

行政院國家科學委員會專題研究計畫成果報告

電動機車技術研發推動小組赴美參加燃料電池研討會 暨參訪相關研究單位報告

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摘要

美國 Alton Jones Foundation 考慮補助 Desert Research Institute (DRI) 與 Texas A&M 大學合作開發電動機車用之燃料電池(Fuel Cell)。Texas A&M 大學之研究小組有意透過我國之台灣經濟研究院與國內各單位合作以開發電動機車。由於電動機車為國科會重點研發項目之一，因此邀請清大萬其超教授、台大化工系顏溪成教授、及工程處葉至誠科員赴美參與該基金會在美國加州 Lake Tahoe 舉辦之燃料電池研討會，會中除與國外燃料電池專家交流外，並了解我國台灣經濟研究院與 Desert Research Institute (DRI)、Texas A&M 大學推動之燃料電池電動機車計畫之構想及可行性。此次行程順道安排參訪美國電力研究所(EPRI)、Ray-O-Vac 電池公司、Johnson Control 公司電池部門、Case Western Reserve 大學之微燃料電池實驗室，其中並與 EPRI 談及共同合作研究電動機車相關計畫之可行性。

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前 言

美國 Alton Jones Foundation 每年贊助各項科技活動之經費達 3000 萬美金。該基金會之資產原先來自石油化學工業，因此願意將活動之重點放在清潔能源方面。目前 Alton Jones Foundation 與美國的 Desert Research Institute(DRI)與 Texas A & M 大學合作開發電動車用之燃料電池 (fuel cell) 。

Texas A & M 大學之研究小組有意透過台灣經濟研究院與國內各單位合作以開發電動機車。由於電動機車本來即為國科會重點研發項目，因此本會先後兩次派員赴美參與該基金會主辦之燃料電池討論會。本次討論會是第二次，在美國加州 Lake Tahoe 舉辦。

國科會指派參與人員為萬其超、顏溪成二位教授和工程處葉至誠。此次討論會共歷經三日，會後顏、葉兩員並順道訪問美中和美東各電池研究單位，包括 Ray-O-Vac 電池公司、Johnson Control 公司電池部門及 Case Western Reserve 大學微燃料電池實驗室。在會前三人也曾拜訪舊金山市郊之美國電力研究所 (FPRI)，該中心替美國政府管理電能、電池與電動車相關之大型計劃。

茲將各訪問、參與點之活動和綜合建議報告如下：

參加燃料電池研討會及拜訪相關研究單位、電池 製造公司

2.1 美國電力研究所(EPRI)

此次訪問之第一站為美國電力研究所 (Electric Power Research Institute , EPRI) , EPRI 總部在舊金山市郊 , 每年運作費用約五億美金 , 均由各電力公司捐助 , 它除了本身做部份研究 , 主要是規劃各種電力相關研究課題 , 然後委託各單位執行。自 1977 年起 , EPRI 即推動電動車之相關研究 , 它涵蓋範圍龐大 , 以實體而言 , 從電動助行車、電動機車等屬於所謂非公路車輛 (non-road EV) 到電動車和公用車輛 (public transportation system , 即巴士) 都有 ; 以性質而言 , 由電池之研發 , 到充放電週邊環境以及相關之標準 (standard and code) 都有涉及。

EPRI 並有一項會員制 , 接受國外單位參與 , 會員可以定時接收各項資訊。據了解 , 包括台電公司在內 , 我國尚無任何一個單位參與。我國有意發展電動車 , 建立資訊中心 , 當然應該有一單位去登記為會員 , 尤其是許多環境面、制度規格面的考慮 , EPRI 已經有許多現成的成果 , 也願意與大家共享。我國實在不需要樣樣從頭做起 , 譬如訂定標準 , 如果閉門造車 , 不但耗費時間、金錢 , 屆時與國際標準不合 , 產品無法外銷 , 等於是做虛工。EPRI 目前與泰國、香港均有合作計劃 , 他們也願意與台灣在電動車方面進行合作。他們有豐富之計劃規劃管理經驗 , 而不代表特定公司 , 立場超然 , 是非常適合與國科會合作之對象。在七月二十四日的討論會議裏 , 雙方認

為有六項主題應有合作的可行性：1. 電動車技術資訊中心的建立。2. 高能電池技術的研究。3. 協助我國科學園區之電動機車示範運行區之設立。4. 充放電環境面議題。5. 相關標準的建立。6. 協助台灣電動機車研究計畫上、中、下游的整合。事實上 EPRI 之亞洲區主管 Mark Lauby 將於今年 8 月來台灣，也希望與我國相關主管見面，進一步討論合作的可行性。本次訪門也見到原在 EPRI 服務，現為我國行政院科技顧問組顧問劉松男博士，他表示今年 11 月在台北舉行之中美工程師聯合會也特別增加了電動車這一項目。

我國各部會增加經費，鼓勵產學各界從事電動車之研發，是一件好事情。但是投入大筆研究經費，只是能誘發各方面提出大批計畫書，主持人原先大多並無相關經驗，也無意全心長期投入，主其事者本身也無一上中下游之整體考慮，最後成了放牛吃草，百花齊放，雖然熱鬧有餘，但是很難成為一項電動車工業的。所以國科會應該與如同 EPRI 之類的單位、國內相關廠商和有經驗的專家建立一規劃團隊，根據我國的現況需求和研究實力，訂定較可行而有系統之研究課題，然後慎選合適之單位進行長期研發。

電動車技術之研發是一項複雜之長期投資，而不應成為產學研各界之短期抄作，否則不但不會有實效，反而不必要的吸收了大批研發資源，影響到其他學門、課題之發展。附件一為在 EPRI 所取得之部份資料，可了解其各項活動，包括對全球會員（EPRI membership）在電動車技術研發上之服務。

2.2 Lake Tahoe 燃料電池研討會

訪問活動的第二站也是重心，就是在 7 月 27 日至 29 日的燃料電池研討會。這次研討會是由 Alton Jones Foundation 與另一家 Energy Foundation 共同舉辦。參與會議的人士大多為美國工業界人士和能源部官員，當然也有少數來自歐洲和亞洲地區。由於燃料電池是一項工業產品之開發，所以與會者之講述內容大多考慮到經濟成本和原料供應之可行性等實際因素，即使是美國 Texas A & M 大學之 John Appleby 教授對於燃料電池之技術分析，也對成本價錢如數家珍。這一點是我國從事應用科學之教授應該學習的地方。

一般來說，由於燃料電池起動時間較長，成本較高，所以大多數人認為現階段若要將燃料電池用到電動車，也應該是混成車型式 (Hybrid)，也就是啟動和加速度之能源來自普通化學電池，如鉛酸電池或是鋰離子電池，而定速度之行駛才靠高能量密度之燃料電池。

美國能源部官員表示未來交通工具之三項基本要素是：(1) 能量來源必須可靠；(2) 成本上可行，不能仰賴補貼；(3) 低污染。該部每年給工業界和學術界約 300 ~ 400 個研究計劃以開發新技術。

電動車在歐美受到重視之主要原因是來自排放廢氣對健康之影響。據美國肺臟協會 Du Melle 先生表示全世界每年有 270 萬人是直接死於空氣污染，這些人大多居住在大城市，而大城市中空氣污染之主要來源是車輛。所以汽車對人類健康之禍害，並不是完全來自於其數量，另一原因是它的污染集中於城市。至於工業生產中所產生之空氣污染對於大氣雖然也有影響，但是污染分散而且比較能作控制處理。因此經常也聽人們提到電動車雖然不排放廢氣，但是製

造電池之程序也會造成空氣污染。不過他們忽略到製造電池所引起的空氣污染量，即使與汽車直接排放之廢氣相當，但是它排放的地點並非集中在城市，所以對人類的傷害程度是輕了許多。

目前燃料電池製造廠家中比較負盛名的是加拿大的 Ballard 公司，他們原先是以製造發電用之燃料電池起家，因技術精良而被數家大汽公司看中為共同開發電動車之夥伴（見附件二）。因此一個成功的電動車工業，必須先具備完善的車輛工業和電池工業，否則任何投入電動車之研發經費，只是為人作嫁或是製造論文。由於燃料電池牽涉到燃料之供應，無論是氫氣、甲醇或是汽油，都必須有完整之供應、運銷系統，所以燃料電池電動車之問世，還必須具備完善之能源工業（energy industry）。

目前 Ballard 與賓士、福特等大公司開發燃料電池電動車，係以巴士為第一目標。這是因為巴士之路線行程較固定，比較可能集中輸送燃料（centrally refuel）。

我國目前集中發展電動機車，雖然是考慮特殊國情而做此決定，但是機車不易集中維修處理，在初期推動時期，如能在城市空氣污染嚴重的地區先引進少數電動巴士，可以讓一般民眾只享受到電動車之優點，而不負擔電動車維護上之煩惱，這是宣導教育上很有效的一項策略。

這次會中領略到電動車從其核心技術到週邊環境、維修和訂定標準規章之複雜性。因此一個國家要發展某一型之電動車輛，必須至少要先有某一型之引擎車工業和某一型之電池工業。譬如在我國要發展鎳氫化物電池為能源之電動機車，由於我國已具有鎳氫化物

製造廠和機車廠，所以才有起碼的發展條件。

電動車輛是一項普及性甚至國際通用之交通工具，所以必須隨發展之成熟度，訂定各項標準與規範（code）。在這方面，歐美已經做了許多，我國之電動車工業已在萌芽，政府有關部門應迅速參酌國外資料訂定我國之標準。

