moreover, joining the LHC project instead of building the SSC would mean that in the late 1990s, all the newest high-energy physics facilities would be in Europe: HERA in West Germany, and the Large Electron Positron collider and the LHC in Switzerland. To the extent that the training and other benefits land near the instrument site, the United States would cease enjoying these. On the other hand, these benefits affect mainly engineers and technicians; the professors and graduate students would be internationally mobile, as they are now.

Risks and Benefits to Technology

The technological risks and benefits for U.S. industry from the LHC would largely depend on the exact nature of U.S. participation and on the CERN procurement contracts. U.S. superconducting magnet makers and DOE often complain that the U.S. industry is excluded from CERN projects. Negotiating the LHC procurement is not likely to be simple because of the perceived technology spinoffs. The analysis that follows assumes that, if the United States contributes substantial funds to CERN, provisions will be made to ensure that U.S. superconducting magnet and equipment makers, as well as European manufacturers, supply the project with its technical requirements. Should U.S. industry be excluded, the commercial benefit of technology spinoffs to U.S. companies would be substantially reduced.

The pooling of U.S. and CERN technology will increase the likelihood that the superconducting magnets and other technical components will receive the attention of the best talent worldwide. As noted above, only in Europe has the manufacture of superconducting magnets for accelerators been undertaken in an industrial setting. Thus, the U.S. superconducting magnet industry stands to gain from an infusion of European technology. Furthermore, many of the same superconducting technology spinoffs that would result from building the SSC should also result from the LHC.

The spinoffs from the LHC are bound to be more widely distributed than those that might occur with the SSC. The superconducting magnets may be built by several companies of various nationalities. This contracting procedure would ensure the spread of superconducting technology to many countries, and the United States would not enjoy monopoly benefits that might be hoped to result from the SSC. The possibility of monopoly benefits may be illusory, however, since CERN may build the LHC even without the United States, ensuring a major European superconducting magnet effort at the same time as the U.S. effort related to the SSC. Japanese firms are also entering this industry.

Lastly, one obvious disadvantage of building the LHC is that it would be located outside U.S. borders. While U.S. construction firms and other suppliers might provide some inputs, the benefits of long-term regional economic development would flow to Europe. This case would not be unique: U.S. military installations located abroad also provide regional economic benefits. The LHC would be different, however, in that most military bases have few if any spinoffs.

Budgetary Risks and Benefits

Since the proposal for the LHC is much less developed than that for the SSC, the estimates of its costs are preliminary. Furthermore, the portion of the costs that would fall to the United States have not yet been negotiated.

Because it will be built in the Large Electron Positron collider tunnel and use the existing infrastructure and older CERN accelerators, the additional costs of the LHC will be primarily for superconducting magnets, cryogenics, and detectors. In his testimony last year, Herwig Schopper stated that the CERN Long Range Planning Committee had calculated that the costs would be between one-quarter and one-third of the costs of the SSC.[5] This would translate into roughly $1.1 billion to $1.5 billion.

However, it is unclear from Schopper's testimony or the Long Range Planning Committee's report what this figure includes. Nowhere in the report is there any discussion of the detector costs. As

5. Testimony of Herwig Schopper, *Superconducting Super Collider*, Hearings before the House Committee on Science, Space, and Technology, 100:1 (April 7-9, 1987), p. 291.

noted in Chapter III, the detectors for the SSC are projected to cost between $900 million and $1.2 billion, although DOE believes they can be built for $720 million. Because the LHC will have only two detectors and the SSC will have four, detector costs are likely to be substantially lower for the LHC than for the SSC. In addition, CERN estimates often exclude support provided to projects by laboratories of CERN and its members. Assuming, as an upper bound, that the LHC detectors cost as much as the two most expensive SSC detectors (a total of $700 million to $800 million) and that laboratory support work is roughly 50 percent of direct costs ($550 million to $750 million), the estimate for the complete LHC may be closer to between $2.4 billion and $3.1 billion.

Should the United States join CERN in building the LHC, the U.S. contribution would have to be negotiated. CERN is supported by most Western European nations, many of whom have substantial resources for high-energy physics. They have shown their willingness to make large investments in accelerators: the Large Electron Positron collider is costing roughly $1.1 billion. On the other hand, the role of U.S. scientists and U.S. component manufacturers would also be open to negotiation. Presumably, the greater the U.S. contribution, the greater the U.S. role, and the negotiations promise to be complex.

