THE GREEN HYDROGEN REPORT

The 1995 Progress Report
of the Secretary
of Energy's
Hydrogen Technical
Advisory Panel

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Executive Summary

Hydrogen and electricity, ultimately derived from renewable technologies, will serve as the clean, inexhaustible energy carriers in the rapidly approaching next century. The widespread introduction of these energy forms would dramatically reduce the nation's air pollution, enhance its energy security, and ameliorate potential global climate problems.

The Hydrogen Technical Advisory Panel (HTAP), established in 1992 to advise the Secretary of Energy on the nation's hydrogen opportunities, has reviewed the U.S. Department of Energy's (DOE) programs and developed recommendations to improve DOE's long-term research, development, and demonstration efforts. HTAP's 20-year plan in renewable hydrogen will revolutionize global transportation systems, thus allowing cleaner and indigenous fuels to be used. In the process, corporate America will be established as the premier commercial supplier of energy in the 21st century. Under the HTAP plan, DOE's hydrogen budget within the Office of Energy Efficiency and Renewable Energy (EERE) would annually range between $40 and $60 million, compared with recent funding of about $10 million. This core funding should trigger at least equal cost-matching from industry and stimulate an expanded, but more coordinated, response within DOE and other federal agencies involved with hydrogen research and development (R&D).

HTAP's *Green Hydrogen Report* calls for an integrated program of basic research on hydrogen production, storage, and utilization; analytical studies on hydrogen use that incorporate life-cycle and environmental factors; an enhanced development program of components for the hydrogen infrastructure; and various project demonstrations.

The plan emphasizes the need to transfer technology to the private sector to encourage the commercial introduction of hydrogen into the marketplace. Concern was expressed that, across the board (and not only in hydrogen), we are losing international competitiveness and therefore, the <u>creation of an industry-government partnership in the form of an authority or consortium</u> might be necessary to facilitate swift progress.

The report also recommends the <u>establishment of research centers of excellence</u> that would largely be associated with universities. These centers would provide a stable academic environment for conducting innovative research and train the cadre of hydrogen researchers who would become our future leaders in the field. In addition, one or more locations should be selected to expand awareness and provide hands-on demonstrations of user-friendly systems for the general public.

Specifically endorsed in the report are <u>transportation demonstrations</u> to best meet anticipated customer requirements. Ground vehicles might initially need to use nonrenewable hydrogen and could be powered by internal combustion engines to gain early day-to-day experience. However, the ultimate goal would be to produce hydrogen from water using sustainable systems with eventual adoption of more efficient, pollution-free fuel cells. A hydrogen freight aircraft that could operate between two airports capable of handling this fuel would also be a useful experiment.

The Green Hydrogen Report sets the stage for a 21st century scenario featuring a higher degree of national self-sufficiency and reliance on environmentally friendly, sustainable energy technologies. The transition to this preferred future remains a formidable task, and one which HTAP is resolved to catalyze.

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The Green Hydrogen Report

1995 Hydrogen Vision Statement

Hydrogen will join electricity in the 21st century as a primary energy carrier in the nation's sustainable energy future. Both electricity and hydrogen will ultimately be derived from renewable energy resources, although fossil fuels may serve as a transitional resource. Future hydrogen suppliers will meet a significant portion of America's energy needs for transportation and other applications, thus offering a non-polluting, inexhaustible, efficient, and potentially cost-effective energy system dependent entirely on domestic energy resources.

Introduction

Adequate and affordable energy supplies play a critical role in the functioning of a modern industrial society. Energy provides us with the ability to heat and cool our homes and offices, to light our buildings and power our appliances and computers, to run our factories, and to travel quickly and comfortably to virtually all corners of the globe. Energy may well be a key to eradicating poverty and enhancing global living conditions. The importance of reliable energy supplies cannot be overstated.

The United States has been blessed with a bounty of energy natural resources. The nation is one of the world's largest producers and consumers of fossil, hydro, and nuclear energy. Yet, the vast bulk of these resources is finite in supply. The United States relies on nonrenewable fossil sources of energy for nearly 90% of its total energy supply. It should be noted that these fuels and, especially oil and natural gas, are increasingly being imported. In 1993, 11% of the natural gas consumed in the United States was imported, mostly from Canada. This fraction is expected to grow to 16% by the year 2010.[1] The nation's oil supply picture is more worrisome. In 1993, net oil imports accounted for 45% of supply, with 12% of total U.S. oil supply imported from the Persian Gulf. This percentage is twice what it was in 1973 at the time of the Arab oil embargo. According to DOE's Energy Information Administration (EIA), oil imports could grow to 60–70% of supply as early as 2010.[2] With most of the world's remaining oil resources located in the unstable Middle East, risks to national security can only grow as dependence on the region for this vital resource continues to increase. This message was conveyed to President Reagan by DOE in a detailed study in 1987.[3] However, little strategic action has been taken to reduce the United States' continued reliance on oil.

Heavy dependence on fossil fuels gives rise to a host of problems beyond the risks to national security. The burning of fuels, especially oil and coal, is the primary source of air pollution that threatens public health and the environment. Smog and acid-forming substances continue to occur at unacceptable levels in many parts of the country, despite continual improvements in the technologies to reduce emissions of sulfur and nitrogen oxides, carbon monoxide, volatile organic compounds (VOCs), and other toxic chemicals.