歐美之電動車發展在現階段集中於電動車和電動巴士。所以研討會中只有一位來自 Desert Research Institute 的 LaVen 先生專門討論以 PEM 型燃料電池推動電動機車之可行性。他在文中也對各種燃料之性能由單位體積和單位重量之觀點來作比較（附件三）。由附件三之表中可以看出純氫之單位重量含能量高於液體燃料，但是若考慮其必須具備之厚實容器，即遠遜於液體燃料如汽、柴油。因此除非在儲氫之技術上有所突破，否則利用重組器（Reformer）配合液體燃料作為電池供氫之方法仍會是中大型燃料電池之主流。

此次研討會在會場外也有電動車之展示，共有兩款燃料電池型電動車（見附件四照片），可惜未做動態示範運行。其燃料為瓶裝高壓氫氣，雖然供應廠商宣稱完全無虞，但相信離商品化尚有一段距離。

2.3 Ray-0-Vac 電池公司

Ray-0-Vac 電池公司創設於 1906 年，總部設於 Wisconsin，Madison，員工總數 2300 人。主要市場為美國本土，年營業額為 2.7billion，美國市場佔有率為 15%。現有國內工廠五座皆位於 Wisconsin 州，國外工廠部份僅在英國一地設有工廠。亞洲部份僅在

香港設有分公司負責行銷事宜。公司主要產品為一般高能電池、可充電式鹼性電池，及鋰離子電池。應用領域為家庭日常用之一至四號電池，及相機用電池。

2.4 Johnson Control 公司電池部門

Johnson Control 公司於 1885 年設立於 Wisconsin 州之 Milwaukee 市，員工 75000 人，其中位於 Milwaukee 本部有 2500 名員工，其主要產品為照明系統、汽車內裝，及鉛酸電池。年營業額為 12 billion，其中鉛酸電池生產之營業額為 1 billion，為美國最大的鉛酸電池製造公司。由於鉛酸電池十分笨重，通常運輸成本十分高昂，因此於美國各地分散設立生產線，以供應市場需求。

Johnson Control 公司副總裁認為，雖然鋰離子電池、鎳氫電池較輕且性能優於鉛酸電池，但是鉛酸電池歷史悠久，它安全且可靠性高，有其市場存在的價值。目前該公司正開發的二種特殊電池為無電解液電池(AGM 電池)及膠狀電解液電池(JL 電池)。

2.5 Case Western Reserve 大學 EDISON 感測器技術中心 (ESTC)

ESTC 是一個世界級的感測技術研究中心，主要發展應用於機械、電子、化工、醫療之微感測技術。ESTC 目前正執行一微燃料電池計畫，每一片微燃料電池發電量約 30-40mWatt，設計應用於手提電腦，預期其使用時數將優於鋰電池。

由於 ESTC 長期從事微感測器的研究，目前該中心有一潔淨度 100 的潔淨室，內有完整的微機電(MEMS)實驗之半導體製程設備並聘有 17 位專職技術人員負責機台操作及維修。該中心除了自行承接研

究計畫之外，同時也接受校內其他系所委託製造晶片。

ESTC 所聘之技術人員薪水並不高但人事卻十分穩定，主要原因為學校有相對配合措施：凡是員工子女就讀該校，其學雜費一律全免。這點值得我國推動的實作中心、貴儀中心，...等參考。

參訪後心得與建議

政府以堅定的決心發展電動機車產業，現階段並以補貼政策提升民間購買意願，惟電動機車的開發除了考量低污染之外，亦應考量能源來源是否穩定可靠以及成本上是否可行，尤其不能長期仰賴政府補貼。現階段燃料電池雖然在儲氫材料方面有所突破，但是氫源供應的環境面問題、安全問題、啟動時間過長，以及成本問題等都是有待克服的，以目前的技術而言，燃料電池電動機車短期內難有商業價值。

美國 EPRI 長期推動電動車相關研究，在電池之研究、充放電週邊環境以及相關標準等方面已累積相當經驗與資料，我國若能借重 EPRI 此方面之技術及經驗，將對推動電動機車行動計畫有實質幫助。EPRI 設有一會員制，接受國外單位參與，會員可定時接收各項資訊，我國有意發展電動機車；建立資訊中心，應可考慮登記為會員。

一個國家要發展一個成功的電動機車產業牽必需具備完善的某一型機車產業及某一型電池產業，否則所投入的研究經費及成果將難以落實至產業應用。我國目前具備機車產業及鎳氫化物製造廠，因此具有發展鎳氫電池電動機車之基本條件。本文建議現階段應整合相關廠商和有經驗的專家建立一規劃團隊，根據我國的現況需求和研究實力，訂定較可行而有系統之研究課題，然後慎選合適之單位進行長期研發。

ELECTRIC TRANSPORTATION BUSINESS AREA

Description

The introduction of electric vehicles into the national vehicle marketplace provides a major opportunity for utilities to increase future sales of electricity. Progress toward the mass production and sale of electric vehicles continues despite technical and investment challenges and resistance from established industrial interests.

In recent years electric utilities, through EPRI's Electric Transportation Business Area (ETBA), have done much to prepare and are now participating in the launch. By taking an effective, non-biased leadership role, the ETBA has been able to ensure technical and economic realism in the development of infrastructure requirements and the demands that will be made on energy suppliers. It is through this role that the most apparent value of this business area becomes clear to its funding partners. In one sense the most important product of the ETBA is its impact on (and expression of its members' wishes in) the electrification of the transportation industry through coordination with the involved councils of government, automakers, and industry-related manufacturers. To complete the portfolio, the ETBA continues to assess utility impacts and develop equipment prototypes to spur industry innovation and deploy devices for laboratory and field testing, as well as continuing its collaboration with other organizations participating in the electric transportation industry. By effectively articulating the alternatives to industry "solutions" that would burden utilities with impractical and expensive requirements, ETBA protects both the utility industry and its customers. The targets presented herein cover a wide range of activities geared toward the successful response of utilities to electric vehicle (EV) deployment.

Available Targets

- 28 ETIP/New Project Development
- 29 Transportation Energy Storage Systems
- 30 Infrastructure Deployment and EV Benefits
- 31 Public Transportation Systems
- 32 Non-Road Electric Vehicles
- 33 Transportation Data Collection/Management *
- 34 Airport Solutions

*New Target in 1998 Offering

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ETIP/NEW PROJECT DEVELOPMENT TARGET

Audience

Utility officers, senior managers, and staff responsible for:

- Business opportunities/development
- Corporate communications
- Customer relations
- Customer service
- Distribution systems
- Economic development
- Electric transportation
- Electric vehicle infrastructure
- Energy services
- Environmental solutions
- Load management
- Marketing
- Market research and planning
- New products and services
- Power delivery
- Public transportation
- Research and development
- Strategic planning
- Utility fleet vehicles
- Utility equipment maintenance

Issues

The recent introduction of commercial electric vehicles (EVs) into the marketplace has sparked the interest of utilities all over the country. Their arrival has changed priorities for many utilities that have not yet been involved in or exposed to the development of the expanding electric transportation industry. Over 100 utilities have opted for electric vehicles as their choice for the alternative fuel vehicles for their fleets under EPAct (Energy Policy Act) requirements. Now, more than ever, all utilities—whether or not in the initial EV launch areas (California and Arizona)—are looking for a basic awareness of the expectations and requirements of the EV industry. ETIP provides this awareness.

EPRI Solutions

ETIP will report on new research results highlights, the utility/EV user interface, past EV research results, field test data, and product developments. Members will receive the latest news in regulation/mandate information and be made aware of other Electric Transportation Associations and Activities. Designed to help utility management make informed decisions on matters related to EVs, ETIP offers a level of insurance against surprises during the deployment of EVs across the nation.

Target Funding Plan Summary

1998 Base Budget Need (SM)	TC/Other (SM)	Total (SM)
\$0.50	\$0.05	\$0.55

Products & Services

The cost of each product includes the 1998 cost to develop and deliver it (in the year shown) as well as the 1998 cost of Strategic R&D. The number and mix of products and services are subject to the

IWC ORGANIZATION & MISSION STATEMENTS

IWC Organization

The Electric Power Research Institute (EPRI) established the National Electric Vehicle Infrastructure Working Council in 1991 to formulate recommendations for a standard electric vehicle infrastructure.

IWC supplies information "products" for a new market, EVs, through a melding of two heretofore entirely separate industry distribution channels—electric utilities and automobiles. Organizations that have never dealt with one another before must now cooperate, coordinate, and collaborate. Auto makers find themselves dealing with utility customers and utilities are dealing with driver issues—a new world for both businesses.

Since IWC is not, itself, a standard-setting body, it makes recommendations to the Society of Automotive Engineers (SAE), Underwriters Laboratories (UL), the National Electrical Manufacturers Association (NEMA), the National Fire Protection Association (NFPA), and other standards organizations. Over the years, the function of the council has expanded to also include collaborative pre-production prototype development and independent testing of EV infrastructure equipment and components.

Led by the Infrastructure Steering Committee (ISC), the IWC is organized into five working committees:

- Health and Safety (H&S)
- Charging Controls and Communications (CC&C)
- Connector and Connecting Stations (C&CS)
- Load Management, Distribution, and Power Quality (LMD&PQ)
- Bus/Non-Road (B/NR)

Infrastructure Steering Committee

The purpose of the Infrastructure Steering Committee is to direct and coordinate the activities of the Infrastructure Working Council. The ISC Charter lays out four specific objectives for the committee and the council as a whole:

- Achieve the timely deployment of an EV infrastructure that meets the needs of the marketplace.
- Encourage IWC committees to consider safety, consumer convenience, and cost and economic considerations.
- Promote consistent standards for the EV infrastructure.
- Direct the application of the resources committed in support of the IWC.

