III.3 MAJOR AUTOMOTIVE FUEL CELL PROGRAMS

Perhaps the most encouraging observation about the ongoing efforts to develop automotive fuel cell technology is that promising programs are being undertaken — many of them collaboratively — by four different types of organizations: industrial developers of fuel cell power plants with exclusive or major focus on PEM technology; a substantial number of generally smaller technical groups (in smaller and large companies) developing PEM fuel cell component, subsystem and system technologies; many of the leading automobile manufacturers; and key government agencies responsible for PEM fuel cell R&D, including among others DOE in the United States, the European Commission Directorates General for Science, Research and Development (No. XII) and Energy (No. XVII), and MITI/NEDO in Japan.

Many of the smaller industrial groups mentioned above see automotive PEM fuel cells as a potentially major business opportunity and thus are investing some of their own development capabilities and resources, both in-house and jointly with fuel cell power plant developers and automobile manufacturers. Their programs and achievements were reviewed in Sections III.A and B, above. Section III.3 summarizes the government programs, and it reports on the programs of the major fuel cell developers and automobile manufacturers in more detail because of the essential role of these organizations in PEM automotive fuel cell power plant development and vehicle integration.

A. GOVERNMENT PROGRAMS

United States

As mentioned previously, the U.S. Department of Energy has been providing substantial support for the development of fuel cells for transportation applications through DOE's Office of Transportation Technologies. Much of this 10 year program has been focused on R&D to establish enabling technologies for the critical components of PEM automotive fuel cells. This R&D is being done under contracts with fuel cell developers and through substantial programs at DOE laboratories, mainly the Los Alamos National Laboratory (LANL) and the Argonne National Laboratory (ANL).

From a modest program of basic research to overcome electrode catalyst performance and life limitations and improve fuel processing reactions, DOE's program expanded to include the development of high-performance PEM stack technology. Complementing the rapid evolution of PEM component and stack technologies in private-sector programs, DOE is continuing its selective support for the development of high-performance, potentially low-cost fuel cell components. The program also has been supporting the development of gasoline fuel processing concepts and systems (including the ADL fuel processor), as well as work on advanced turbomachinery for air management of pressurized fuel cell systems. In view of the critical importance but largely undeveloped state of fuel cell power plant systems integration, DOE in recent years began to support multi-phase PEM fuel cell system development and integration efforts. Appendix C presents summaries of current DOE-funded programs in automotive fuel cell technology; Appendix D lists the supporting R&D projects carried out at seven DOE National Laboratories.

In 1997, DOE substantially expanded the systems component of its transportation fuel cell program by awarding “PRDA” contracts for development and delivery of integrated fuel cell power plants to several teams of organizations that, between their members, should have the capabilities required to successfully address the key technology and systems issues identified earlier in this report (see, for example, sections II.2.E and III.1.D). A summary of these new efforts is given in Appendix E. Overall, DOE’s annual budget for automotive fuel cell R&D now is approximately $30 million not counting the extensive private sector cofunding.

A special role in the U.S. efforts to develop fuel cell engines for automobiles is played by the previously mentioned “Partnership for a New Generation of Vehicles” (PNGV). PNGV, formed in 1993 under a Presidential Initiative as a partnership between the domestic automobile industry and the Federal Government, is to advance U.S. automotive technology in general, improve automobile manufacturing competitiveness, and foster the development of a family car with a 80 mpg fuel efficiency. PNGV is serving as a focus and coordination agency for many federally and privately funded automotive technology development and engineering programs[1]. Federal funding (budgeted primarily through DOE) is concentrated on advanced technologies in pursuit of the 80 mpg fuel efficiency goal. The technical strategies being followed include vehicle weight reduction, improvement of aerodynamics, and development of advanced, high-efficiency power sources.

Early in PNGV’s program, PEM fuel cells were being recognized as having the best long-term potential for high efficiency and low emissions, and they were selected as one of PNGV’s automotive power plant options. This selection substantially increased the interest in automotive fuel cells, and it increased support for budgeting and implementing collaborative programs to develop PEM fuel cell power plant technology. While fuel cells were not selected for near-term development of prototype

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[1] Besides DOE, the Departments of Commerce, Defense and Transportation, the Environmental Protection Agency, NASA and the National Science Foundation participate in PNGV.

automotive engines under its program, PNGV recognizes the fundamental potential and the remarkable development progress of PEM automotive fuel cells.

In its 4th report, the standing committee charged with review of the research program of PNGV recommend that "U.S. government and industry investments in research and development [of fuel cells] should, therefore, be continued at current levels or even be increased for an extended period." Equally important, virtually all PNGV-affiliated organizations active in developing the various aspects of automotive fuel cell technology have continued (in may cases, expanded) their own programs.

Europe

The European Commission (EC) began to support fuel cell research and technology development (RTD) for transportation applications in 1993 through the JOULE Progamme which is overseen by the EC Directorates for Science, Research and Technology and for Energy. From an early focus on compact reformers and reformer-fuel cell stack-vehicle integration, the EC transportation fuel cell program has grown to include development of advanced stack technology. Current plans include development of a metallic membrane for separating hydrogen from processed fuel, advanced stack development for PEM and for direct methanol fuel cells, and a feasibility study of hydrogen vehicles and their supporting infrastructure.

At about 23 million ECU of cumulative funding through mid-1997, the EC program in PEM automotive fuel cells is still modest. However, the program has strong private-sector participation and cofunding, a clear rationale, and reasonable prospects for being expanded further. Appendix F summarizes the strategy, funding and projects of EC's automotive fuel cell program.