The burning of fossil fuels also results in the emission of carbon dioxide (CO_2), the most important of the so-called greenhouse gases. The buildup in the atmosphere of CO_2 and other greenhouse gases could result in long-term changes in the earth's climate system, with potentially serious impacts on agriculture, coastal communities and infrastructure, water and energy supplies, and natural ecosystems. The United States and other industrialized countries are the primary sources of greenhouse gas emissions, including CO_2. On October 15, 1992, the United States ratified the United Nations Framework Convention on Climate Change, pledging to emit no higher levels of greenhouse gases in the year 2000 than it did in 1990. This commitment will be difficult to fulfill in the face of expected economic growth and the corresponding need for larger amounts of energy.

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[1] Energy Information Administration, U.S. Department of Energy, *Annual Energy Outlook 1994*, DOE/EIA-0383 (94), p. 70.

[2] Energy Information Administration, U.S. Department of Energy, *Annual Energy Outlook 1994*, DOE/EIA-0383 (94), p. 35.

[3] U.S. Department of Energy, Energy Security, *A Report to the President of the United States*, March, 1987.

Solutions to the linked problems of national security, declining domestic oil and natural gas supplies, air pollution, and global warming will unquestionably require long-term changes in the fuels and technologies that we use to meet our energy needs. Over the long term, the United States (as well as other large consumers of fossil fuels) will have to develop and use new energy sources that emit (on net) far less CO_2 than conventional fuels and that are also sustainable. Presently, there are few such candidate energy sources: nuclear fission, hydroelectric power, solar technologies (solar cells, wind, solar thermal, and biomass), and geothermal power plants. Nuclear fission now supplies about 20% of U.S. electricity, but for a variety of reasons, the future, as we see it now, for this energy source can only be described as bleak.

The Role of Hydrogen

With the exception of biomass (which can be used to make liquid or gaseous fuels or burned directly to make electricity), the most promising long-term energy sources—wind, photovoltaic (PV) cells, solar thermal electric, geothermal, hydro, and nuclear—produce only electricity. Electricity is an ideal energy form for stationary uses in buildings and factories. At the point of use, electrical power can meet consumer needs for heating, cooling, lighting, and powering appliances with essentially no pollution or other serious environmental side effects. There are two circumstances, though, in which renewably generated electricity faces formidable problems. One is in transportation in which lightweight, high energy-density electrical storage systems are still under development. Without such devices, it will be difficult for electricity to meet most of the nation's ground and air transportation needs. The second problem arises when the electricity is generated from certain solar-electric generators, such as PV cells, or wind machines. Such electricity is, by nature, intermittent and available only when the sun shines or the wind blows. Hydrogen is a leading candidate to solve both of these problems. It provides convenient and affordable energy storage and can be inexpensively converted to electricity or used directly as a fuel.

Hydrogen is the lightest and most abundant element in the universe. It constitutes about 93% of all atoms[4], or three-quarters of the mass of the universe. The element is very reactive chemically and occurs as a free element only in trace amounts. On earth, it is found in water (H_2O), fossil fuels (basically, compounds of hydrogen and carbon), and all plants and animals.

Hydrogen gas (H_2) is not a primary fuel in the same sense as natural gas, oil, and coal. No wells produce hydrogen gas from geologically identified deposits. Rather, hydrogen is an energy carrier, like electricity. Hydrogen is a secondary form of energy, produced using other primary energy sources, such as natural gas, coal, or solar technologies. More than 8 million tons of hydrogen are consumed in the United States each year, primarily by the chemical and petroleum industries. While National Aeronautics and Space Administration's (NASA's) use of hydrogen in the Space Shuttle program is today the only significant fuel application, this transportation amount represents only about 0.1% of the hydrogen consumed. Most of this hydrogen is made from natural gas (which is mainly methane [CH_4]) in a process called steam reforming. Production of hydrogen from water—either through electrolysis or direct photochemical reactions—is the most likely long-term source.[5]

When hydrogen burns, it releases energy as heat and produces water ($2H_2 + O_2 \longrightarrow 2H_2O$). No carbon is involved, so using hydrogen produced from renewable or nuclear energy as an energy resource could eliminate carbon monoxide and ozone air pollution and reduce greenhouse warming. (Direct burning of hydrogen may still produce small amounts of nitrogen oxides, however.)

Hydrogen and electricity can be considered opposite sides of the same coin. Electricity can be readily used to produce hydrogen via electrolysis. Reversing the process, hydrogen can be consumed to produce pollution-free electricity via a fuel cell. Though fuel cells were conceived in the 19th century, powerful versions were not developed until 40 years ago. Unlike internal combustion engines, these battery-like devices involve no high-temperature combustion and thus produce none of the smog-forming nitrogen oxides.

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[4]Brady, James E. and Humiston, Gerarde E., *General Chemistry, Principles, and Structure*, 3rd Edition, p. 588.

[5]It takes the electrolysis of about 2.78 gallons of water to produce the energy equivalent of 1 gallon of gasoline.

Hydrogen Technical Advisory Panel's Recommendations to the U.S. Department of Energy

In 1993 the HTAP established three committees to develop recommendations for DOE. These committees, on Research Priorities, Surface Transportation, and Hydrogen-fueled Aircraft, developed reports on their respective topics. These were presented to, and approved by, the entire HTAP and have been combined in the present report to DOE to facilitate budgetary and program planning.