■ Health and Safety

The H&S mission is to "enhance the safety of people, their property, and the environment from potential hazards that may be uniquely associated with operating and maintaining an electric vehicle through research, development of codes and standards, education, and technical advisory services."

■ Charging Controls and Communications

The mission of CC&C is to "lay out and define the operation and communication between the utility, the electric vehicle supply equipment, and the vehicle in order to provide for:

- Safe, cost-effective charging
- Interoperability of supply equipment and vehicles from different manufacturers
- Features that will enhance vehicle ownership
- Future expandability and compatibility"

■ Connector and Connecting Stations

The C&CS mission is to "support the development of standard physical and electrical configurations for the transfer of energy and the exchange of information at the utility/vehicle interface through collaborative design, development, and evaluation."

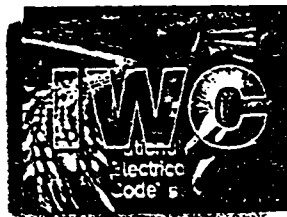
■ Load Management, Distribution, & Power Quality

The mission of LMD&PQ is to "minimize the impact of EV recharge loads on the utility distribution and generation systems through identification and resolution of critical issues relating to load management, distribution planning, and power quality."

■ Bus/Non-Road

The mission of B/NR is to "promote consistent standards, minimize cost, and ensure operational safety within the electric bus and non-road industry by:

- Evaluating and applying and/or modifying the information and results that are developed in the other IWC committees
- Developing/recommending resolution to issues not addressed by the other IWC committees"

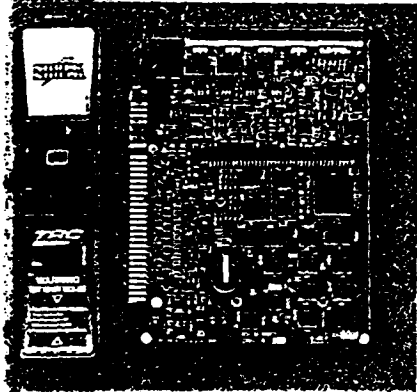


IWC has tackled the complexity of electric vehicle infrastructure issues with three primary priorities: safety, consumer acceptance, and minimization of the possibility of even minor environmental impacts of EV use.

Safety is the overriding consideration for EV infrastructure. Consumers will be dealing with electricity differently than they have in the past. Power levels for electric vehicle charging at home will be similar to

those for a range or clothes dryer. The big difference will be that the consumer will connect and disconnect the EV every day. Anyone who has occasionally struggled with plugging in and unplugging a clothes dryer understands how difficult it can be. Substantial force is needed to engage or disengage the plug, and live pins can be exposed. EV charging must be much easier and safer.

Personnel Protection Devices



IWC and EVI Inc. Charge Circuit Interrupt Devices (CCID)

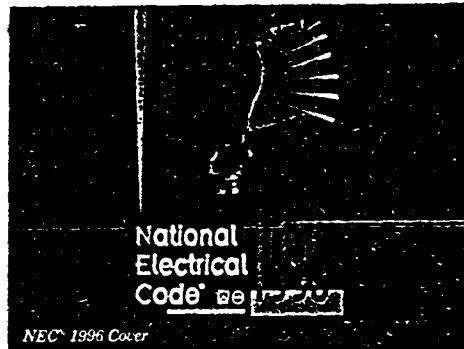
Fail-safe electric shock and short-circuit protections must be built into EV infrastructure equipment and its wiring. The IWC has developed specifications and tested new classes of Personnel Protection Devices (PPDs) for electric vehicle supply equipment in home and commercial use.

These devices ensure safety in single-phase and three-phase AC and DC products rated up to 600 volts. Two manufacturers have produced PPDs that meet UL standards.

National Electrical Code[®] Article 625

Consumers must be confident that EV equipment is a safe to operate as any other electrical product. The IWC has devoted a substantial portion of its energies to revisions of the National Electrical Code. Its recommendations have been accepted and published in

the 1996 Code. With field use and experience, the IWC is submitting modified language for the 1999 edition of the Code to the National Fire Protection Association.



NEC 1996 Cover

Model Building Code

EVs require new wiring, circuits, and equipment at your home, and perhaps where you work.

Installation of EV equipment will require building permits and inspections. Building codes vary greatly across the country, even from city to suburb.

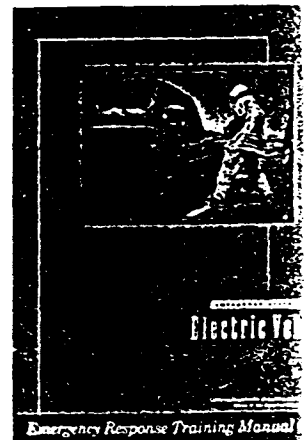
The IWC has produced model building code language that will ensure consistent and safe installation of EV-related equipment. Model language has been submitted for consideration in jurisdictions around the country.

Minimum Ventilation Required in Cubic Feet per Minute (cfm) per Parking Space Equipped to Charge an Electric Vehicle			
Branch Circuit Amperage Rating	Branch Circuit Voltage Single-Phase		
	120V	208V	240V or 120/240V
15	37	64	74
20	49	85	99
30	74	128	148
40	99	171	197
>40 or Three-	For single-phase values >40 amperes: cfm = (volts x amperes) / 48.7 For three-phase values: cfm = (volts x $\sqrt{3}$ x amperes) / 48.7		

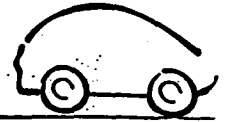
Proposed Model Code Ventilation Table

Emergency Response Training

Regardless of their inherent safety, EVs and EV equipment will eventually be present at the scene when firemen, medics, or police are called to an emergency. Training these individuals in what to expect and how to respond to EVs is a critical undertaking. The IWC has assisted in the publication and distribution of thorough emergency response procedures that are now in use in California and available nationwide.



Emergency Response Training Manual



Fuel Cell Electric Vehicles

Fuel cells, invented in 1839, combine hydrogen and oxygen in the presence of an electrolyte to produce electricity and water. But their high cost, bulky size and reliance on hydrogen has always made them impractical for commercial use. In October 1997, however, a "breakthrough" in fuel cell technology that "would transform the auto industry" was announced. Specifically a fuel cell system had been produced to pioneer a prototype electric car with gasoline as the fuel source—although it could also use ethanol, methanol and natural gas. A key element of the system is a reformer which converts gasoline into hydrogen.

The fuel cell vehicle (FCV) could prove to be the holy grail of the automotive industry if costs come down and technology advances fast enough. At this point, however, it is nothing more than a hopeful prototype, hyped by media attention that inaccurately portrays it as a current reality. The FCV is a promising technology—for the future. Battery electric vehicles (BEVs) are already on the road and improving—today.

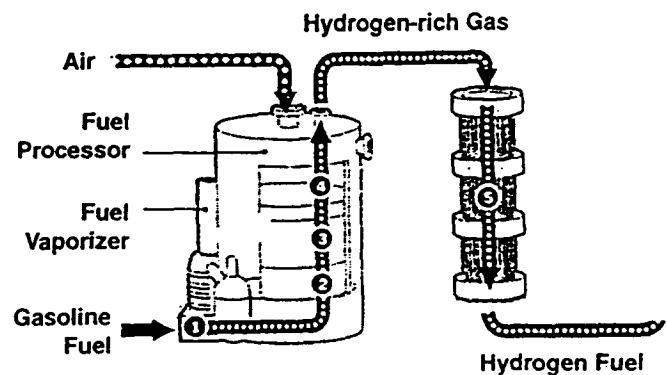
"... the automotive landscape is littered with 'can't miss' technologies [like Mazda's rotary engine] that never hit the mark."

LA Times, August 13, 1997

Fuel. FCVs would use a "stack" of many fuel cells—each about a foot square with the thickness of a computer disc—connected in series, occupying the equivalent of 20 to 25 gallons of space and weighing 125 pounds. Reformers that process methanol, a simpler fuel than gasoline, have been available for some time but they are too big for cars, and the infrastructure does not exist for methanol fuel delivery. Indeed, building a national hydrogen or methanol system of refineries, pipelines and service stations would cost up to \$500 billion to \$1 trillion. Gasoline remains the fuel of choice because it is readily accessible. But it, too, has its drawbacks. The recently announced gasoline reformer breaks complex hydrocarbon molecules into hydrogen and carbon monoxide, which is then converted to carbon dioxide. This is a complicated chemical system, is difficult to manufacture inexpensively, decreases a FCVs energy efficiency by about 10 percent, and releases carbon dioxide emissions. By comparison, fuel delivery for BEVs is simple since homes and businesses already have 120 and 240 volt electricity as a reliable, easy to use, fuel source.