Japan

MITI has been funding a broad-based fuel cell R&D program since many years. The overall organization of this program — which is planned and coordinated by MITI's New Energy and Industrial Technology Development Organization (NEDO) — is shown in Appendix G which also includes the program's PEM fuel cell R&D activities and the targeted power plant characteristics. Automotive applications and technology are not the main subject of the MITI/NEDO fuel cell program: the PEM technology R&D budget is less than 10% of total fuel cell funding (about 6 billion ¥, or approximately $46 million, per year), and only a part of the PEM fuel cell activities address automotive power source applications. The Panel obtained technical information on two key MITI/NEDO projects during its visits with Mitsubishi Electric (compact reformer) and Asahi Chemical (advanced PE membrane).

B. FUEL CELL TECHNOLOGY DEVELOPERS

In the Panel's view, resolution of the performance, operability and cost issues surrounding PEM automotive fuel cell development will depend to a large extent on the capabilities and resources that the major fuel cell power plant technology developers and automobile manufacturers will bring to bear during the next 3-5 years. Accordingly, the Panel augmented its technical questions of these organizations with inquiries about corporate strategies, plans and resource commitments for automotive fuel cell development and prospective manufacturing. Broadly speaking, the Panel encountered two different responses: articulation of strong corporate commitments and plans to achieve technical and market leadership in PEM automotive fuel cells on the one hand, and more cautious expressions of interest on the other. This interest is driven by a number of factors that include corporate involvement in government-funded development programs, awareness of the commitments made by competitors, and fuel cell technology and business advocacy positions by a minority of staff and/or management. Significantly, several organizations in the latter group were moving toward more active, committed strategies during the Panel's study.

Ballard Power Systems (BPS)

BPS stands out in the first group of organizations. The senior technical and business management of BPS provided the most definitive information on their business plans, the scope of these plans is the most comprehensive, and the capabilities and resources being committed by BPS and its allies are the most extensive among PEM fuel cell developers. Specifically, the BPS-Daimler Benz-Ford alliance is committing more than Can.$1 billion (about U.S. $750 million) to developing all aspects of PEM fuel cell technology to the point where mass-manufacturability is established and the key manufacturing processes are defined.

Ballard management believes that the alliance now has the financial resources, facilities and key technical staff needed to reach this point over the next 2 years. Ballard anticipated these needs and has been working since mid-1996 to meet them; they now have about 200 technical staff working on automotive stack technology out of a 450 staff total. Manufacturing expertise and facilities of Daimler Benz (and, presumably, from Ford) are being integrated into the overall effort. Within that effort, BPS is responsible for PEM automotive stack technology and manufacturing. Presently, make/buy decisions on various fuel cell components are being made, and the stack design will be frozen by the end of 1998. Rough estimates have been established for the layout and costs of a pilot manufacturing plant (capacity several thousands of fuel cell stacks per year) and the first production plant (hundreds of thousands of stacks per year).

Ballard's plan calls for establishment of pilot-scale stack production by 2000, using processes representative of a commercial operation. Between now and 2002, BPS will produce a limited number of stacks for U.S., European and Japanese customers, to stimulate evaluation of the technology and development of a market. BPS expects to produce the stacks necessary for 40,000 fuel cell engines in 2004, 70,000 in 2005 and 100,000 in 2006. BPS has major although still preliminary commitments from Daimler Benz and Ford who have stated their intent to produce commercial quantities of fuel cell electric vehicles beginning in 2004, in the assumption that go-ahead decisions are made in about 2 years from now.

The Panel considers these projections credible in view of Ballard's rapid progress toward its technical objectives (see e.g., Figures III-1 and -2); Ballard's comprehensive, systematic development program and the availability of the resources needed to sustain and expand it; the extensive, state-of-the-art development and testing facilities; Ballard's strong focus on cost, manufacturability and manufacturing; the clear business strategy of BPS management; and the extent and quality of the collaborations BPS has established with Daimler Benz and Ford.

International Fuel Cells (IFC)

IFC is among the world's leaders in fuel cells on the basis of the organization's many years of experience and its extensive fuel cell development and fabrication capabilities and facilities. Previous report sections (III.1.A-D) presented information on IFC's growing involvement in PEM automotive fuel cell technology development. Until recently, however, this involvement appeared limited to the roles of a DOE contractor for PEM stack development and a member of DOE-funded teams to develop integrated PEM automotive power plants. In January 1998, United Technologies Corporation (UTC), the parent of IFC, announced the commitment of substantial corporate resources to accelerate the development of gasoline-fueled PEM fuel cell power plants/engines for automobiles. While details of the UTC commitment were not available, the reorganization of IFC for this new business orientation, and the associated increase of technical staff (reportedly, from 90 to 150) assigned to it, are considered significant by the Panel.

IFC management is now discussing partnerships in the fuel cell engine business with automobile manufacturers throughout the world. The next 6-12 months should clarify how the UTC/IFC initiative is structured and whether it is likely result in a viable new competitor in the emerging fuel cell industry.

Other PEM Fuel Cell Developers

As summarized in Table III-1, other competent organizations are engaged in PEM fuel cell stack and system development; their technical achievements were discussed in Section III.1.A. Several of these organizations — in particular AlliedSignal and Siemens — have the corporate resources and capabilities required for commercialization of automotive fuel cell technology. Both companies also have major energy conversion technology and system capabilities that reinforce their capabilities for development of fuel cell electric engines. So far, however, they have not made corporate commitments to automotive fuel cells as a potentially major new business area. Other companies such as Plug Power and DeNora are active as partners in government-funded automotive fuel cell stack and system development programs. Plug Power and DeNora do not have the large resources required for establishment of production facilities on the level of an automotive mass market and are, therefore, aiming for other PEM fuel cell markets with less demanding technical and cost targets.

C. AUTOMOBILE MANUFACTURERS

Many examples exist of promising advanced technologies that did not make it in the marketplace because the organizations capable of transforming the technologies into technically viable and marketable products were not involved in their development. No competitive fuel cell electric vehicle (FCEV) is likely to materialize without the direct involvement and leadership of major automobile producers, nor is the public likely to turn to a new automotive product that does not have their backing. Just as important, and as discussed throughout this report, the prospects for cost-competitiveness of fuel cell electric engines — and thus of FCEVs — are tied closely to mass manufacturing on a scale that is familiar to, and feasible for, major automobile manufacturers only.