This analysis assumes that the U.S. contribution to the LHC will fall between 25 percent and 33 percent of the total costs. The cost to the United States would then be between $600 million and $1.0 billion. Thus, joining CERN in the construction of the LHC instead of building the SSC without international contributions would result in a U.S. budget savings of between $3.5 billion and $4.5 billion, relative to the estimated cost of $4.5 billion to $5.1 billion for the SSC.

Design Risks

The design of the LHC is likely to be riskier than that of the SSC. The configuration of the LHC magnets, as currently conceived, would be much more complicated than that of the SSC. In order to produce high energy levels in the small circumference of 27 kilometers, very powerful magnets of 10 tesla would have to be built.[6] The SSC magnets are

6. A tesla is a unit of magnetic strength, defined as one weber per meter squared (see glossary).

of 6.6 tesla and are considered very powerful by normal standards. The research program for the LHC magnets has modified the design of the magnets being built for the HERA accelerator in West Germany and achieved about 9 tesla in a small test magnet, but is still far from proving the technical and economic feasibility of those magnets.[7]

The superconducting magnets for the LHC may also require an unusual dual-bore design. The Large Electron Positron collider tunnel may not accommodate two additional rings of superconducting magnets. Consequently, each magnet may be required to contain bores for two separate proton beams, which will add technical complications. By contrast, the SSC's superconducting magnets, like the Energy Saver and Tevatron I magnets, have only one bore.

In order to achieve its high mass reach in a small space, the LHC has to increase the number of interactions among particles in its beams to achieve the desired event rate (luminosity). This might result in so many interactions, however, that the detectors are unable to track them properly. Conversely, if the LHC lowers its luminosity, it lowers its mass reach and may miss some phenomena of interest. Thus, while reusing the Large Electron Positron collider tunnel for the LHC would reduce the cost of the conventional facilities, it would increase the cost and functional risks of the technical components.

Because of the complex nature of the LHC's superconducting magnets and the fact that the LHC will be competing with the Large Electron Positron collider for time in the tunnel, the LHC may fall behind schedule. Moreover, although it is currently given the same schedule expected for the SSC, the time pressure may be removed if the United States cancels the SSC and joins CERN's project.

Political Risks

While the Congress was able to stop building the Isabelle particle accelerator at the Brookhaven National Laboratory for technical reasons and might be able to slow down other scientific programs, committing part of the U.S. science budget internationally will place

7. Designers of the LHC hope to use superconducting magnet technology developed by the SSC research program.

more international constraints on Congressional actions. Additionally, CERN may decide not to build the LHC. If both the SSC and the LHC were deferred indefinitely or canceled, high-energy physics might stagnate or leadership might pass to Japan and the Soviet Union, both of which have high-energy physics programs. On the other hand, the LHC might become very attractive to CERN members if the United States shares the costs and lends prestige to the project by supporting it.

BUILD AN ELECTRON-POSITRON LINEAR COLLIDER

The choice of a proton-proton ring collider for meeting the objectives of high-energy physics is based on extending a known accelerator technology, albeit in a large increment. Physicists, however, can also use electron-positron linear colliders for many of the same experiments and some have suggested that, instead of building the SSC, the United States should build an electron-positron linear collider as its next major accelerator. Instead of building the SSC, the Congress could increase R&D funding for these accelerators and begin planning construction of an electron-positron linear collider.[8]

High-energy physics has traditionally had both proton and electron-positron accelerators, as they tend to complement each other scientifically. As costs rise, however, the high-energy physics community and the Congress will have to consider whether the U.S. science budget can continue to fund both types of accelerator.

Electron-positron linear colliders may require 15 to 20 years of research before they can achieve the energy levels of the SSC. The new accelerator technologies, however, are expected to be able to reach levels of energy approaching those of the LHC in the late 1990s.

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8. For a technical version of this debate, see Freeman Dyson, "Alternatives to the Superconducting Super Collider," *Physics Today* (February 1988), p. 77. Responses from critics and his rejoinder appear in the May 1988 issue of *Physics Today*. For a detailed discussion of types of particle accelerators, see National Research Council, *Physics Through the 1990s: Elementary-Particle Physics* (Washington, D.C.: National Academy Press, 1986), pp. 98-131. CERN is also considering an electron-positron linear collider, called CLIC. See *Report of the Long Range Planning Committee to the CERN Council*, pp. 30-40 and Appendix II.