Gasoline Reformer Operation

- ①&② Fuel is vaporized and mixed with air producing CO_2 and H
- ③ Sulfur compounds are removed
- ④ Steam is added to form H and CO_2 from the CO
- ⑤ Any remaining CO is burned



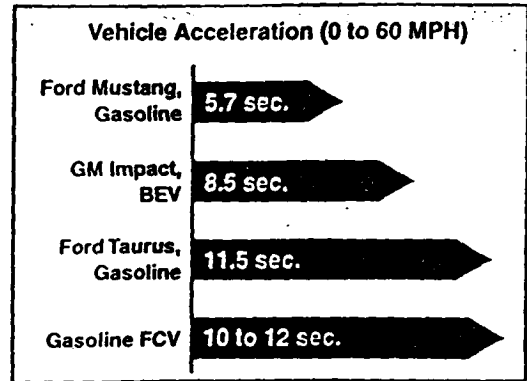
Source: Arthur D. Little

Availability. Most of the world's leading auto makers, including Daimler-Benz, Toyota, Honda and the Big Three U.S. firms have recently announced major fuel cell projects. Daimler is the most aggressive, having poured \$450 million into a strategy to mass produce 100,000 FCVs a year by 2005. This timeframe may be optimistic because many difficult engineering problems have to be solved. For example, FCV cooling currently requires a radiator surface so large that vehicle body shapes would have to be radically different than those in the market today.

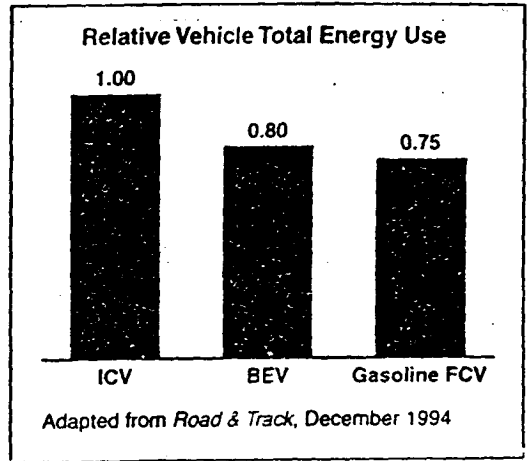
"Given the large amount of development work that remains to be done, however, introduction of fuel cells into mass market vehicles appears likely to be beyond the 2010 time frame."

ORNL & Lawrence Berkeley Labs,
US DOE, October 1997

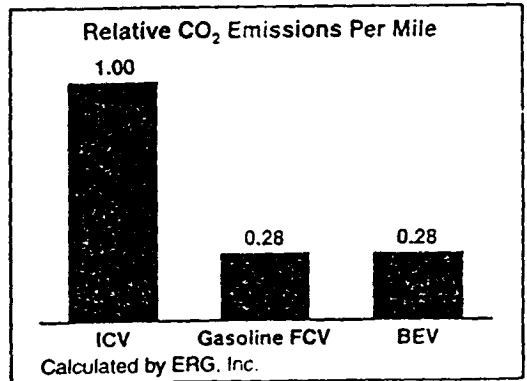
Performance. Like all technologies, FCV performance will drive consumer acceptance. The initial FCV should have a range of about 250 miles between refuelings. In comparison, internal combustion vehicles (ICVs) have a range of greater than 400 miles, and, by the year 2000, BEVs will likely provide more than 295 miles between charges, which will require only 10 minutes to accomplish. Consumers generally expect cars to have an acceleration rate of 0 to 60 MPH in 10 seconds. FCVs will likely require 10-12 seconds. Some BEVs already beat that rate with 8.5 seconds. Ironically, an FCV will be equipped with an advanced battery—weighing 280 pounds and occupying 20 gallons of space—to provide extra power for starts and passing.



Efficiency. FCVs will likely provide much greater energy efficiency than current ICVs, but BEVs remain the most efficient of all. An ICV loses more than 80 percent of its gasoline energy either as heat, which flows out of the tailpipe, or as friction in the drive train. Proponents claim that FCVs will deliver 84 percent of the energy in gasoline to the fuel cell, which turns most of that energy into electricity. This claim may be overstated, however, because the reformer consumes a great deal of energy. In October 1997, the U.S. DOE stated that "fuel cells in conjunction with gasoline reformers would be 70% more efficient than current gasoline engines". That means that BEVs and gasoline FCVs have approximately the same total (entire fuel cycle) energy efficiency. Indeed, total BEV energy requirements will steadily decline because new, combined cycle natural gas electricity plants with efficiencies near 60% are much higher than the coal and nuclear stations now in use.



Emissions. Despite claims heralded in the media, a gasoline FCV is not a zero-emission vehicle, and would not meet the qualifications for California's zero emission vehicle mandate. Only BEVs qualify as zero emission, because they have no point-of-use emissions, and their fuel comes from power plants, which are subject to regulation and located away from populated areas to minimize emission impacts. Gasoline FCVs do have point-of-use emissions. They release carbon monoxide and reactive organic gases such as benzene and formaldehyde. And because they are tailpipe emissions, they will likely occur in densely populated urban areas. On a global basis, significant quantities of CO₂—which is a greenhouse gas—will be emitted through the reforming of gasoline.



Cost. Proponents claim that FCVs having attributes similar to those of an ICV Ford Taurus priced at \$17,300 (1992 dollars), would cost about \$25,000 while a similar BEV would have a sticker price of \$27,000. These claims are surprising for two reasons. First, the fuel cells and reformers are still more than 10 times as expensive as a comparable ICV engine. Second, BEVs have been steadily decreasing in price. In fact, the U.S. DOE predicts that with tax credits BEVs will soon cost only \$3000 more than a comparable ICV.

The recent breakthrough in FCV technology was an important step toward commercialization. Nonetheless, FCVs remain on the drawing board while BEVs are on the road.

EPRI

Electric Power Research Institute
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December 1997

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BALLARD

Source
Fortune

Date
March 30, 1998

INNOVATION

Bright-eyed, his silver hair a little wild at the fringes, Dr. Ferdinand Panik, 56, clearly relishes piloting a very special Mercedes vehicle briskly past the apple orchards on the outskirts of Nabern, Germany. The 40-foot ultramodern Nebus (for "new electric bus") is virtually silent under way. In the engine bay normally occupied by a growling diesel are several "stacks" of fuel cells that, without combustion, make electricity to drive the motors that turn the wheels. From a hilltop nearby, a castle looks down on new labs and workshops that automaker Daimler-Benz is equipping for a top-priority fuel-cell development program that could make the noisy, polluting piston engines that power the world's cars, trucks, and buses as obsolete as the steam locomotive.

The work at Nabern is the most visible evidence of an accelerating wave of R&D by automakers and component suppliers around the world that have committed more than \$1 billion to fuel-cell power systems. The concept has always had an arresting simplicity. Remember the high school chemistry experiment in which, through the addition of a bunch of electricity, water is electrolyzed into its constituent hydrogen and oxygen gases? A fuel cell is a device that accomplishes precisely the reverse. It combines hydrogen and oxygen electrochemically to form water, giving off heat and electricity. The juice can power whatever you want to plug into it.

Fuel cells have long supplied electricity on spacecraft, but they are priced like crown jewels. The car people are excited by a different kind of fuel cell. Development work has shrunk the price of this version by roughly a factor of ten in the past decade. The cost is still more than ten times too high. But encouraged by the progress to date, industry is hoping that big-ticket R&D will bring down the cost much further, along with that of related "drive train" hardware such as fuel-processing devices, electronic controls, and motors.

Those who love the macho roar of piston engines needn't fear for their imminent demise, for the fuel cell's success is definitely not guaranteed. Nevertheless, executives at Daimler-Benz and other

They're putting more than \$1 billion into a revolutionary power system. Daimler-Benz wants to be out first, and GM is "totally serious."

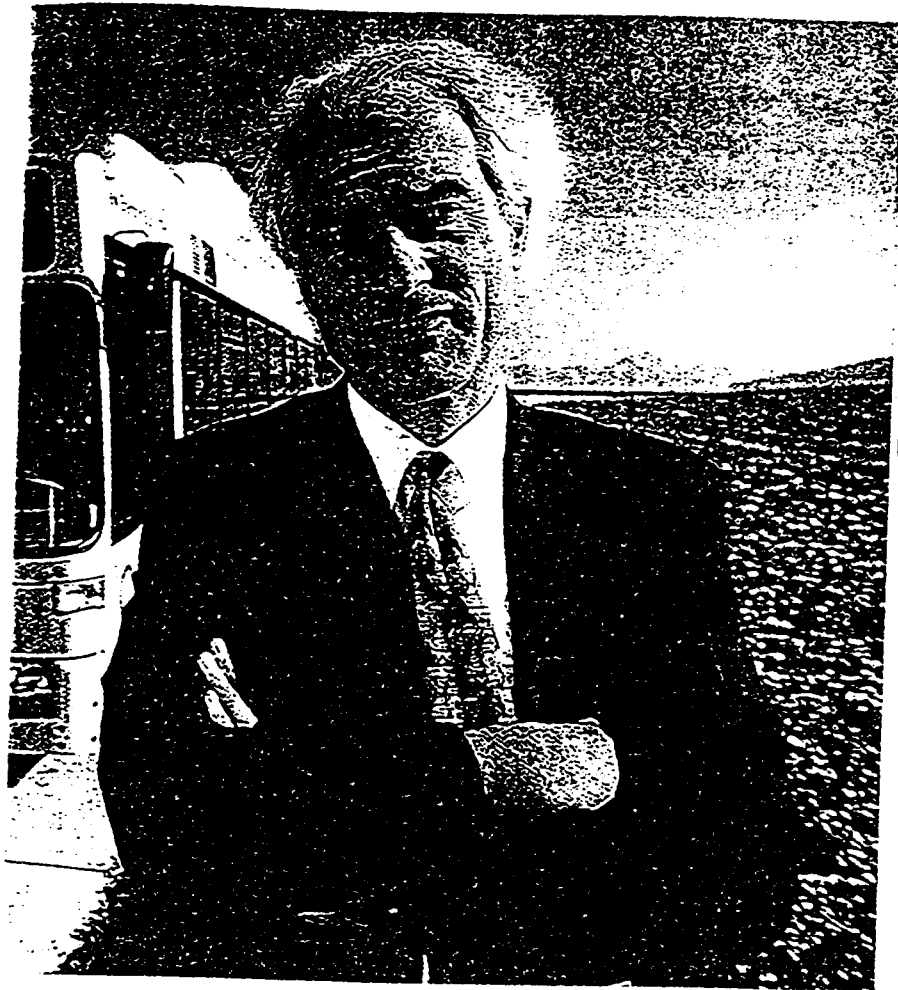
THE AUTOMAKERS' BIG-TIME BET ON

FUEL CELLS

BY STUART F. BROWN



The latest Mercedes fuel-cell test car makes its way on a road test.