Report on Research Priorities

HTAP suggests a 20-year national program to bring the United States to the point of having hydrogen-fueled commercial aircraft and terrestrial vehicles competing successfully in the global marketplace and integrated with other system applications. The result would be clean and affordable power and transportation using domestic energy resources, with the world's hydrogen market involving significant participation from U.S. companies.

DOE's research and development priorities should be crafted within a larger, overall context for supporting hydrogen research. There are several important factors that must be kept in mind in designing the hydrogen program, such as economic, environmental (climate and air pollution), and national security issues. For this reason, DOE should establish its research priorities in consultation with other potentially affected agencies, including the Department of Defense (DOD) (taking into account both DOD's needs for energy as well as potential defense conversion and technology reinvestment initiatives); NASA (Space Shuttle and next-generation aircraft); and the Department of Transportation (DOT) (clean car initiative). Such a government-wide, cooperative effort—within and outside DOE—could be guided by DOE's EERE. EERE should strive for an integrated, adequately funded research and development program that lays out, year by year, goals and the programs necessary to achieve them.

Although HTAP fully recognizes that hydrogen research should be coordinated across the government, we will, in this section, limit ourselves to only those hydrogen programs that fall specifically under the jurisdiction of the Assistant Secretary of EERE. Our recommendations, however, apply to both the utility and transportation offices of the EERE Secretariat. We also stress that our proposed 20-year plan (see Figure 1) will need to be complemented by parallel research efforts and funding on fuel cells and other hydrogen systems that are not currently under the purview of the renewable hydrogen program. Parallel demonstration projects would be supported with significant co-funding from industry and states. In particular, both the transportation and utility demonstration projects would receive only minimal support from the Federal budget.

Figure 1 displays a graphical summary of our proposed 20-year budget plan and associated priorities. An expanded hydrogen R&D program would strengthen current research activities and include the following new areas: development of advanced hydrogen utilization and conversion technologies, engineering development to verify technical performance, and the development of interim processes for producing hydrogen. Safety research would also receive more support. Carefully conceived demonstration projects should be supported. Finally, technology transfer and venture capital developments should be incorporated as important factors in the development of the overall hydrogen program. These issues are discussed in more detail below.

- ***Basic research program:*** The core R&D program should continue its focus on the development of new concepts for hydrogen production, storage, energy conversion, and related issues. It should also include shorter-term, directed R&D efforts aimed at understanding and optimizing existing concepts. Centers of research on hydrogen would focus primarily on these basic topics.