In this context, the major commitment of Daimler-Benz to fuel cell electric engine and vehicle development through the joint venture with Ballard Power Systems was a milestone that signaled automobile manufacturer involvement on the necessary scale. Especially during the last 12 months, it has become clear that many of the world’s largest automobile manufacturers also are, or are becoming, engaged in major programs to develop and, if possible, commercialize fuel cell electric engines and vehicles in the next decade. The Panel made a significant effort to understand not only the technical progress but the corporate strategies and commitments of these programs, as summarized in the next several sections.

Domestic Automobile Manufacturers

All three major U.S. car makers are engaged in fuel cell electric engine (and vehicle) development although to different degrees and with different strategies. At first, their involvement probably was fostered by the companies' key role in PNGV which had identified fuel cells as one of the promising high-efficiency engine options for the future. Also, fuel cells held out promise to become a fundamentally new and superior response to the continuing pressures from Federal and State agencies (including prominently the California Air Resources Board) for ever-lower vehicle emissions.

More recently, the awareness of vigorous fuel cell engine development programs by foreign manufacturers (especially those of Daimler-Benz and Toyota) may well have accelerated decisions to increase program scope, commit more resources, and enter into strategic alliances to develop all aspects of the technology. This awareness probably was heightened by the memory of the near-disastrous competition with foreign car manufacturers in which the industry found itself in the 1970s and 1980s. Fortuitously, U.S. automobile manufacturers at present are in the financial position to invest the resources required to resolve the many difficult issues reviewed in this report and, if justified by the progress and prospects, make the investments in production facilities. The current corporate activities, plans and commitments of Chrysler, Ford and General Motors are discussed below.

1. Chrysler

Chrysler has a relatively modest program in fuel cell electric engine and vehicle development, and much of the effort is being carried out in the context of the DOE-funded PNGV program. Chrysler's corporate funding is focusing on the integration of PEM fuel cell subsystems procured from outside the corporation into fuel cell power plants and fuel cell electric vehicles. The key effort here is Chrysler's proof-of-concept battery-fuel cell hybrid vehicle which is being designed to operate on gasoline and targeted for completion in early 1999. The necessary fuel processor will be supplied by Delphi; Chrysler is the systems integrator and will supply the hybrid drive train and the control system. The hybrid battery will be large enough to handle power demand during start-up and for acceleration/hill climbing.

Chrysler staff mentioned a number of technical issues and concerns requiring resolution, including sulfur level in gasoline (need for removal in the refinery or, alternatively, demonstration that the fuel cell can operate properly on sulfur-containing gasoline for at least 100,000 miles); difficulty of removing CO down to the <10 ppm level; unavailability of compact air handling turbomachinery with the needed high efficiency, adequate transient response, and low cost; lack of suitable batteries for hybrid vehicle applications; and the cost increment likely to be added by the fuel cell power plant and the other components such as the battery since the complete hybrid power system must be cost-competitive with IC engines.)

The FCEV development and commercialization schedule below was mentioned as a possibility, but to date no specific strategy and/or resource commitments to such a schedule appear to have been made by Chrysler.

PNGV concept vehicle	2002
Prototype meeting PNGV goals	2006
Order of fuel cell components in quantity	2006/2008
Limited production	2008/2010
Full production	2016

Factors and issues mentioned by Chrysler staff as bearing importantly on the prospects of automotive fuel cells include the following:

(1) No major changes in petroleum availability and price are expected before 2010 which is likely to limit the economic advantages of high-efficiency fuel cell power plants.

(2) The power generation market may emerge as an earlier, technoeconomically easier application of PEM fuel cells, but investments in PEM fuel cell technology are driven mainly by the automobile application, at least at present.

(3) A “successful” battery (for all-battery EVs) might negatively impact the prospects for fuel cell electric engines.

(4) Fuel cell electric vehicles will need to offer advantages — such as lower fuel consumption — at competitive prices if consumers are to buy them.

At present, Chrysler does not seem committed to be a major player in automotive fuel cell engine/vehicle development and commercialization. Consistent with this perception of the Panel, Chrysler staff stated that the company would initially buy all key fuel cell components/subsystems. If and when a mass market of ≥100,000 vehicles per year develops (e.g., after 2010), Chrysler will acquire fuel cell engine technology appropriate for its automobile products. (The recent merger with Daimler-Benz could provide Chrysler with a logical source of fuel cell technology and, also, increase DB’s focus on gasoline.)

2. Ford

Ford has a long history of developing electric, hybrid and alternative fuel vehicles and evaluating advanced power source technologies for vehicle propulsion. The discovery and development of sodium ion-conducting solid-electrolyte batteries, the ETX series of experimental vehicles and, currently, the Electric Ranger pickup truck are examples of advanced developments that have given Ford experience in electric vehicle power sources and drive trains much of which is relevant to fuel cell electric vehicle propulsion.

As explained to the Panel, Ford's experience in marketing battery-electric and alternative fuel vehicles has been less than positive up to now, for two reasons that can be expected to become important issues also for fuel cell electric vehicles, (1) the high price, especially of battery-electric vehicles such as the Electric Ranger but also of CNG vehicles, and (2) infrastructure-related issues for EVs and CNG vehicles but also for methanol vehicles with IC engines. The high cost of installing refueling/recharging facilities, especially those permitting rapid fueling (CNG) or battery charging, is a major disincentive for service stations, and slow-filling/charging home installations are a significant financial burden for individual owners.