THOMAS PANIK—DAIMLER

Dr. Panik, who runs Daimler-Benz's fuel-cell program, foresees cleaner, fuel-saving buses and cars whose power plants have fewer parts than today's piston engines.

automakers are confident they can pull off the remaining development work and apply the needed mass-production wizardry. Panik, a senior VP who has been running Daimler-Benz's fuel-cell effort full-time for the past year, says he has few doubts on that score. He foresees power sources with far fewer moving parts than today's engines. Says Panik: "In the end I believe the fuel cell can be done for the same price as the piston engine, or lower. And I believe it can let the owner travel 50% farther for the fuel used, with an engine that will be truly maintenance-free."

It will also pollute less, auto folks point out. They're hoping that fuel-cell cars will be an acceptable alternative in jurisdictions like California that have mandated that substantial numbers of "zero-emissions vehicles" be available early in the next century. And carmakers are confident that fuel-cell cars will outperform other environment-friendly vehicles—the battery cars and battery-piston hybrids that are already in limited production.

Daimler is so stoked about the fuel-cell drive train that it plans to have production versions of the Nebus coming off an assembly line in 2004. Even more eye-popping is the company's goal of having fuel-cell cars in sale that same year. That will require an

extra set of solutions. The Nebus is fueled by compressed hydrogen carried in roof-mounted tanks. That's okay for bus fleets that return to a central garage for refueling. But the family flivver will need to run on a liquid fuel, such as gasoline or methanol, dispensed at ubiquitous filling stations. To do this the car will need a micro-chemical plant onboard capable of extracting hydrogen from the fuel as it rolls along. We're working on that too, say Panik and his colleagues as they escort a visitor to a demonstration model of a fuel-cell car, the methanol-powered Nekar E, which has already logged time on the road.

The Nekar E, along with the Nebus, is one of four demonstration fuel-cell vehicles that Daimler-Benz has engineered and put on the road in just three busy years. The largest such collection any motor company is known to have, it underscores the seriousness of Daimler-Benz—one of whose founders in 1888 invented the first automobile—as it proclaims its goal of being the first auto company to mass-market the piston engine's successor.

Daimler-Benz teamed up with other companies late last year to join its partnership with Ballard Power Systems of Vancouver, B.C., which has done some of the most impressive work in improving

fuel cells. The three-company alliance will develop and build fuel-cell "engines" and power trains, which the automakers will use in their own vehicles and sell to other car companies. Ford's commitment of \$430 million to the alliance comes on top of the \$320 million Daimler has already allocated to its longer-running partnership with Ballard. "We want to be leaders in bringing these fuel-cell vehicles out," says Gary Heffernan, Ford's corporate technology manager.

Not to be left behind, other carmakers and technology companies have large-scale development programs under way:

- General Motors has a fuel-cell program "at least as big as" its research into hybrid and battery-electric cars, says Byron McCormick, executive director for global alternative propulsion. He won't cite a number but says that the program represents "significant dollars." He adds, "We are totally serious. The fuel cell is so compelling because of its enhanced efficiency and low pollution that we just have to go after this aggressively."

- Toyota, which already sells a hybrid car in Japan, has a development program under way there that's estimated by outsiders to involve some 200 researchers. Last year at two major auto shows, the company exhibited a version of its RAV4 sport-utility vehicle, equipped with a demonstration fuel-cell electric power train of its own design.

- International Fuel Cells, part of United Technologies' Hamilton Standard unit, is launching a venture to commercialize fuel cells for cars. Already a builder of fuel-cell systems for the space shuttle and for stationary power generation, IFC has 60 people in its automotive program and will soon add more.

Today's car engines are inefficient because they are subject to unyielding thermodynamic limits first described in 1824 by French scientist Sadi Carnot. A fuel-cell power train has no such limits and is theoretically 1.5 times as efficient as its piston-engine counterpart.

Daimler's experimental vehicles use fuel-cell stacks supplied by Ballard, which began working with the automaker in

BALLARD

Source

The Globe & Mail

Date

March 18, 1998

Ballard blasts to new high

\$3.6-million GM contract boosts stock \$17.25 to \$182.25

BY CAROLYN LEITCH
Investment Reporter

Shares of Ballard Power Systems Inc. rocketed ahead \$17.25 to a new 52-week high of \$182.25 yesterday after the company announced that it had won a \$3.6-million contract from General Motors Corp.

The shares of the fuel cell maker have now gained 75 per cent in about five weeks on the Toronto Stock Exchange. During yesterday's session they climbed as high as \$188 before settling back.

Ballard, based in Burnaby, B.C., said GM will use the fuel cells developed by Ballard for re-

search into developing an electric car. Ballard will also provide equipment and services.

Yesterday's surge put Ballard's market capitalization at a dizzying \$4.2-billion, despite the fact that the company is not expected to generate significant revenue for years. Market watchers have speculated that investors are itching for Ballard to announce a lucrative contract.

GM has been buying Ballard's fuel cells since 1991. Is this relatively modest sale to an existing customer the news the market has been anticipating?

"I have no idea," said analyst David Dvorchik of Taurus Capital Markets Ltd. in Toronto. "I

would think that there is a whole slew of similar-type deals that the company is negotiating."

Analyst Robert Chewning at Morgan Stanley Dean Witter in New York is also baffled by the runup.

He said the market may be looking for significance in the fact that GM, which has been engaged in its own research into fuel cell technology, is now turning to Ballard.

"The fact they they are coming to Ballard and ordering a fuel cell — what do people read into that? It may indicate that they're behind in their own development."

Please see *Ballard* / B4

• From Page B1

He added that while the contract is "not the biggest, not the smallest," that Ballard has received, it can be viewed as another endorsement from a major car maker.

Mr. Chewning also believes the attention focused on the company helps to fuel the stock's rise. "Obviously this has attracted a lot of the media. It's a self-fulfilling prophecy."

Mr. Chewning calls Ballard "a very tough company to value." He downgraded the stock to "neutral" from "outperform" earlier this month.

Mr. Dvorchik of Taurus also believes that the market may read the small contract from the world's largest auto maker as a harbinger of things to come.

Auto makers are racing to develop alternatives to the traditional internal

combustion engine. Ballard's proprietary fuel cell produces electricity without combustion. The technology is favoured as a way to cut emissions and pollution.

"GM is a large company and obviously doesn't want to be left out of the loop," Mr. Dvorchik said.

But he points out that the purchase of some technology is not as significant as taking an equity stake in Ballard, as both Ford Motor Co. and Daimler-Benz AG have done.

Ford owns 15 per cent of Ballard and Daimler-Benz owns another 20 per cent. That partnership is aiming to introduce a fuel-cell-powered vehicle in 2004.

Earlier this month, Mobil Corp. said it had joined this alliance on projects that include alternative fuel vehicles.

BALLARD

Source

The Globe & Mail

Date

March 6, 1998

Ford-Mobil alliance includes Ballard project

But B.C. company's stock drops as analyst cuts recommendation

BY GREG KEENAN
Auto Industry Reporter

An automotive and an energy giant are hooking up to develop new fuels and engine technology, including advances aimed at making the fuel cells developed by Ballard Power Systems Inc. commercially possible.

Ford Motor Co. and Mobil Corp. said they formed a strategic alliance to work on short-term, medium-term and long-term projects, including improving fuel and engine technology and creating a wider market for alternative fuel vehicles.

"The longer-term project focuses on the technology needed to develop a commercially viable compact fuel process for fuel cell powered vehicles," the companies said in a joint news release.

Ford owns 15 per cent of Ballard, a fuel cell maker that has been a stock market rocket for the past 18 months. Daimler-Benz AG of Germany owns another 20 per cent of the Burnaby, B.C.-based company.

"This is an extension of our partnership" with Ballard and Daimler-Benz, Bradford Bates, Ford's manager of alternative power source technology, said during a conference call about the deal.

He said the partnership is aiming for introduction of a fuel cell powered vehicle in 2004.

"That's a very aggressive time schedule."

But he cautioned yesterday that the companies "have just really started down the path" toward a commercially feasible fuel processor. "I couldn't say that we're close at all."

The fuel processor would convert gasoline or diesel to hydrogen, which in turn would be converted by the fuel cell to electric power to run an engine in a family-sized sedan.

Developing such a processor would eliminate a key roadblock in the way of fuel cells because it would not entail the creation of a new fuel infrastructure. Without such a processor, a new fuel infrastructure would be required and cars might have to carry a large hydrogen tank.

In the Ford-Daimler-Ballard partnership, Ballard is responsible for developing the fuel cell that converts the hydrogen to electricity to power the engine.