In fact, building such a machine is part of the agenda needed to advance accelerator technology in general.[9]

Electron-Positron Linear Colliders

An electron-positron linear collider accelerates electrons and positrons in a straight line into a collision with each other. Unlike the LHC or the SSC, these colliders have no rings: they simply use two particle sources and the power sources to accelerate the particles at opposite ends of a straight tunnel, analogous to holding two shotguns muzzle to muzzle and pulling the triggers at the same time. The simplicity saves the costs of superconducting magnets that are needed to keep high-energy particles moving in a circle.

These electron-positron colliders are attractive in that the particles need not have as much energy as the protons in the SSC to yield similar results. Because protons are composed of quarks and other particles, when two protons collide the effective energy available for scientifically interesting interactions is less than the total energy of the particles. The SSC beams of 20 trillion electron volts each will give only enough energy to create interesting interactions in the range of 3 trillion to 4 trillion electron volts. The rest of the energy will be used by interactions not of immediate interest. In an electron-positron collision, all of the energy is available for such interactions. A collision of electrons with positrons at 3 trillion to 4 trillion electron volts is thus equivalent to the collision of protons with protons at 40 trillion electron volts in the SSC. At present, there is no linear collider in operation that can reach such energies.

The reason electron-positron linear colliders may be important is that, unless there are unforeseen developments in accelerator technology, the SSC will probably be the last U.S. proton-proton accelerator: building a circular accelerator larger than 53 miles in circumference is difficult to conceive and likely to be very expensive. If accelerator energies are to increase, new types of accelerators must be developed. DOE already has a program to develop these. One Con-

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9. Department of Energy, *Report of the HEPAP Subpanel on Advanced Accelerator R&D and the SSC* (December 1985), p. i. This report is referred to hereafter as *The HEPAP Report on Accelerator R&D.*

gressional option is to support the developing technology rather than the established one.

The largest, and in fact the only, electron-positron linear collider built so far is the Stanford Linear Collider in Stanford, California. The collider is 2 miles long and has a collision energy of 100 billion electron volts. However, it is having problems producing the particles it is intended to study and has been temporarily shut down.

Using current technology from the Stanford Linear Collider, physicists cannot duplicate SSC experiments. Using this technology to produce energies comparable to those of the SSC, the collider would have to be 200 miles long, which would be prohibitively expensive. Based on the cost of the Stanford Linear Collider, a 200-mile-long facility necessary to match the SSC would cost $16 billion.[10]

Successful operation of the Stanford Linear Collider is an important step in confirming several design concepts of such colliders. Nevertheless, while the Stanford Linear Collider will provide useful information, its characteristics are quite different from those of a linear collider that can achieve several trillion electron volts, and thus it is not possible to simply scale up the Stanford Linear Collider.[11] Research is, therefore, focusing on improving the capabilities of electron-positron linear colliders.

The DOE panel on alternative accelerator design estimates that it will be five years before a clear direction in electron-positron linear colliders emerges. It may take an additional 10 to 15 years before a linear collider can be built that will have the same mass reach capabilities as the SSC.[12]

It might be much easier, however, to build an electron-positron linear collider that will approach the capabilities of the LHC. Despite its problems, the Stanford Linear Collider has begun to prove many of

10. *The HEPAP Report on Accelerator R&D*, p. 35.

11. The Stanford Linear Collider's design is different from the likely design of future electron-positron linear colliders because it was constrained by pre-existing facilities.

12. *The HEPAP Report on Accelerator R&D*. Similarly, CERN does not expect technology for the CLIC, its own version of the electron-positron linear collider, to develop in less than 10 to 15 years.

the concepts needed for higher-energy electron-positron linear colliders: most of the problems seem associated with older technology incorporated into the Stanford Linear Collider from a previous accelerator.[13] Some of the recent research conducted at Stanford suggests that the time needed to complete a machine with a mass reach of 0.6 trillion to 1 trillion electron volts might be less than previously thought. Lastly, *The HEPAP Report on Accelerator R&D* suggested that design and construction of machines with mass reach levels between those of the Stanford Linear Collider and the SSC might become feasible by the early 1990s. Thus, an electron-positron linear collider at an intermediate energy level could be built in the late 1990s, assuming the current R&D program is successful. By comparison, even if the Congress approves construction of the SSC in early 1989, it will be at least eight years before the SSC is ready for experimental work.