Specific concerns articulated by Ford staff during the Panel's visit (which occurred before Ford joined the Daimler Benz-Ballard alliance) were whether consumers will buy FCEVs ("why buy") if these do not offer substantial advantage(s) over ICE vehicles. Continued low gasoline prices might restrict the appeal of high-efficiency FCEVs to operators of high-mileage vehicle fleets. When discussing the emission benefits of FCEVs, the staff noted that Ford already has vehicles that meet SULEV standards with CNG-fueled IC engines, LEV (possibly even ULEV) standards with dual-fuel or gasoline IC engines. Despite these concerns, Ford has been engaged in fuel cell subsystem and vehicle development for several years, primarily through its participation in DOE-funded, PNGV-coordinated efforts to evaluate PEM fuel cell stack technology and, currently, assemble breadboard-level fuel cell power plants.

Beyond these efforts, Ford has proposed to use its P-2000 lightweight (Taurus size) experimental ICE vehicle as a test bed to evaluate experimental fuel cell systems. Ford will likely adopt a pure fuel cell vehicle power system . However, hybrid configurations — ranging from addition of a small battery for regenerative braking and supplementary power, to a small fuel cell used as "range extender" for a battery EV — have not yet been ruled out. Also uncertain at present is the ultimate cost of FCEVs in mass production since the required in-depth cost studies have not yet been done for fuel cell-based propulsion systems. Initially, FCEV costs will undoubtedly be high but mass production might eventually result in costs comparable to ICE vehicles.

No information was provided about the extent of Ford's internal fuel cell effort but it is generally known that it has been limited to the evaluation of candidate technologies (such as stacks, hybrid batteries, etc.) through testing of technology acquired from outside the company, and extensive studies of system alternatives (including fuel infrastructure). Despite the uncertainties and concerns about the technology and cost issues, potential benefits and customer acceptance of FCEVs, Ford appears determined to be a major player if and when PEM fuel cell engines begin to emerge as a viable alternative to IC engines. This determination is attested to by Ford's investment[2] of Can. $ 412.5 million in the Daimler Benz-Ballard joint venture and its additional investment of about U.S.$ 150 million in ECo, a new joint venture (with Daimler-Benz and Ballard Power Systems) for development and manufacturing of electric drive trains.

Regarding possible schedules for development and commercialization of FCEVs, Ford staff noted that the time between establishment of key components and the first commercial production of a car is 2-3 years for established (ICE) technology, perhaps 5-6 years for new technologies such as fuel cells. Since major components/subsystems of FCEVs (for example, on-board hydrogen storage for hydrogen-air fuel cells; fuel processors for methanol- or gasoline-powered fuel cells) are not yet established, commercial FCEVs are probably about 10 years away.

It remained unclear whether this tentative schedule already is part of Ford's strategy and plan for introduction of fuel cell electric vehicles. Assuming that the commercialization timeline discussed above (Section III.3.B) for Ballard Power Systems is maintained, the co-ownership in DBB Fuel Cell Engines would seem to provide Ford with fuel cell-based automobile power plants in time for commercialization of a fuel cell electric vehicle in — or possibly before — 10 years.

[2] With this investment, Ford acquired a 15% ownership of Ballard Power System (BPS) and a 23.3% share of Daimler-Benz Ballard Fuel Cell Engines (DBB).

3. General Motors

GM probably has more experience with electric vehicles than any other major automobile manufacturer and is the first one to introduce a battery-powered personal car (the EV1) to the consumer market. A second EV product (a lead acid battery-powered S10 pickup truck) is just being launched. As pointed out to the Panel during its visit with GM, to date only about 20% of the limited market projected for the EV1 has materialized, ostensibly because of the vehicle's high price, its restricted driving range, and the recharging infrastructure which is still quite limited even in the areas selected for market launch. The imminent switch from lead acid to nickel metal hydride batteries will increase the range and utility of the EV1 but also its cost; it may therefore not expand the market. GM is aggressively pursuing expansion of recharging infrastructure and increased incentives for electric vehicles through efforts with States, utilities and electric vehicle coalitions. Also, GM is proceeding with efforts to reduce the cost of next generation EV components and is committed to increase production volumes of EVs in step with anticipated cost reductions. These efforts are intended to help resolve the Catch 22 problem in which high price limits a product's market, the limited production volume precludes the major cost and price reductions possible only with mass manufacturing, and the high price/limited market situation persists as a result.

Several aspects of GM's battery EV initiative are relevant for fuel cell electric vehicles, including successful development of advanced electric drivetrain technology, establishment of local/regional marketing initiatives and infrastructures, and initial experience with customer acceptance. Significantly, from proving the concept 7 years were required to move EV1 through the stages of technical feasibility and preliminary assessment of the market to launch the product in 1997. From the EV1 experience and its growing involvement in automotive fuel cell component and system development, GM has concluded that:

(1) Achievement of competitive cost for a fuel cell engine (≤$ 3000 was mentioned as a target) will be even more difficult than for batteries because fuel cell engines are more complex systems than batteries.

(2) Start-up, system control, driveability and potential for some emissions are issues for fuel cell development beyond those encountered with batteries; cold start is a particularly difficult problem since it must be accomplished in seconds, not minutes.

(3) Large resources (hundreds of millions of dollars) will be required to resolve these issues and develop fuel cells into an engine technology that can be mass manufactured at the low costs

needed. Fuel processor and balance of plant may well pose more difficult cost challenges than the stack.

Presently, PEM automotive fuel cell technology is in the proof-of-concept stage. In GM's view, this applies to all current programs, including GM's own fuel processor and fuel cell system laboratory "breadboard" systems. Several redesigns will be required before technical feasibility can be proven by demonstrating acceptable performance and safety. In subsequent phases, a number of redesigns of components, systems and, eventually, the complete fuel cell electric engine-vehicle system will be required to integrate technology advances, cost-reducing design changes, infrastructure learning, and responses to customer/market signals. Market launch can be undertaken only after reliability and durability is established, prospective costs are near targets, and an adequate infrastructure is in place. Finally, several more redesigns and establishment of volume production will be necessary before FCEVs can be commercially viable.