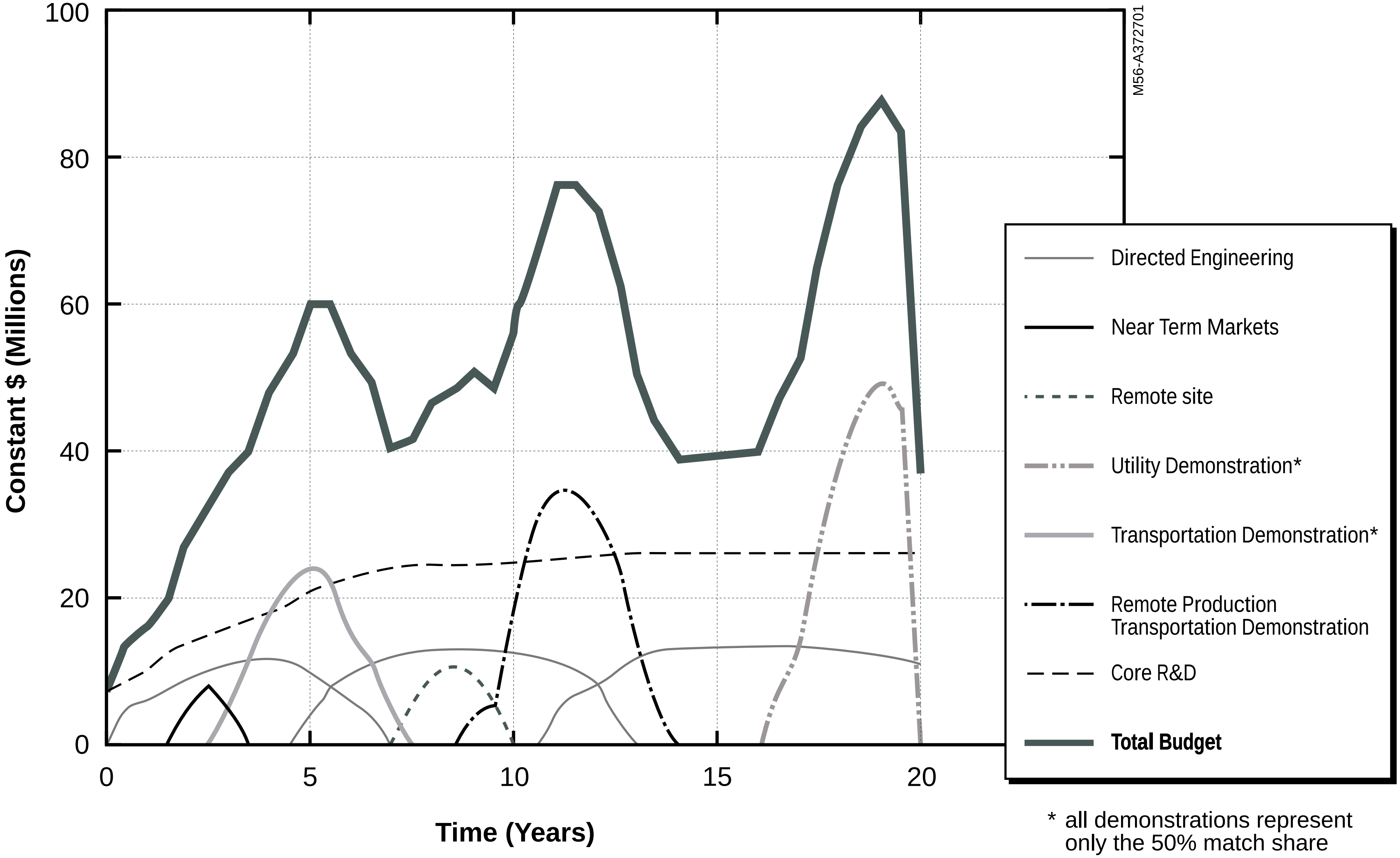

Figure 1. Proposed 20-year budget

- ***Analytical studies:*** The total system incorporating advantages provided by renewables would place hydrogen in a more competitive framework. A comprehensive treatment of externalities, life-cycle analysis, and environmental considerations would be warranted.

- ***Components testing:*** There is an important need for new technologies for the engineering, fabrication, and testing of component subsystems for hydrogen applications. These subsystems include storage and transmission technologies, hydrogen production processes (including reformers), energy conversion devices (e.g., fuel cells, turbines, and internal combustion engines), auxiliary components (e.g., sensors, valves, and filters), and importantly, safety-related equipment.

- ***Project demonstrations:*** Carefully monitored demonstrations of specific hydrogen applications can yield valuable insights and lessons into hydrogen utilization and potential problems. Such projects are also a measure of technical progress and can serve as important educational tools for the general public. The timetable for demonstrations must be carefully coordinated with underlying research efforts and priorities. Examples of potential demonstrations are provided in Appendix A.

- ***Technology transfer:*** Planning for the systematic transfer of technology to the private sector should be an integral part of the program. Cooperative programs among potential industry users, universities, and the national laboratories will be essential in components testing and project demonstrations. Industrial participation should be sought early in the R&D process to assure that subsystems can be manufactured and that commercial components will eventually be available. Industrial participation will also be essential in the transition from small-scale demonstrations to large-scale commercial applications. The creation of an industrial consortium (see below) to ensure industry participation in these initiatives would increase the likelihood of success in the demonstration and scale-up phases of these research efforts.

- ***Hydrogen industry consortium:*** DOE should support the formation of an industry spearheaded authority or consortium to stimulate industrial partnerships for cost-sharing and other major hydrogen ventures. HTAP members believe that the commercialization of hydrogen technologies is being stymied partly because of government restrictions, academic research practices, and the self-imposed limitation of the National Hydrogen Association to information-sharing. The combination of these factors has led to a vacuum of leadership for potential industrial participants. An industry-focused organization, initially co-funded by the federal government, and subject to somewhat relaxed anti-trust regulations, could play an important role in stimulating the transition to a national hydrogen economy.

  The purpose of the authority would be to catalyze and focus industrial support for hydrogen energy. The scope of the management activities would include the development of various end-use technologies, as well as a hydrogen infrastructure. The authority could solicit support from private institutions that are interested in air quality, renewable energy, and energy security. Involvement of other government agencies would also be facilitated by the existence of the authority. Recommendations for advanced technology could feed back into the DOE’s core hydrogen R&D effort. Generally, the authority would be able to deal with problems and opportunities that might arise during the introduction of hydrogen into the nation's energy system.

  The authority might also choose to establish an independent safety review panel to monitor hydrogen demonstration projects, including those sponsored by DOE. The participation of local safety authorities in project reviews would be strongly encouraged and could be a major plus in expediting demonstrations, avoiding unnecessary delays, and assuring that all location-specific safety regulations are met. The safety panel could help ensure that preventable accidents do not occur.

- ***Research centers of excellence:*** DOE, through a national competition, should create one or more centers of research excellence in hydrogen technology and systems. The National Renewable Energy Laboratory could serve as the coordinating interface with DOE. These centers could be associated with strong academic institutions to facilitate growth in the number of hydrogen researchers and encourage the basic research that is essential to innovation and the creation of new technologies and industries. A followup HTAP survey has been conducted to guide this program.

Report on Hydrogen Fuel in Surface Transportation

Renewably generated hydrogen will power pollution-free vehicles of the future. All of the necessary technologies to achieve this goal have been proven in concept, although a great deal of research and development still is needed to improve range and performance and to reduce the costs of fuel cells and renewably generated hydrogen. Still, existing technologies can be adopted to both begin using hydrogen on a limited scale as an automotive fuel and to demonstrate technological—if not economic—feasibility. Advanced internal combustion engines (ICE) can power ultra clean hydrogen transportation vehicles until efficient, emissionless fuel cells become commercially available. Current hydrogen storage technologies can serve safely and effectively in carefully chosen vehicle applications while advanced hydrogen storage methods are developed. It is possible to begin immediately building a renewable hydrogen infrastructure from the present hydrogen industry. The gas and electric infrastructures can supply primary energy to an expanding hydrogen industry, with increasing renewable energy content over time.