While the issue of what fuel will be in fuel cell powered cars has been one roadblock, another has been the cost of the devices themselves, since the world's auto makers insist that consumers won't pay more than current prices even if the environment will be better off.

Ballard and its partners are still working on that aspect.

The investments made by Ford and Daimler in Ballard last year powered the company's stock well past the \$100 mark on the Toronto Stock Ex-

change to a 52-week high of \$141.25.

The shares took a plunge yesterday, however, after the company was downgraded to "neutral" from "outperform" by analyst Robert Chewning at Morgan Stanley Dean Witter in New York. The share price fell \$7.60 to \$130.90 in trading on the TSE. Volume was 171,000 shares.

Mr. Chewning said he changed his rating on the stock before the Mobil-Ford alliance was announced and he downgraded it because the stock has risen so high.

"This stock was up 57 per cent above the level it was at when the Ford deal was announced," he said.

The Mobil-Ford deal is positive news, he added. "Clearly one of the issues has been the distribution infrastructure for the fuel and this may be the solution."

Mobil and Ford will spend tens of millions of dollars on the projects, company officials said during the conference call.

The medium-term project is a direct-injection diesel system, which would reduced carbon dioxide emissions, but would have no impact on range, reliability or affordability, Ford chairman Alexander Trotman said in the statement.

The short-term project is figuring out why there aren't more alternative fuel vehicles on the road now and what Ford and Mobil can do about it.

BALLARD

Source

Business Week

Date

March 2, 1998

Science & Technology

AUTOMOBILES

DETROIT'S IMPOSSIBLE DREAM?

Fuel-cell cars on the road by 2004—that's the promise. Now it's crunch time

Two years ago, Bradford B. Bates of Ford Motor Co. predicted he wouldn't live to see cars powered by the space-age devices that are his passion—fuel cells—because that would be three decades in the future. Now Bates, who's 60 and a key fuel-cell researcher at Ford, says he expects to be able to purchase an electric car powered by the devices "before I give up driving." Indeed, he's now striving to fulfill Ford's promise to put a fuel-cell car on the road by 2004. Quips Bates: "I never apologize for being smarter today than I was yesterday."

Propelled by political and competitive pressures, Detroit has made an amazing conversion to environmentalism. Until now, the auto industry has been an environmental bad guy, lobbying fiercely against any treaty that would limit auto emissions in an effort to mitigate global warming. Now, barely a week goes by without one of the Big Three announcing an initiative to tackle global warming or reduce dependence on fossil fuels.

Most startling of all, though, is the pledge to bring out fuel-cell cars by the middle of the next decade. Suddenly the fuel cell, once found only on NASA spacecraft, has become Detroit's pet project for "going green."

Fuel-cell cars would appear to be the perfect antidote to today's ozone-depleting, smog-making vehicles. Through a chemical reaction between hydrogen and oxygen, fuel cells generate the juice to power an electric motor—and the only emission out the tailpipe is a trickle of water. The technology is even ahead of current electric cars, with their limited-range batteries and long recharging times. With fuel cells, drivers would "recharge" by filling up at the same ser-

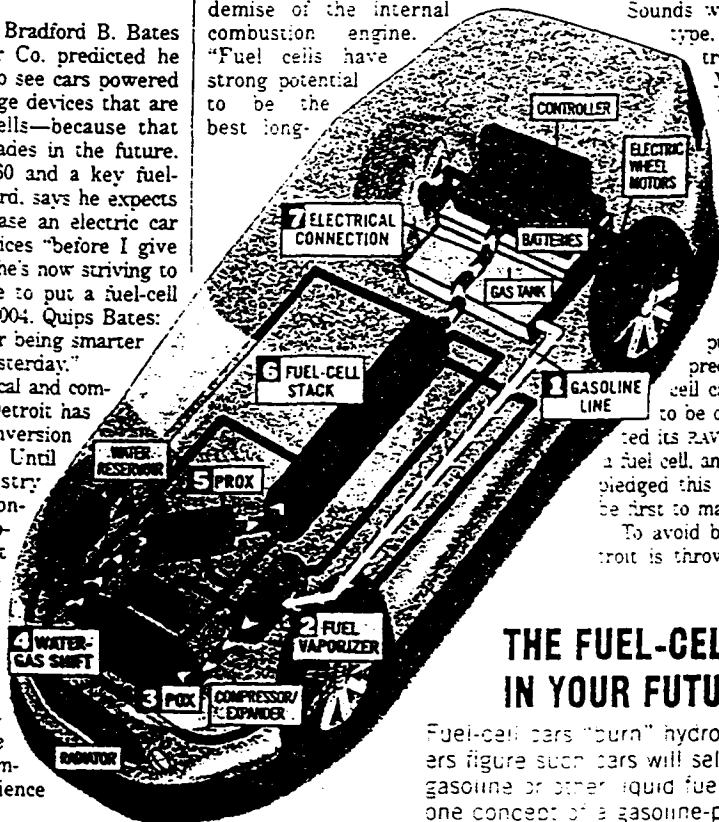
vice station they've always used. That's because new technology can extract hydrogen gas from liquid fuels.

As a result, even Detroiters are predicting what was once unthinkable: the demise of the internal combustion engine. "Fuel cells have strong potential to be the best long-

term solution," says General Motors Vice-Chairman Harry J. Pearce. "Our fuel-cell test vehicle gets 80 miles per gallon and has a driving range of 300 miles."

Sounds wonderful. But GM's prototype, like all the others in Detroit, hasn't left the lab yet. Mercedes-Benz and Toyota Motor Corp. have actually rolled out operational fuel-cell vehicles—but they're not yet for sale. Mercedes showed a tiny A-class car in September with a backseat and trunk stuffed with the various high-tech gizmos. The company is aggressively pursuing the technology and predicts it will sell 40,000 fuel-cell cars annually by 2006. Not to be outdone, Toyota has outfitted its RAV4 sport-utility vehicle with a fuel cell, and President Hiroshi Okuda pledged this month that Toyota would be first to market such a car.

To avoid being left in the dust, Detroit is throwing hundreds of millions



THE FUEL-CELL CAR IN YOUR FUTURE

Fuel-cell cars "burn" hydrogen, but auto makers figure such cars will sell only if they run on gasoline or other liquid fuel. Here's a look at one concept of a gasoline-powered fuel-cell car:

- 1 GASOLINE LINE Feeds liquid fuel from the tank to the fuel vaporizer.
- 2 FUEL VAPORIZER Heats gasoline to convert the liquid to gases.
- 3 POX The partial oxidation reactor combines gasoline vapors with air, producing hydrogen and carbon monoxide.
- 4 WATER-GAS SHIFT Steam acts as a catalyst to convert most of the carbon monoxide to carbon dioxide and additional hydrogen.
- 5 PROX The preferential oxidation unit injects air to convert the remaining carbon monoxide into carbon dioxide, leaving hydrogen-rich gases.
- 6 FUEL-CELL STACK Hydrogen gas is chemically combined with oxygen, producing electricity for the motors that propel the car.
- 7 ELECTRICAL CONNECTION Carries electricity from the electric motors that make the wheels spin. Also, a thicker metal bar, the battery, stores the car initially until the fuel-processor system warms up.

DATA: ARTHUR D. LITTLE; CHRYSLER CORP.

Science & Technology

at fuel-cell technology. Ford is investing \$420 million to join with Mercedes and fuel-cell supplier Ballard Power Systems Inc. in Vancouver, B.C. Chrysler Corp. has hooked up with GM's Delphi unit, an auto-parts supplier, and expects to be cranking out 200,000 fuel-cell cars by 2010. And GM is reassigning legions of engineers to fuel-cell development and boosting their budget, according to company officials. "As the heat turns up, the dollars come in," says Andrew J. Farah, GM's engineering manager of battery systems.

SAFETY QUALMS. Yet despite the influx of cash and talent, the auto makers face daunting technical challenges to meet their new deadlines. "Our target to commercialize these vehicles by 2004 has a lot of risk," admits John R. Wallace, Ford's director of alternative-fuel vehicle programs. Bates puts it bluntly: "We don't know how to get there."

Cost is the biggest roadblock. If a Ford Taurus were outfitted with a fuel cell today, its sticker price could soar to \$200,000, says Ford Chairman Alexander J. Trotman. That's because an electric car needs about 80 kilowatts of power for acceptable performance. With fuel cells, the per-kilowatt cost now stands at roughly \$250. So just the fuel cell would run \$20,000. Add on the tab for several other expensive elements (illustration, page 66), and a fuel-cell car is 10 times more costly. The per-kilowatt cost hasn't changed for two years. So why the new optimism? Detroit now expects it can slash costs to \$25 per kilowatt, from the previous target of \$35, says Bates. For now, though, that's just a dream. "It's amazing how the hurdles get higher," says Ballard Power Chief Financial Officer Mossadiq S. Umedaly.

Still, there has been substantial progress. Ten years ago, a fuel-cell vehicle would have cost \$20 million—and only a city bus could have accommodated those hulking devices. Engineers have since shrunk the size needed for a car to something on the order of a suitcase. And the costly materials used in fuel cells are being replaced or the quantity needed is being reduced. For example, the cost of platinum used as a catalyst on the electrodes of an 80-kw fuel cell has dropped from \$33,000 in 1984 to \$500 or less. Projecting these trends forward, Umedaly says that by 2008, when Ballard expects to be producing 250,000 fuel cells annually, they'll cost no more than a traditional engine.