GM did not provide a time table for this sequence because of the uncertainties associated especially with the early phases. An analogy with the EV1 schedule would suggest about 7 years to market launch, broadly consistent with the statement of GM's Board Vice Chairman (at the Automotive News World Congress, January 1998 in Detroit) that GM would have a "production-ready fuel cell vehicle by 2004."

The current and planned commitments of GM to fuel cell electric engine and vehicle development were not revealed to the Panel. However, by GM's own estimation several hundred million dollars will be required over the relatively near term to establish a technology leadership position, and the growth and corporate consolidation of GM's fuel cell activities in a dedicated organization make clear that GM intends to be among the leaders. The corporation appears fully committed to the development and commercialization of fuel cell electric vehicles "if it can be done."

Automobile Manufacturers in Europe and Japan

During its study, the Panel became aware that as many as ten[3] or more automobile manufacturers in Europe and Japan were engaged in the evaluation and development of fuel cells for automobile propulsion. In the collection and review of information, however, the Panel covered only about half of these, in the belief that it was sufficient for the purposes of this report to assess what we

[3] Including at least Daimler-Benz, Peugeot, Renault, Volkswagen and Volvo in Europe; Honda, Mazda, Mitsubishi, Nissan and Toyota in Japan.

believed to be the most advanced efforts. This section covers only three of these manufacturers: Daimler-Benz and Toyota who are generally believed to be leaders in the field and have announced their intent to offer FCEVs commercially within 6 years, and Honda who demonstrated its commitment to electric vehicles by launching the EV Plus and who has accelerated its fuel cell development program substantially over the last few years.

1. Daimler-Benz

The long history of automotive technology leadership of Daimler Benz carried over into a broad investigation of alternate vehicle power sources and fuels during 1970s and 1980s. The involvement with battery and hybrid electric vehicles[4] (cars as well as buses) has given DB extensive experience with electric drivetrains and their integration into vehicles which is directly applicable in the development of fuel cell electric vehicles.

As explained to the Panel during its visit in September 1997, DB's exploration of fuel cells as possible automotive power sources began in 1990, initially with focus on hydrogen as fuel. In 1994, DB researchers completed their first experimental FCEV, the NeCar 1 van, which served as a test bed for the components and the system characteristics of a 50 kW hydrogen-air fuel cell. The NeCar 1 fuel cell stacks were supplied by Ballard; ten stacks of the type shown on the left in Figure III-1 were required to generate 50 kW. The fuel cell power plant used most of the van's passenger space and all of its cargo volume. Since then, DB working with Ballard evolved the hydrogen-air fuel PEM power plant technology to the point where the fuel cell engines used in the NeCar 2 van and NeBus vehicles no longer intrude in either cargo or passenger space. Both vehicles store hydrogen under high pressure in cylinders mounted on their roofs, and hydrogen storage now dominates the volume required by the fuel cell power plant.

Daimler Benz is continuing development of hydrogen-air fuel cell power plant technology for possible commercial application in buses. They believe that, for buses, storage of compressed hydrogen on the roof of vehicles is likely to become acceptable with further advances of safety aspects and reduction of costs. If and when hydrogen production and fueling facilities of acceptable costs become

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4 Daimler-Benz has been active in battery and hybrid electric vehicles for about twenty years. Since 1987, the DB subsidiary AEG has been developing the sodium-nickel chloride ("ZEBRA") battery in a major joint venture with Anglo-American Ltd. One Panel member (FRK) was given the opportunity to test a ZEBRA battery-powered experimental EV based on the new Mercedes Benz A-Class. Installed in a number of these vehicles, ZEBRA battery prototypes are demonstrating specific energy around 100 Wh/kg, long cycle life, and good power. A decision on the establishment of a facility for production of about 30,000 battery packs per year is pending. If a go-ahead decision is made soon, ZEBRA batteries could become commercially available in 2001 at about $300/kW, with potential for further cost reductions if/as production volume increases. ZEBRA battery-powered A-Class cars are a candidate for meeting DB's ZEV obligations in 2003.

available, hydrogen-air fuel cell buses could become part of strategies to reduce urban emissions of air pollutants (with possible emission credits against ICE vehicle emissions) as well as emissions of carbon dioxide[5].

In DB's view, unpressurized liquid fuels are needed for smaller vehicles providing individual transport. In 1996, when DB began to consider fuel cells as a future engine for mass-produced automobiles, methanol was selected as fuel because of the greater ease and higher efficiency of processing methanol into a hydrogen-rich gas. Methanol also is considered more compatible with longer-term resource and greenhouse gas strategies. Finally, methanol offers some albeit currently rather uncertain prospects for its direct use in automotive PEM fuel cells which would greatly simplify the fuel cell engine. On the other hand, at present there is little or no "infrastructure" for supplying large quantities of pure methanol. DB has, therefore, initiated discussions with the methanol and oil industries to stimulate discussion and possible development of suitable methanol production and distribution infrastructures.

A special organization ("Fuel Cell House" = FCH) was formed in 1996 to lead the DB fuel cell vehicle program. Headed by a Senior Vice President who reports directly to the DB Executive Vice President for Passenger Car Development, FCH has about 30 staff members of its own, and it can call on the entire capabilities of DB including the corporate research groups and vehicle testing facilities as well as the engineering expertise and facilities of Mercedes Benz.

The Daimler-Benz FCH also is empowered to enter into special arrangements. At the time of the Panel's visit, the most important of these had just become official: formation of Daimler Benz-Ballard Fuel Cell Engines (termed DBB in the following), as part of a set of transactions that included acquisition by DB of a 25% share in Ballard Power Systems (BPS). DBB, owned 2/3 by DB and 1/3 by BPS, was invested with Can.$110 million in cash from the parents as well as with all of the automotive fuel cell stack and system technologies of BPS and Daimler-Benz[6]. Other DB-external alliances of the Fuel Cell House cover fuel processor catalyst development and electric drive train optimization/cost reduction.