In addition to technological breakthroughs, national resolve is needed to pursue hydrogen as a pollution-free, renewable domestic transportation fuel. That resolve must be built upon a clear understanding of what is possible with hydrogen as a transportation fuel. Before the end of this century, the ability of hydrogen to serve in the transportation system of the next century could be technologically demonstrated. It is essential to show that hydrogen can power vehicles efficiently, safely, conveniently, and without pollution. Suitably sized fleet demonstrations would provide a foundation for the maturation of hydrogen vehicle and infrastructure technologies. Demonstrations would also engender public confidence and acceptance of hydrogen. (See Appendix B for information of demonstrations involving surface transportation).

Hydrogen as a transportation fuel has numerous attractive features, including:

- Positive impacts on air quality, taking into account pollutant emissions from fuel production, storage, transportation, and consumption

- Safety comparable to that of conventional vehicles

- Attractive costs, relative to other "zero-emission" technologies, calculated on a life-cycle basis

- Readily available hydrogen from the present domestic infrastructure, with growth potential for the future

- Comparability, relative to other zero-emission vehicle options, in terms of performance, comfort, range, and refueling time.

In the transition period leading to fuel cell powered vehicles, hydrogen could be burned in internal combustion engines, hybrid electrics, or leveraged applications with fossil fuels. DOE core R&D programs are necessary to continue expansion of the technology base. The demonstration program should not detract from the basic R&D work, but rather stimulate and focus it. Demonstration work should be funded in addition to basic research.

Technology development for transportation applications should strive to meet the following technological goals for the indicated time periods.

Fuel Cell Development:

- Meet near-term (1996) performance criteria of 0.5 kW/kg and 600 kW/m^3 at 0.6 V/cell, and mid-term (2001) performance criteria of 1.0 kW/kg and 1,000 kW/m^3 at 0.6 V/cell

- Develop production technology that makes cells available for near-term (1996) demonstrations at $2,500 per kW with 3,000 hours mean-time between overhauls, and long-term (>2010) demonstrations for production automobiles at $50/kW with 5,000 hours mean-time between overhauls.

Systems Analysis Research:

- Analyze vehicle design options (ICE, ICE hybrid, FC, FC hybrid) by an auto industry specialist who understands the interrelationship between power requirement, energy efficiency, fuel storage weight and chassis weight for vehicles with equal performance

- Perform analysis of infrastructure growth issues, starting with the present hydrogen industry and proceeding through a transition to quad-level transportation use, with progressively increased production from renewable energy sources

- Develop advanced hydrogen storage technologies that offer improvements over state-of-the-art compressed gas in terms of volume, storage, delivery, and refueling rates, cost, and weight

- Address hydrogen safety issues, including flame detection and fuel cell-compatible odorant technology

- Perform comparative safety analysis of hydrogen to its closest commercial equivalent—natural gas.

Report on Hydrogen-Fueled Aircraft

Liquid hydrogen could well become the fuel of choice to power airplanes in the 21st century. Our increasing reliance on imported oil, growing CO_2 emissions from the transportation sector, and persistent air pollution all point to the need to develop long-term, sustainable alternatives to the use of oil for conventional aircraft.

The environmental and health-related problems posed by conventional aircraft fuels are not yet common knowledge. It has been estimated that at Los Angeles International Airport alone, emissions from aircraft take-offs and landings produce the equivalent of nitrogen oxides (NO_x) and hydrocarbon emissions from 1,000,000 and 300,000 cars, respectively. As emissions from cars are further reduced to comply with state and federal regulations, the pressure to reduce emissions from aircraft, especially in nonattainment areas, will grow, thus lending support to the introduction of inherently cleaner aircraft powered by hydrogen. The payoffs in improved aircraft performance and reduced environmental impacts, combined with the introduction of hydrogen in other domestic applications, will lead to the expanded use of hydrogen throughout the economy, with consequent improvements in technologies and lower costs.

The long lead times in developing and introducing new energy sources make it essential that we immediately begin a serious effort to introduce hydrogen as an aviation fuel. The United States has historically played a key role in fostering advanced aviation technology. Hydrogen could fuel some portion of the next generation of advanced commercial aircraft and complement the goals of making airplanes more efficient, quieter, environmentally friendly, and perhaps safer.

Compared to conventional aviation fuels, liquid hydrogen is radically different. It offers several distinct advantages over jet fuel, including the reduction of specific fuel consumption and reduced engine maintenance and noise. A negative factor is the requirement of more complex ground systems for refueling, servicing, and maintaining aircraft.

Based on the extensive analysis and experimentation that have been carried out worldwide, it has become clear that there are no insurmountable technical barriers to the introduction of hydrogen-fueled aircraft. This is not to say, though, that there are not many remaining technical challenges to be overcome. Important modifications will be required to allow present-day aircraft to operate on hydrogen. For example, an aircraft designed to operate solely on hydrogen would have a wider body or longer fuselage, or both, to accommodate the greater volume of fuel required. At the same time, it would also have a smaller wing area due to the decreased lift requirements of hydrogen (compared to jet fuel, pound for pound, hydrogen has three times the energy). Hydrogen aircraft would store liquid or possibly slush hydrogen that would be vaporized and combusted in the aircraft's engines.

On the ground, extensive modifications of the existing infrastructure would be required for aircraft refueling. The hydrogen could be produced either on or off site but it would be liquefied (at -252.8˚ C, -423˚ F) and stored on site. The liquefied fuel could be distributed either by pipelines to hydrants at refueling islands where the planes would be refueled or by cryogenic tanker trucks operating between the storage tanks and the aircraft.