As fuel-cell costs have come down, however, another obstacle has risen: the need for an onboard fuel "refinery" to

extract hydrogen from a liquid fuel. Selling consumers on the safety of modern techniques for storing hydrogen gas could take longer than perfecting an economical fuel-cell car. "Most of us remember the Hindenburg," says GM's Pearce. Besides, nobody wants to mount a torpedo-like storage tank on a car's roof. Finally, there are no hydrogen filling stations now—and building the infrastructure for distributing hydrogen to corner service stations would take billions of dollars.

That's why auto makers plan to run fuel cells on methanol or gasoline, using

The environment takes a hit with the ADL approach, though. Extracting hydrogen from methanol or gasoline produces carbon dioxide as a by-product—although only a fraction of the CO₂ that combustion produces. "The fuel cell has great potential, but it's certainly not the solution to global warming," says David E. Cole, director of the University of Michigan's Office for the Study of Automotive Transportation.

Another problem: It takes 10 minutes to warm up a fuel processor. Until then, the car must run on a 500-pound nickel-metal-hydride battery, which now



Ten years ago, a fuel-cell car would have cost \$20 million. Now, it's \$200,000 and dropping

GM SHOWS OFF ITS TECHNOLOGY AT THE CHICAGO AUTO SHOW

a so-called fuel processor to tap the hydrogen contained in the liquid. But these minirefineries are in their infancy—"at the stage that fuel cells were 5 or 10 years ago," says Christopher E. Barroni-Bird, Chrysler's head fuel-cell researcher.

Pulling hydrogen from gasoline was first demonstrated last October. The processor was developed by Arthur D. Little Inc. (ADL) of Cambridge, Mass., in conjunction with the Energy Dept., and plans to announce on Feb. 24 the formation of a company, Epyx Corp., to sell the processor, which can also run hydrogen from methanol and ethanol, a corn-based fuel. "There used to be tremendous scorn for our technology," says Jeffrey M. Bentley, vice president and technology director at ADL. "Now we get board-level attention."

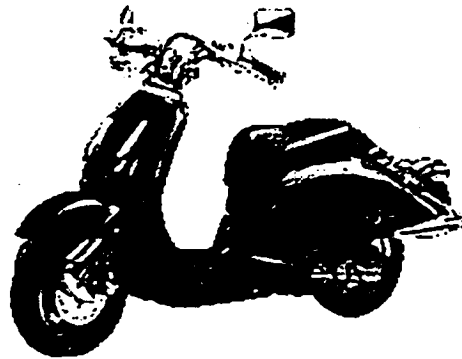
costs \$20,000. "That's completely unacceptable," says Barroni-Bird. "We need it to be less than one minute" to shrink the heft and cost of the battery.

PROMISES, PROMISES. Other pieces of the fuel-cell puzzle are falling into place. Impressive progress has been made in developing transmissions, for instance. While consumers haven't flocked to battery-powered cars, the R&D that went into them helped Detroit cut the cost and improve the reliability of the motors and generators. Insiders say that GM, thanks to its EVI electric car, has an edge in electronic controllers, which coordinate all the high-voltage operations of the drive system. By 2000, these sources expect GM to have an electric transmission equal in cost to a traditional automatic transmission.

Still, researchers may have trouble keeping up with the public-relations machine. Already, engineers are looking for wiggle room in the pronouncements by senior managers. Even Ford's Bates has a hard time accepting the newfound optimism. "We really have no confidence these things will completely deliver on their promise," he admits. "But the promise is a great, powerful, and very profitable one." It risks sending the German and Japanese auto makers into a

By John Nagtegaal

Fuel Cell Performance and Application Criteria



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Fuel Considerations

PEM fuel cells are designed to run on high purity sources of hydrogen. Advances in the storage of hydrogen have not kept pace with the progress of fuel cell performance. The leading contenders for hydrogen storage are compressed gas, cryogenic storage, and metal hydride storage. Recent failures of ultra-lightweight compressed gas cylinders (those with plastic liners rather than aluminum) have raised serious suspicion about their long term safety. Cryogenic storage works well for large systems, but the complexity and cost of developing a cryo-infrastructure has limited the seriousness of this approach. Hydrides have been slowly improving over the past few years and promise to offer high density, premiere safety, and a reasonable cost. More experimental storage techniques such as nano-tubules, nanofibers, or micro-spheres may prove to provide superior fuel storage in the future, but need more research efforts to develop commercially. As such, considerable research is being done in reforming more traditional fuels such as gasoline, diesel, methanol, ethanol, propane, and natural gas. Direct comparison of the alternative fuels is complicated by the uniqueness of the required storage vessels. Table 3 lists the physical and thermodynamic properties of each fuel and specifies the effect of the fuel container as a fraction of the fuel system mass. For simplicity, the volume of the fuel container is assumed to be equal to the volume of fuel it contains (no wall thickness). This assumption is excellent for liquid fuels, and over-estimates the specific energy for gases and cryogenic vessels.

Fuel Name	Fuel Density KG/L	LHV KWH/KG	Container Wt fraction decimal	Comb Density KG/L	EQ Specific Energy KWH /L	EQ Energy Density KWH /KG
H2 gas 2200 psig	0.012	33.25	0.96	0.0005	0.02	1.33
H2 gas 3500 psig	0.019	33.25	0.944	0.0011	0.04	1.86
H2 cryogenic liq	0.071	33.25	0.85	0.0106	0.35	4.98
H2 1.5% Ni hydride	0.120	33.25	0.985	0.0018	0.06	0.50
H2 micro-spheres	0.025	33.25	0.90	0.0025	0.08	3.33
Methane 3500 psig	0.155	13.80	0.48	0.0806	1.11	7.18
Propane liq / vap	0.585	12.80	0.35	0.3804	4.87	8.32
Methanol liq	0.791	7.39	0.1	0.7123	5.26	6.65
Gasoline liq	0.703	12.34	0.1	0.6323	7.80	11.11
Ethanol liq	0.787	9.29	0.1	0.7086	6.58	8.36
Diesel liq	0.749	12.25	0.1	0.6738	8.26	11.03

Table 3. Properties of alternative fuels and storage

Entries in Table 3 are arrived at as follows (left to right): Fuel densities have been calculated at standard conditions for each fuel (gas, liq, etc). The enthalpy of reaction has been calculated from the lower heating values of each fuel as listed in the CRC handbook [2]. The container weight fractions have been gathered from vendor data on exotic containers and guessed at 10% for metal fuel tanks. The combinational density has been calculated by adding the container mass fraction with no additional assumed volume. The equivalent specific energy is the fuel enthalpy multiplied by the combinational density. The equivalent energy density is the fuel enthalpy multiplied by the expression $(1-Wt)$ as listed in the table.

Table 3 identifies that hydrogen has potential as a compact fuel but currently suffers from lack of storage density. Recent studies of hydrogen storage by nanofibers and other carbon structures claim to provide an energy storage as high as 65% by mass fraction. If these technologies can be proven and made consumer safe, energy densities for pure hydrogen storage will leap to >20 KWH's per Kg. This will push the effective driving range of automobiles over 300 miles per fueling. Achieving this energy storage density with hydrogen will signify the beginning of the end of the fossil fuel era. Until then energy storage density among the traditional fuels will overshadow hydrogen as traditional fuels range from 5 to 10 times the densities of commercially available hydrogen storage.

On-Board Fuel Reforming

Table 3 clearly illustrates that many fuel cell applications in the near term may require on-board fuel reformation (the automobile among them). On-board fuel reformation will diminish the energy density of the fuel in much the same way as spatial and parasitic losses reduce the performance of the fuel cell. The reformation process requires high quality heat (heat at a high temperature) to maintain the conditions required for the reformation process. This heat must come from sacrificing a portion of the fuel as a feed stock. This fuel is sent into a catalytic burner to keep the temperature above some critical level. The reformer itself is highly insulated to prevent heat from escaping unnecessarily. Typically, 15 to 25% of the fuel fed through the reformer is sacrificed. Another portion of the exiting fuel is consumed by the purification process that eliminates impurities (namely CO and desulfurization) in the hydrogen stream. A typical overall reformer efficiency is between 60 and 70%. Reformer technology (especially small-scale reforming) is still in its infancy, such that 70% will come to be an easily obtainable mark in upcoming years. As such, 70% is used as the efficiency in upcoming energy calculations.

The significance of the reformer efficiency is that it reduces the effective energy content of all fuels in Table 3 except for pure hydrogen. In this respect hydrogen nudges 30% closer to the performance of traditional fuels on this basis alone. When comparing fuel use through a fuel cell against use in a combustion engine, all fuels receive an effective benefit because of an overall increased efficiency. A fuel cell operating at 45% net efficiency and reforming fuel with 70% efficiency will provide an overall thermodynamic system efficiency of 32%. This is significantly higher than most two-cycle engines operating dynamically. The assumed efficiency for two-cycle IC engines is 16%. This suggests a new scale of fuel comparison based on what is attained through normal combustion of gasoline. Multiplying ϵ and γ in table 3 by the overall efficiency of 32% and dividing the entries by the equivalent energetic content of burned gasoline (15% efficiency) provides for a comparison of alternative fuels normalized to gasoline combustion. Note that diesel combustion can be as high as 25% efficiency. The entry in Figure 6 for diesel (dodecane) is with respect to gasoline combustion, not to diesel combustion. Plotting diesel against its own combustion would show efficiency improvements of approximately 30% (1.3 in Figure 6).