DBB's business objective is to develop and commercialize automotive fuel cell engines that will be sold by Ballard Automotive (another new company, owned in equal amounts by Ballard and DBB) to

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5 The voluntary 25% reduction of CO_2 emissions from cars offered by German automobile producers between now and 2005 creates a substantial incentive for introduction of high-efficiency fuel cell engines.

6 As noted above (see Ford), the ownerships of BPS and DBB were broadened and their resources increased when Ford joined the alliance of Daimler-Benz and Ballard.

the world’s automotive industry, with first call by DB. The stacks for DBB-produced fuel cell engines will be supplied by BPS, at least for the foreseeable future. Automotive fuel cell stack development is led by BPS, development of fuel processors and complete fuel cell systems/engines by DBB. Both companies are working in parallel on product and manufacturing technology development.

Management and key technical activities of the Daimler-Benz Fuel Cell House and DBB are being consolidated in one facility in Nabern near Stuttgart, Germany. About 75 technical staff are engaged primarily in methanol fuel processor development and in the integration of the required subsystems into complete fuel cell power plants. Component and subsystem development is focusing on configurations amenable to mass manufacturing and on advanced manufacturing techniques, taking advantage of the modern automotive engineering and manufacturing development expertise and techniques (such as computer-aided design and rapid prototyping) available at the various Mercedes Benz R,D&E facilities in the Stuttgart area. Daimler-Benz engineering staff believe that fuel cell technology is fundamentally better suited for very rapid, low-cost manufacturing than conventional engine production.

As discussed earlier (see Section III.1.D), a major recent milestone was the completion of NeCar 3, the world’s first but still experimental methanol fuel cell-powered car using the Mercedes A-Class platform. Over the next 2 years, every part of the fuel cell engine will be developed to the point where processes for mass production are established and engine performance and cost can be estimated with confidence. Subsequent generations of NeCar vehicles will represent increasingly packaged versions of the engine technology. NeCar 5, scheduled for late 1999, will approach a production prototype configuration, with room for 4 persons and luggage in the rather small A-Class vehicle. As presently envisioned, this vehicle will have customer-acceptable operating characteristics with methanol-based fuel cell power alone although DB would have the experience and technology base to go to a battery-fuel cell hybrid configuration if considered necessary.

At the end of 1999, a decision will be made whether to invest in manufacturing facilities for fuel cell engines. A go-ahead decision presupposes management confidence that fuel cell engines and vehicles will be able to compete with conventional engines and vehicles on all points while being cleaner and more efficient. Daimler-Benz top management recognizes that a positive decision is not assured but is confident that DBB with its allies have the ability to engineer all aspects of fuel cell engine technology to the point of commercial viability when mass-produced — at least 100,000 engines and vehicles per year once full production is first established, and growing to perhaps 500,000 or more units per year eventually.

Several years and investments of more than $ 1 billion will be needed from this decision point until the various manufacturing facilities are in place and operating reliably. Additional time will be required until FCEVs can be offered to the general public; even with a completely successful program, this cannot occur before 2004/5. The Daimler-Benz Management Board is prepared to support the necessary investments in the belief that the fuel cell is the potentially best alternative to the internal combustion engine given the requirements for ever cleaner engines and the emerging pressures to reduce carbon dioxide emissions from automobiles.

2. Toyota

Toyota has investigated alternate automotive power sources for several decades, seeking a leadership role in reducing the environmental impacts of the automobile. More than 25 years ago, Toyota started a battery EV program which ultimately resulted in the RAV4 EV that is now commercially available in parts of the U.S. In 1995, Toyota jointly with Matsushita committed to the construction of the world's first plant for production of nickel-metal hydride batteries developed and engineered for electric vehicles. This plant is now supplying the batteries for the RAV4 EV and the Honda EV Plus, giving these battery EVs ranges of more than 100 miles under realistic driving conditions. Toyota's "Prius" car is the first ICE engine-battery hybrid vehicle available commercially (at present only in Japan) from a major automobile manufacturer.

Because of the publicity Toyota has been receiving for its work on fuel cell electric vehicles, the Panel made its October 1997 visit and discussion with the Toyota fuel cell team a high priority. As explained to the Panel, Toyota's efforts to develop automotive fuel cells first focused on hydrogen as fuel and on the consequent need for a compact and inexpensive technology for on-board storage of hydrogen. An advanced alloy was developed which permits storage of hydrogen as a metal hydride in 1/8 of the volume that would have been required by the same amount of gaseous hydrogen compressed to 3000 psi. Work on lower-cost hydrogen storage alloys is continuing but Toyota is now concentrating on methanol as a fuel more likely to become broadly available for fuel cell electric vehicles at an acceptable cost in the foreseeable future. Toyota's program addresses every aspect of fuel cell power plant and FCEV technology, from basic research to increase performance and reduce cost of MEAs, to the integration of key subsystems into fuel cell engines and into the RAV 4 EV platform that serves as Toyota's experimental fuel cell vehicle.

The features of Toyota's fuel processor and fuel cell stack (both developed and built in limited quantities in-house) were described in Sections III.1.A and B. Toyota technical staff stressed in the discussion and their questionnaire responses that breakthroughs (perhaps best interpreted as major technical advances) are still needed to achieve the stringent cost goals especially for the key components of the stack. The staff also noted that the need to be competitive with ICE engines and vehicles will define fuel cell power plant performance, operating characteristics and reliability requirements but detailed specifications for the various fuel cell subsystems had not yet been derived from these requirements. Because key features of a number of components and subsystems are not yet defined, their manufacturing development cannot be initiated at this time.