North America has a well established commercial hydrogen delivery system. New facilities can be constructed safely, typically within an 18- to 30-month period. Routinely, thousands of safe deliveries to hundreds of locations are made by conventional transportation methods. To date, the disadvantages and uncertainties relating to the use of hydrogen tend to be more economic than technical and relate to the costs of producing, liquefying, storing, and delivering hydrogen to the aircraft.

To facilitate the introduction of hydrogen into the commercial aircraft sector, DOE should support formation of a national hydrogen-fueled aircraft consortium, perhaps under the umbrella of the authority already described. The purpose of the aircraft consortium would be to support the development and introduction of hydrogen-fueled aircraft. It would do so by bringing together representatives of industry and government to create and implement a long-term research, development, and demonstration program with specific goals, strategies, and schedules. The program plan developed by the aircraft consortium would be sent to Congress and federal and state agencies for review and project funding. This consortium could also develop legislative initiatives at the federal and state levels to accelerate the introduction of hydrogen-fueled aircraft. The aircraft consortium would involve broad industry and regulatory participation and be supported by joint government and industry funding.

Aircraft consortium activities could be coordinated by in integration management contractor (IMC) operating under a five-year government contract (DOT, DOE, or NASA) with full responsibility, authority, accountability, and control. The IMC would coordinate with other related hydrogen activities, including international efforts. The IMC would maintain close liaison with other government/industry/academic hydrogen activities to insure compatibility and consistency with the progress and goals of other national hydrogen programs and projects. Task efforts, individually approved by the funding sources, could be subcontracted as appropriate by the IMC.[6]

The scope of the aircraft consortium would include development of tasks, budgets, schedules, strategies, and work justifications. It would also include the identification and tracking of milestones, reporting, workshop coordination, technical studies, field testing, comprehensive safety assessments supported with field data, oversight of niche market/small-scale start-ups, and eventually, recommendation of commercial market penetration to achieve timely and expected payoffs. The various demonstrations and projects are described in Appendix C.

[6]Still another alternative would be the formation of a Cooperative Research and Development Agreement where public and private collaborators share costs and the results of related technologies using the IMC as integrator.

Conclusion

Hydrogen will be a critical and indispensable element of a decarbonized, sustainable energy system. This makes major federal RD&D investments in hydrogen production, transmission, storage, and use a high priority today in view of the major scientific, technological, and economic obstacles to commercial deployment of hydrogen energy systems. HTAP recommends a 20-year national program to revolutionize global transportation systems, which would allow developing and industrialized countries to use domestic energy sources. Air pollution as a global environmental threat would thus be virtually eliminated and the United States would be established as the premier commercial supplier of hydrogen.

Appendix A

General Demonstrations of Hydrogen Technology

Consideration should be given to the following projects for near-term (5-8 years), intermediate-term (10-13 years), and long-term (17-25 years) demonstrations.

Near-Term Demonstrations

Blended-Fuel Demonstration

There is considerable interest in reducing emissions from electric power generation. One way to achieve this is to blend hydrogen with natural gas. This blended fuel could be used to generate electricity in turbines or burners or be distributed by a participating utility to selected customers, such as industrial users who are large energy consumers. This demonstration could easily be accomplished using existing technology and shows an immediate, although small, emission reduction. With market and consumer involvement, valuable experience would be obtained in hydrogen storage and distribution. This demonstration could be sited near an existing source of hydrogen, such as a facility producing by-product hydrogen.

Areas of research for this demonstration include:

- Emissions and performance characteristics of turbines and boilers burning a blended fuel
- Stationary storage systems
- Hydrogen production systems
- Hydrogen separation processes (e.g., from waste streams) and control and handling technology (e.g., valves and sensors).

Intermediate-Term Demonstrations

Industrial Cogeneration

Hydrogen is widely used in industrial processes and is also cogenerated in industrial chemical facilities. In general, hydrogen produced as a by-product is either burned off or sold to a hydrogen distributor. Development of more efficient energy conversion technologies, such as fuel cells, ICE generators, or turbine generators, would allow the development of systems to produce electrical power very efficiently for use in industrial facilities.

Enabling technologies include:

- Large, stationary fuel cells
- Large, optimized hydrogen-fueled ICEs
- Hydrogen-fueled turbines
- Hydrogen separation processes
- Stationary storage systems.

Renewable Hydrogen Demonstration

Various PV battery systems have been installed at remote sites to power medical equipment, irrigation pumps, lights, refrigerators, and even small villages. Parallel demonstrations should be undertaken for hydrogen produced from renewable energy technologies. The hydrogen could be used in gas ranges for cooking, in fuel cells for electricity, and in transportation applications.

Technologies that would be developed in these applications include:

- Electrolyzers optimized for intermittent power
- Systems designed for operation in harsh environments
- Many of the technologies referenced earlier.

Long-Term Demonstrations

Production and Transportation of Hydrogen from Remote Hydroelectric Sites

Hydroelectric power from existing dams is one of the cheapest sources of electricity today and will likely remain so for some time. Electricity produced at off-peak hours is an attractive means of producing hydrogen from a renewable resource. This hydrogen, generated using advanced electrolysis technology, could be transported by pipeline or ocean transport to well-defined markets where experimental applications would be undertaken. The Euro-Quebec project is an ambitious attempt at such a demonstration. The proposed project would entail developing the following underlying technologies:

- Advanced electrolysis
- Long-distance hydrogen pipelines
- Stationary hydrogen storage
- Hydrogen utilization technologies.