Fuel Cell Use of Reformed Fuels

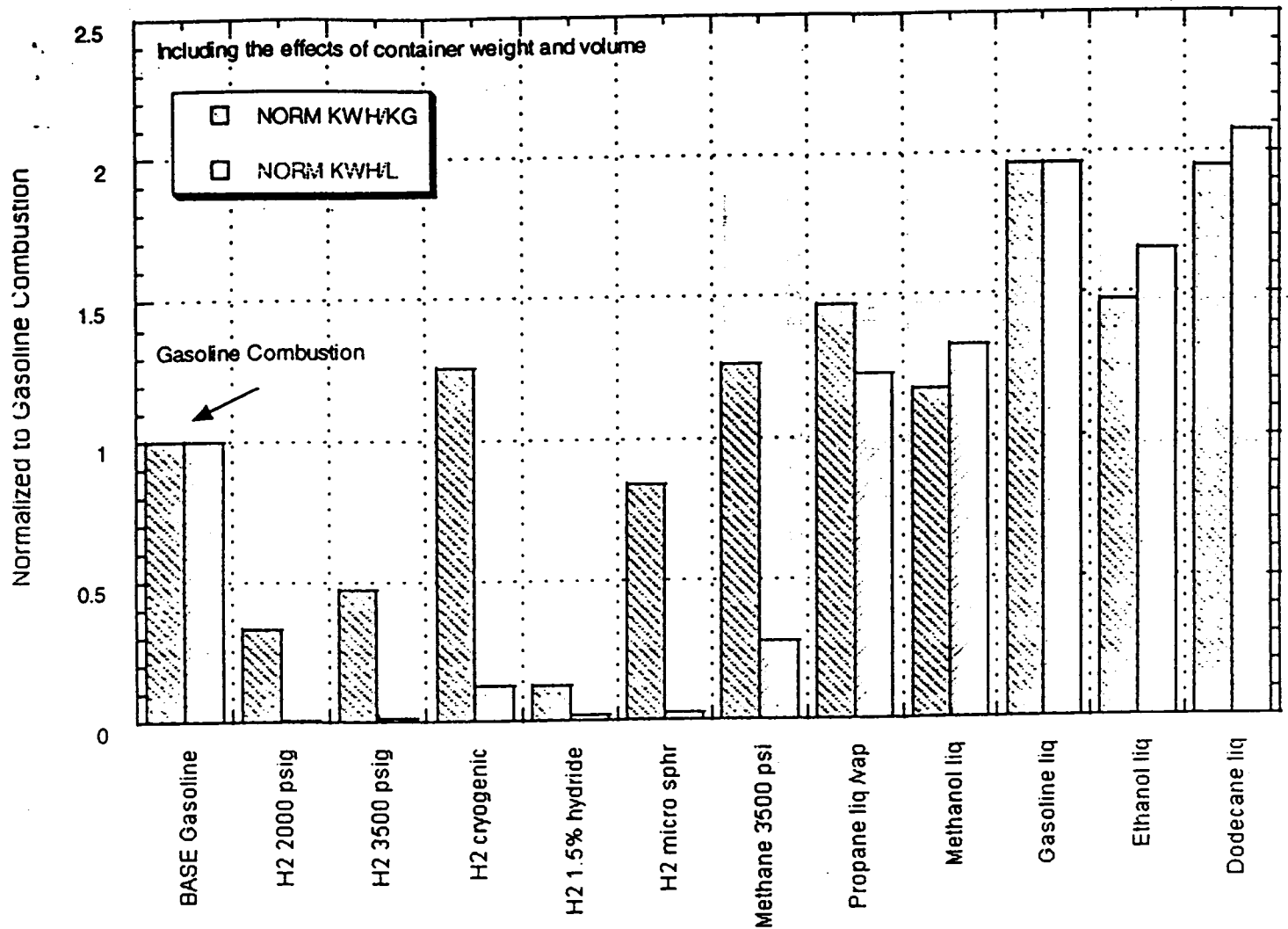


Figure 6. Relative Net Energy obtained from Alternative Fuels in a Fuel Cell

Figure 6 shows that reforming gasoline and diesel for use in fuel cells will offer far superior economy to gasoline combustion while propane, ethanol, and methanol will provide slightly better fuel economy based on the analysis so far. Direct hydrogen storage will have difficulty finding its home in applications that are volume critical given current storage technologies.

In addition to the efficiency losses suffered by reformation, there are spatial penalties to consider as well. The physical size of the reformer will be significant for a good number of would-be applications. For the sake of modeling, the reformer power density will be expressed as a multiple of the fuel cell power density (remembering that the two are sized together proportionately). The make up of a reformer will be similar to that of a fuel cell (plates and tubes) but is likely to have a higher material density (mostly metallic). The reformer characteristics will be chosen to be about 250% the power density of the modern

fuel cell with respect to mass and 350% the power density with respect to volume. These scales lead to assigned figures of merit of $\epsilon = 2.5 \text{ KW /KG}$ and $\gamma = 5.0 \text{ KW /L}$ respectively and will represent a good near-term target for industry. To reflect the generality of the selected reformer parameters, the reformer size is modeled as a constant with respect to reformer capacity (as opposed to the detailed technique by which the fuel cell size was modeled).

It is apparent that the relative spatial penalty of the reformer goes down as the amount of fuel carried goes up. For example the physical size and weight of a 1KW reformer (a reformer that passes enough fuel to support a 1 KW net fuel cell) in an application carrying a month's fuel supply will be an insignificant portion of the system size. Conversely, the same reformer in an application carrying 30 minutes worth of fuel will dominate the size and weight of the fuel system. To incorporate this concept into the performance parameters of replacing IC engines, fuel storage will be defined in terms of hours of operation (stored fuel energy divided by application power). Figure 7 illustrates the relationship between the size and weight of the reformer and the amount of fuel storage for gasoline.

Spatial Penalties of On-Board Gasoline Reforming

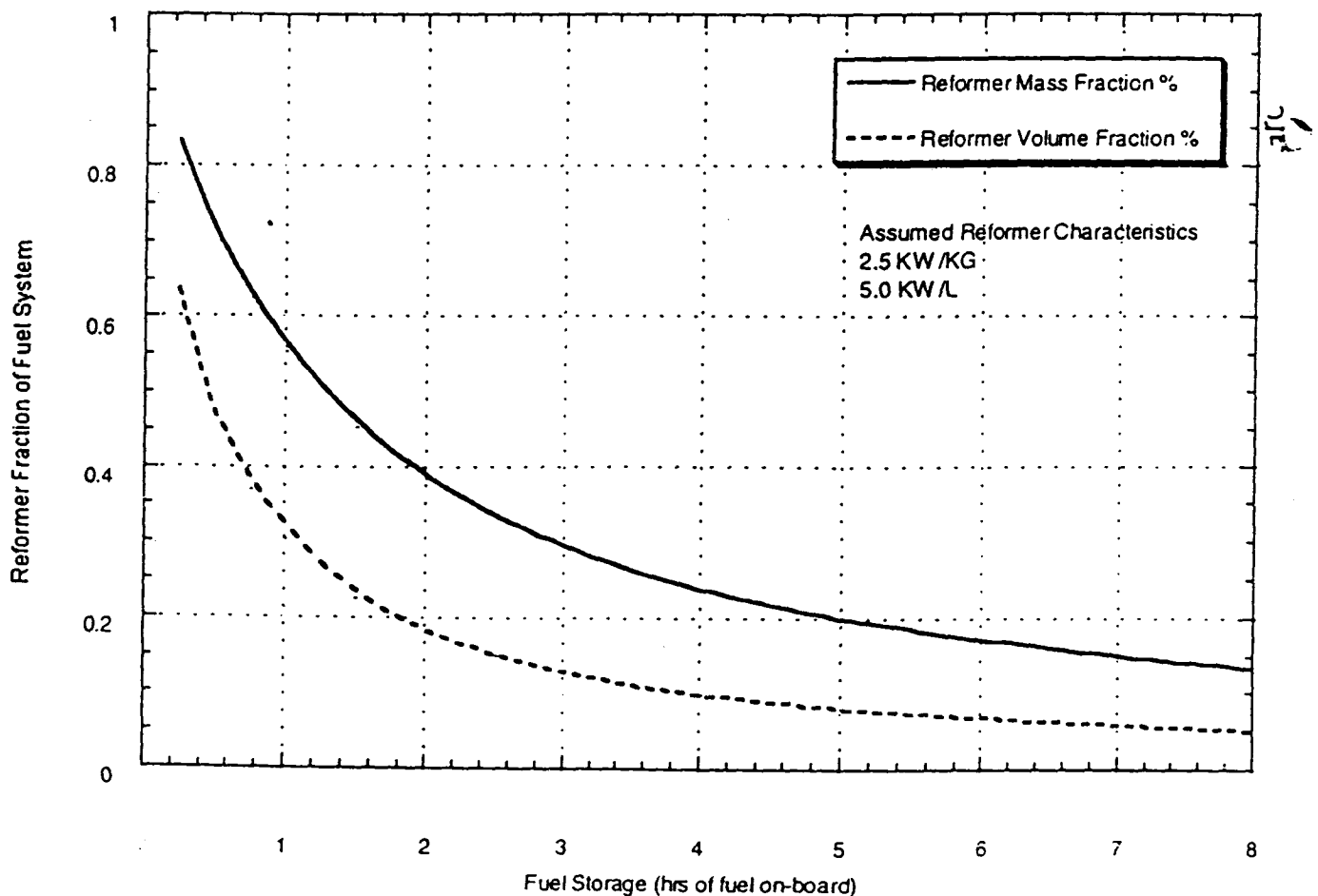


Figure 7. Spatial penalties of on-board gasoline reforming