An important aspect of Toyota's approach is that their fuel cell will be part of a hybrid vehicle power system which will use a nickel-metal hydride battery and an electric drive train much like the RAV4 EV. The hybrid battery will reduce the demand for rapid response (including cold start) and peak power of the fuel cell engine. Consistent with this, the fuel cell engine will be rated at 25kW (see Table III-15) compared to the more typical 50-60kW of other developers. The battery will be capable of about 25kW as well, for a total peak power output of 50kW. The drawbacks of hybrid drive systems — greater system complexity and the cost of the battery — apparently are judged acceptable by Toyota, perhaps on the basis of the experience with, and expectations for the Prius hybrid vehicle.

The subsystem layout of Toyota's methanol-fueled "FCEV" was shown in Section III.1.D (Figure III-5); a mockup of this configuration was exhibited at the 1997 Frankfurt International Automobile Exhibition. According to Toyota, a functionally integrated but still experimental vehicle is now being operated to demonstrate technical feasibility and to serve as a test bed for improving engine and vehicle operating characteristics. Toyota's plans are to follow this with a "feasibility prototype" soon after the year 2000 and, assuming sufficient progress, with a production prototype. The Toyota fuel cell team was reluctant to give a timetable for these milestones because of the major uncertainties surrounding the achievement of cost reduction goals. They pointed our that the step from feasibility to production prototypes can take between 10 and 15 years[7], as was the case for their battery electric and hybrid vehicles.

[7] The Panel notes, however, that Toyota already has both, the fully developed electric drive train of the RAV4 EV and the hybrid technology of the PRIUS which is produced in near-commercial quantities. The availability of these technologies could considerably shorten the time to commercialize Toyota's FCEV once the fuel cell engine itself is developed to the point of economic manufacturability.

The Panel was unable to obtain estimates of the resources committed to Toyota's fuel cell and FCEV development program and was not given the opportunity to see any of the facilities dedicated to the program. The best indication that these resources and facilities are likely to be extensive comes from staff comments to the Panel that "Toyota wants to be first with fuel cell-powered electric cars" and from a recent statement by Toyota's President Hiroshi Okuda that, notwithstanding Daimler Benz' stated intent to put fuel cell vehicles into the market by 2004/5, "our engineers have a strong feeling that we will be first to market."

3. Honda

Honda stresses its continued commitments to increasing the efficiency and reducing the environmental impacts of their cars. Sustained pursuit of these corporate objectives through Honda's engineering leadership has resulted in a number of important firsts that range from compliance with early emissions legislation in the U.S. with the CVCC engine, to the recent commercialization of the first cars meeting California's ULEV standards and the launching in 1998 of a 200-mile range CNG-fueled fleet automobile emitting only 1/10 of ULEV standards.

New technology is playing a key role in Honda's efficiency and "environmental friendliness" strategy, as evidenced by the EV Plus, the first purpose-built electric vehicle commercially available with a nickel-metal hydride battery. A novel light-weight ICE-ultracapacitor hybrid drive train is an important current development toward very high efficiencies. Both of these technologies contain elements that might become used in future fuel cell-powered electric vehicles.

Honda's PEM fuel cell program, started in 1989, to date has not sought much publicity. However, Honda invited the Panel to visit the Wako R&D Center for a thorough briefing and a laboratory tour of Honda's PEM fuel cell development and testing facilities. In Honda's corporate view, fuel cell electric vehicles offer the best prospects for minimizing[8] or, in the longer term, perhaps eliminating both, air pollutant and greenhouse gas emissions. Other key arguments include higher fuel efficiency and the possibility to broaden Japan's fuel supply base by linking transportation to natural gas via methanol as the fuel for FCEVs. In Honda's view, the fuel cell will eventually replace the IC engine although no time frame was mentioned. Consistent with the potential importance of the fuel cell and Honda's strong engineering orientation, Honda staff believe that they must master all aspects of this new power source technology. Similar to Toyota's, Honda's fuel cell development program is therefore

[8] Honda's current target for methanol fuel cell emissions is ≤10% of ULEV standards.

carried out in-house at this time; make-or-buy decisions will come once Honda's competitiveness can be assessed against the capabilities and costs of outside suppliers of fuel cell components and subsystems.

Honda's current technical focus and some of their achievements to date were mentioned in Sections III.1.A and B, above. Honda staff emphasized that their work still is R&D to establish the core technologies for a future fuel cell engine. The currently committed staff resources and modern lab-level component fabrication and stack testing facilities are consistent with this but likely to increase in the near future. Assuming continued R&D success, Honda anticipates entering an approximately 5-year phase of subsystem integration and power plant field tests. The implication from this is that, given complete success, FCEV commercialization could begin around 2005/06 , but in Honda's view the timing of market penetration is likely to be different in the U.S., Japan, the European Community and Asia, reflecting significant socio-economic differences.

The initially higher cost of FCEVs will be a challenge; for example, each EV Plus is still being sold at a loss. The platform for Honda's fuel cell electric vehicle has not yet been defined, and it is not yet clear how the costs of FCEVs will compare to those of battery EVs. In any event, the important cost comparison is the one with ICE-powered cars. Despite the anticipated challenges, Honda is committed to make the necessary investments in technology development, engineering, manufacturing development and production facilities because of the ultimate potential of FCEVs. Honda's expectation is that FCEVs and, also, CNG-fueled ICE vehicles eventually will capture market share even from high-efficiency ULEVs.

Summary of Major Programs and Prospects for FCEVs

In summary, major efforts are underway in the North America, Europe and Japan to develop PEM fuel cell technology and systems for automobile propulsion. They are being undertaken by the organizations whose participation and leadership is essential if a commercially viable automotive fuel cell electric engine and vehicle is to emerge: leading automobile manufactures with track records in advanced automotive technology, including the development of electric and hybrid vehicles. Equally important, the world's leaders in PEM fuel cell technology are, or will be, participating in key alliances with these manufacturers. The integrated efforts are supported by well-focused government R&D programs of significant size (especially in the United States), and they draw on the advanced technology leadership of a growing number of organizations who look to PEM automotive fuel cells as a potentially large business opportunity for their specialized products and skills.