Lockheed Hydrogen Plantship

Lockheed Aerospace has proposed a project to deliver municipal waste to a floating platform where hydrogen would be produced from it, with permanent disposal of the carbon dioxide in the deep ocean. (A report on this proposal was presented at a 1992 HTAP meeting.) There is a reported ready market for the hydrogen at competitive prices. Under optimistic assumptions, this concept could be demonstrated within the decade, making it a near-term application. Directed engineering projects to support this concept have previously been identified. However, there could be other open ocean and floating technology needs.

Appendix B

Demonstrations Involving Surface Transportation

Hydrogen bus demonstration

The first step toward utilizing hydrogen in surface transportation should be a 10-bus demonstration on a highly visible route in a region where there is a major market for low-emission vehicles. Although buses make a relatively modest contribution to overall motor vehicle air pollution, they offer more visibility and are easier to adapt to new kinds of power systems and hydrogen storage options. On a per vehicle basis, emission-free buses can make a large contribution to improving air quality. The bus demonstration should serve as a starting point for developing technologies that will ultimately be used in the much larger private motor vehicle market.

The bus demonstration is meant to be just the first of many hydrogen energy projects that could be managed by the authority. As indicated, the authority's charter would include the full range of end uses, including stationary power, aircraft, and infrastructure. There may be many opportunities for synergism, such as ground vehicles utilizing hydrogen “boil-off” near liquid-hydrogen aircraft demonstrations. Another example involves coordinating grid electricity with fuel cell reformer systems to optimize electric and hydrogen supplies as a system.

The scale of demonstrations should be large enough to avoid the appearance of an experiment. A 10-bus fleet on strategically selected routes would provide the visibility and scale that the project requires. The fleet should include fuel cell buses, internal combustion power systems, and hybrids designed for eventual replacement by fuel cells.

DOE's contribution for this initial demonstration, with continued operation through the year 2000, is estimated at $21 million. The first 4 years (1994-1997) would require about $17 million for the buses and a fueling facility. The total budget for this activity would include DOE's contribution plus the greatest level of cost-sharing the authority could negotiate with interested parties. For example, a participating transit authority should, at a minimum, be willing to contribute the prorated cost of 10 conventional buses, including fuel and maintenance costs, over the period of the demonstration. Bus and fuel station providers should also make contributions through cost sharing. Defense Reinvestment, Clean Car programs, and so on may be approached to acquire additional vehicles, program management and analysis, and infrastructure to leverage the $21 million, 6-year DOE commitment. Demonstration site selection could be made by the authority based on participation of state and local governments, private foundations, defense contractors, and proximity of hydrogen production facilities.

An approximate schedule for establishing the authority and conducting the initial demonstration project is shown in Figure B-1. The authority would be established over a period of 6 months. A core of key individuals, assembled in the first few weeks, could begin drafting a program plan and negotiating with potential authority members and sources of support. A review of international efforts will need to be conducted to determine the state of the available technology and avenues for optimal progress. At the end of the first year, a Phase I request for proposal (RFP) would be due. Four months thereafter, contracts would be issued for the Phase I design work. The 1-year design effort would define the vehicle and infrastructure options available for the demonstration. The Phase II RFP would be due at the beginning of 1996. Subsequently, the technologies selected for inclusion in the demonstration would be identified and contracts for fabrication and testing would be awarded. By late 1997, the status of the various selected technologies would be apparent and contracts for Phase III operation and analysis would be granted.

The actual demonstration would take place in 1998 and 1999. The two-year operating experience and data would provide valuable information about what can be done with hydrogen in motor vehicles. A basis for assessing public acceptance and infrastructure issues would be in place. Policy-makers would then have a firmer basis for planning ways to utilize hydrogen vehicle-related technology in the 21st century.

Hydrogen light vehicle demonstration

In addition to this bus demonstration program, a design for a light-duty vehicle utilizing hydrogen as a fuel should be developed and a limited number of vehicles produced. These vehicles would also be tested in fleet applications. At least some of the hydrogen used in these demonstrations should be derived from renewable energy technologies. Technologies needing further research and development for this demonstration include fuel cells (sized for light-duty vehicles), advanced ICE, on board hydrogen storage/delivery systems, refueling station technologies, electrolyzers suitable for renewable energy sources, systems integration, and safety analyses for all the above.

To be successful, these demonstrations will require close coordination and cooperation among different technology offices within DOE and among DOE and other government (federal, state, and local) agencies.

The overall recommendation of the HTAP is that an early start is necessary to fulfill the hydrogen energy demonstration requirements of the Matsunaga Act by the end of this century. Demonstrations of buses and light-duty vehicles are not greatly different from a renewable hydrogen production demonstration or any other significant scale engineering demonstration. In every case, potentially useful technologies must be identified and qualified for the project. This is followed by design, fabrication and test activities, operation, and analysis. Between each step and the next are time-consuming procurement processes and negotiations.