Risks and Benefits to Science

The principal scientific benefit of building an intermediate range electron-positron linear collider to investigate phenomena at up to 1 trillion electron volts is that it would advance high-energy physics at a lower cost, freeing up funds for other science, including other high-energy physics. The range of up to 1 trillion electron volts would expand high-energy physics' current capabilities and permit investigation of many of the phenomena in the standard model at this energy level, including some versions of the Higgs Boson.

Compared with joining CERN in building the LHC, this machine would give U.S. high-energy physicists access to a state-of-the-art research instrument. It would also provide one more instrument worldwide on which to perform high-energy physics experiments. Moreover, it would lead U.S. physics through the design of the next generation of accelerators.

On the other hand, an electron-positron collider would have only one detector. While this reduces costs, it also means that fewer experiments can be performed, which reduces the scientific potential of the

13. See "More Setbacks at SLAC," *Scientific American* (October 1988), p. 25. See also, Mark Crawford, "Racing After the Z Particle," *Science* (August 26, 1988), pp. 1031-1032.

instrument. Electron-positron colliders, however, can run at higher interaction rates than can proton-proton colliders without overwhelming the detectors, producing the same number of interesting phenomena in less time.

An intermediate-energy electron-positron linear collider carries more risk than the LHC of not being able to explore the highest reaches of the 1 trillion electron volts range as thoroughly as the SSC.

Risks and Benefits to Technology

Assuming CERN builds the LHC and the United States builds an electron-positron linear collider with a mass reach of 1 trillion electron volts, the European superconducting magnet industry would probably grow in sophistication relative to the U.S. industry. As noted, the LHC's superconducting magnets will have to be very powerful and sophisticated. By contrast, because they are linear and do not have to bend particle beams, electron-positron linear colliders use fewer, if any, superconducting magnets. Consequently, this part of the U.S. industry may fall behind, although the magnetic resonance imaging industry is still growing and has yet to take full advantage of the superconducting magnet technology that has been developed so far for the SSC.

Budgetary Risks and Benefits

Because much of the technology is as yet undeveloped, the preliminary cost estimates are especially unreliable. To a certain extent this estimate freezes the technology artificially, since physicists have just begun to examine ways to reduce these costs. Should these experiments present positive results, the preliminary estimates cited here would be obsolete.

The estimate contains three cost components: the linear structure, the power source, and other components such as detectors. Assuming acceleration gradients of 186 million electron volts per meter, an accelerator with a mass reach of 1 trillion electron volts would have to be 7 kilometers long, including an extra 30 percent in length for infrastructure. Using the $50 million to $100 million per kilometer suggested by *The HEPAP Report on Accelerator R&D*, the structural costs would total between $350 million and $800 million. Since the report was issued, power source costs have decreased dramatically. The report suggested that stored energy costs equivalent to those of the SSC would total $40 billion. Current experiments and anticipated manufacturing improvements suggest that $400 million to $800 million spent on a power source might be sufficient for an intermediate energy collider. Detectors, R&D, and other costs might add $250 million to $500 million. Thus, with the understanding that such an estimate is surrounded by a high degree of uncertainty, CBO's calculations suggest that such a machine would cost about $1 billion to $2 billion.[14]

Design Risks

Electron-positron linear colliders are still quite small in energy terms. They carry a high risk of never being able to deliver what they promise. It is quite possible that building larger scale electron-positron linear colliders could uncover unsuspected problems. Similarly, scientists may encounter obstacles in scaling up linear colliders that could make them more expensive than the SSC. Or they may be able to build an instrument with a mass reach of only 0.6 trillion electron volts rather than 1 trillion electron volts in the planned time, which would further lower the scientific potential. (The instrument would still be three times as powerful as the next most powerful electron-positron collider currently planned.) The uncertainty attached to the potential of these devices is high, although experts seem optimistic about the ability of the technology to succeed.

14. Many of the assumptions for these calculations are derived from *The HEPAP Report on Accelerator R&D*, pp. 33-39. For power source cost assumptions, see D.B. Hopkins and others, "An FEL [Free Electron Laser] Power Source for a TeV [trillion electron volt] Linear Collider" (paper presented at the LINAC 1988 Linear Accelerator Conference, Williamsburg, Virginia, October 3-7, 1988).