In the Panel's estimate, the R&D investments made to date and the commitments for next few years by major fuel cell developers and automobile manufacturers already are between $1.5 and 2 billion, and additional resources — both, financial resources and technical capabilities — are likely to be committed as programs move increasingly from R&D into the larger and more expensive phases of engine systems integration and evaluation/testing, engineering of component, subsystem and system technologies for low cost mass production, and development of the required manufacturing processes.

The efforts to date already have resulted in major technical advances, especially in PEM fuel cell stack technology but also in other critical subsystem areas, as discussed in earlier sections of this report and summarized in Figure III-7. From its discussions with fuel cell developers and automobile manufacturers engaged in automotive fuel cell engine development, the Panel tried to indicate the current status of the leading efforts in the industrial development timeline of Figure III-8, recognizing that this simplified representation of multifaceted programs reflects both subjective judgment and substantial uncertainty due to rather incomplete information on some of the programs.

Probably more important than any comparisons of program status, Figure III-8 shows graphically the point made repeatedly in this report: that major steps are still ahead even for the most advanced programs before confident predictions are possible on the commercial prospects of fuel cell electric engines and vehicles, and still more time will be required until FCEVs can be launched.

At this time, the most compelling arguments for the Panel's cautious optimism about these prospects are that remarkable technical advances have been achieved in a relatively short time, and that the promise of the fuel cell as a new, fundamentally cleaner and more efficient automobile engine is being pursued with an unprecedented combination of resources by powerful organizations acting in their own interest and with strong public support. The Panel, therefore, considers the statements of several major automobile manufacturers — that they expect to have production-ready fuel cell electric vehicles by the year 2004 — as bona fide expressions of the automakers' plans and confidence. Given the current status, the steps still ahead, and the limited time available for their completion as shown in Figures III-7 and III-8, success at every turn and manufacturing investment decisions at the earliest possible times will be required to commercialize fuel cell electric engines and vehicles in a short 6 years from now.

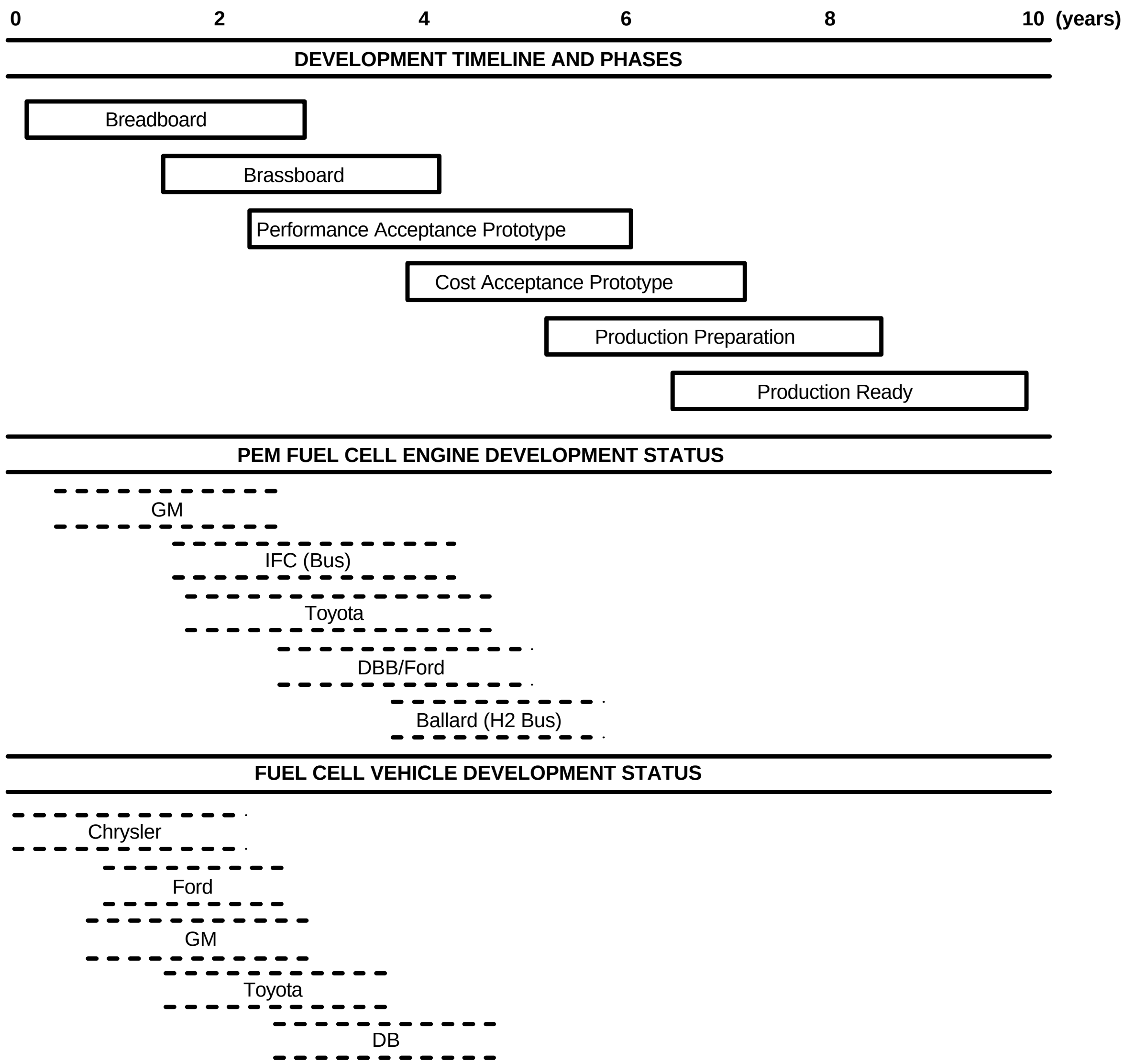

Figure III-8. Fuel Cell Electric Engine and Vehicle Development: Program Timeline and Status