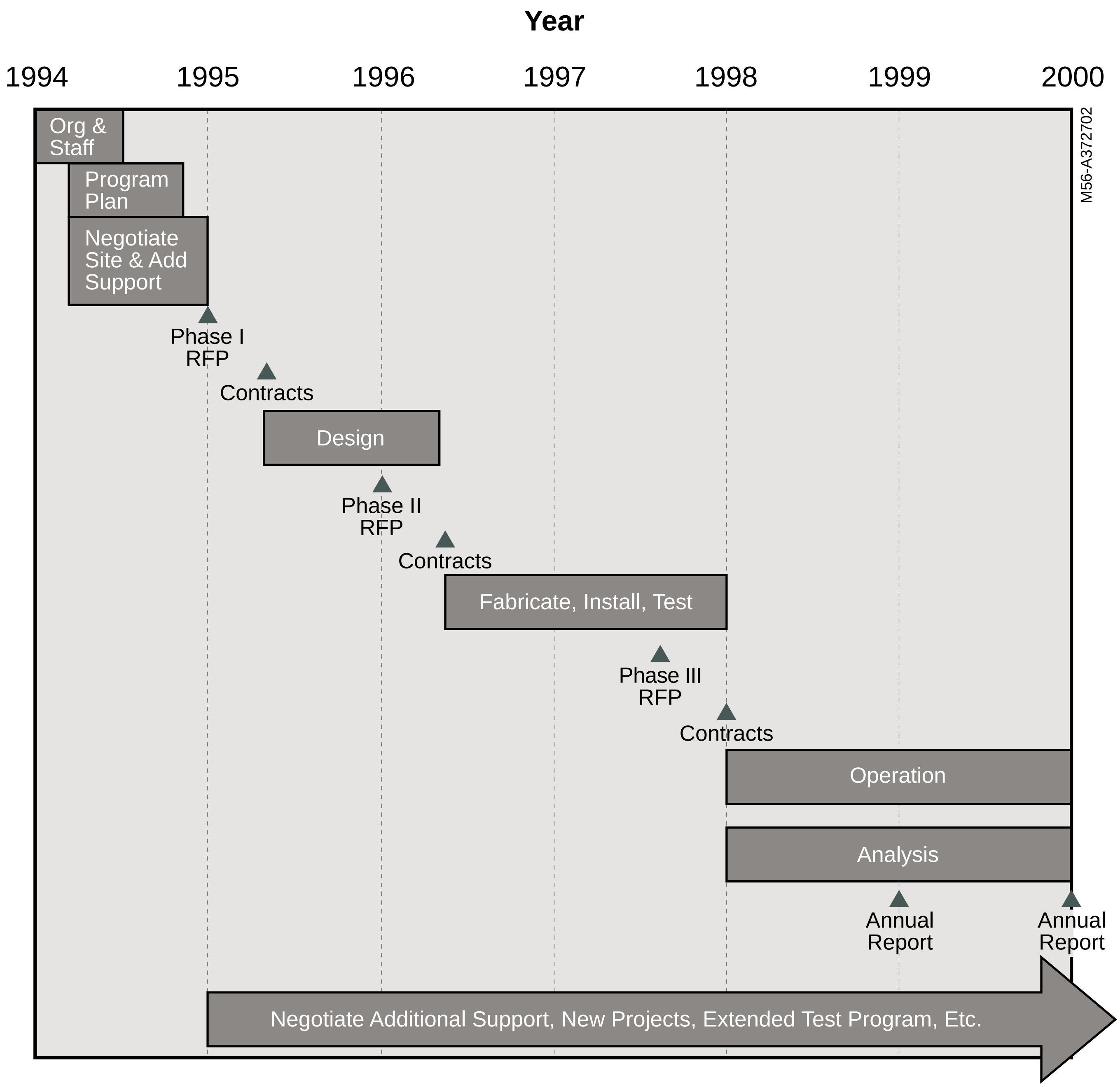

Figure B-1

Schedule for establishing the vehicle authority and conducting the first hydrogen vehicle demonstration. Continued activity is projected into the 21st century in pursuit of commercialization of hydrogen vehicle technologies.

Appendix C

Hydrogen-Fueled Aircraft Demonstrations

Small-Scale Airline Operation

This project would explore the feasibility of hydrogen-powered aircraft in normal commercial operations. For example, the plane for this demonstration might be an all-cargo DC-9F or equivalent operating between two airports, with established liquid hydrogen facilities, on routine cargo missions (e.g., Federal Express).

This project would require early identification of:

- Regulatory and certification requirements
- Safety requirements
- Basic core technical requirements with minimal servicing and support logistics
- Joint industry/government sponsorship with government funding covering the more costly risk elements
- Potential problems and related issues for larger applications.

Flying Laboratory and Test Bed

Should reviews justify the need and cost-effectiveness, another near-term goal would be the development of a flying hydrogen laboratory and test bed. A modified surplus military aircraft could be used to test and evaluate:

- A variety of on board fuel storage and delivery systems
- Safety systems monitoring
- Environmental emissions analysis
- Duty cycle analysis
- Specific cryogenic fuel attributes of liquid hydrogen
- Acquisition of other empirical data needed for large-scale aircraft systems.

Research Studies/Analysis

A number of studies and analyses need to be performed as part of the overall development of hydrogen-fueled aircraft. Some of these may have to be completed before any commitment is made to aircraft development or hardware research. Examples include the following:

- Update atmospheric evaluations previously performed and clearly identify experimental test requirements for further research
- Develop overall pathway energy and economic analysis to serve as a baseline for further refinement and reference
- Initiate comprehensive infrastructure requirement analysis from near-term goals to long-term critical elements
- Develop an end-to-end safety survey program identifying elements or issues requiring further research, test, and evaluation
- Identify sequential hardware/component development requirements including cost schedules and priorities
- Initiate an FAA certification program (regulatory and test provisions).

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