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SAVANNAH RIVER BUS PROJECT

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Abstract

The H2Fuel Bus is the world's first hybrid hydrogen electric transit bus. It was developed through a public/private partnership involving several leading technology and industrial organizations in the Southeast, with primary funding and program management provided by the Department of Energy. The primary goals of the project are to gain valuable information on the technical readiness and economic viability of hydrogen buses and to enhance the public awareness and acceptance of emerging hydrogen technologies. The bus has been operated by the transit agency in Augusta, Georgia since April, 1997. It employs a hybrid IC engine/battery/electric drive system, with onboard hydrogen fuel storage based on the use of metal hydrides. Initial operating results have demonstrated an overall energy efficiency (miles per Btu) of twice that of a similar diesel-fueled bus and an operating range twice that of an all-battery powered electric bus. Tailpipe emissions are negligible, with NOx less than 0.2 ppm. Permitting, liability and insurance issues were addressed on the basis of extensive risk assessment and safety analyses, with the inherent safety characteristic of metal hydride storage playing a major role in minimizing these concerns. Future plans for the bus include continued transit operation and use as a national testbed, with potential modifications to demonstrate other hydrogen technologies, including fuel cells.

Introduction

The Savannah River Bus Project involves the development, manufacture and testing of the world's first hybrid hydrogen electric transit bus, known as the H2Fuel Bus. The project seeks to successfully transfer technologies developed at the Department of Energy (DOE) Savannah River Site (Aiken, South Carolina) for defense applications to commercial use in a public transit bus. The project is a technology verification activity that seeks to establish the technical feasibility, economic viability, and environmental benefits of hydrogen as a transportation fuel. Solution of hydrogen infrastructure issues (e.g. refueling, liability, safety, etc.) and the public awareness and public acceptance of hydrogen as a vehicular fuel are additional objectives. The H2Fuel Bus was developed through a partnership between federal and local government, universities, non-profits, and industry. The majority of the funding for the project was provided by the DOE Savannah River Operations Office (70%) and the DOE-EE Hydrogen Program Office (15%). The H2Fuel Bus is a 33-foot transit bus which will be operated in regular passenger service in the city of

Augusta/Richmond County, Georgia. The primary goals of the project are to gain valuable information on the technical readiness and economic viability of hydrogen buses and to enhance the public awareness and acceptance of emerging hydrogen technologies.

Discussion

The bus employs a hybrid internal combustion engine/electric drive propulsion system. Fuel is supplied to the engine by using waste heat to release hydrogen from a metal hydride storage system. The use of inherently safe metal hydride storage overcomes public concerns about hydrogen safety. Initial operating results indicate an overall energy efficiency equivalent to 7.5 to 9.0 miles per gallon. This is more than twice that of a similar bus with a diesel engine, and it equals or exceeds projected goals for current hydrogen fuel cell buses, such as those being deployed in Chicago. The tailpipe emission levels of nitrogen oxides (NOx) are some of the lowest ever measured for an internal combustion engine. Preliminary results indicate NOx emissions of less than 0.2 ppm, which is below the Los Angeles ambient air quality standard for a first-level alert.

The bus has undergone extensive testing and is expected to enter regular transit service in the Spring of 1998. Funding from the Department of Energy Office of Energy Efficiency and Renewable Energy during Fiscal Year 1998 provides for test operations and data collection/analysis, including ongoing technical support, specialized maintenance, and hydrogen fuel costs in excess of conventional diesel fuel costs. Continued bus operation provides valuable additional data on the hydrogen system reliability, operating and maintenance requirements, long-term performance, economics and customer acceptance. This information is essential in order to determine the commercial potential of the technology and to attract continued private industry participation. Public transit operation also provides opportunities to inform the general public and to gain broader public acceptance and support for hydrogen as an alternative fuel.

Technical Goals

The Savannah River Bus Project set out to achieve the following technical goals:

- Maintain a Gross Vehicle Weight Rating of 33,000 pounds while integrating a hydrogen engine/generator set and metal hydride storage system into a standard battery-electric transit bus (Note: It was important not to exceed the GVWR to which the electric bus had been certified by the manufacturer).
- Have speed and acceleration characteristics equal to or better than a diesel bus
- Achieve a fuel energy efficiency of two times that of an equivalent diesel-fueled bus
- Achieve an operating range in excess of 100 miles between refuelings (twice that of an equivalent battery-powered bus)
- Achieve negligible tailpipe emissions
- Satisfy all insurance liability, regulatory, safety and licensing requirements
- Operate the bus in regular passenger service
- Demonstrate economic viability based on projected costs for mass produced unit

Major Barriers to Meeting Technical Goals

The H2Fuel Bus is the first hybrid hydrogen electric bus. It also employs the largest mobile metal hydride bed ever installed on a vehicle. Furthermore, the H2Fuel Bus was designed to be operated in regular transit service by normal bus drivers and maintenance personnel. These goals required the project to overcome several major barriers, including the following:

- Weight, physical stability, chemical resistance and thermal conductivity for metal hydride powders
- Compact, durable, and cost-effective metal hydride storage container requirements
- Minimization of NOx emissions from hydrogen internal combustion engine
- Integration of IC engine/gen set with existing battery electric drive system
- Infrastructure issues including refueling, insurance, permitting, public acceptance
- Current high cost of metal hydrides and first-of-a-kind vehicle

Approach/Background:

In order to achieve the stated technical goals and overcome the perceived major barriers, the following design approach was selected:

- Select state-of-the-art electric bus compatible with partial battery replacement (Blue Bird Electric Q-Bus)
- Employ a series hybrid internal combustion engine/electric design arrangement
- Utilize well-tested metal hydride materials based on defense experience (LaNi5)
- Design improved storage device (SRS-patented aluminum foam tubular design)
- Utilize extensive exhaust gas recirculation and constant volume injection engine design to minimize exhaust emissions
- Establish broad-based partnership to address infrastructure and cost issues

The hybrid ICE/electric design approach allowed the bus to be constructed using an architecture that is fully-compatible with future fuel cell power designs, but avoided the near-term developmental and cost issues associated with current fuel cell technology. As fuel cells become commercially available, a power train consisting of a "fuel cell engine" in place of the internal combustion engine could be adapted. The fuel storage, electric drive power train, auxiliary battery system, and many other bus components and systems would remain as demonstrated on the H2Fuel Bus.

Partners and Responsibilities

The H2Fuel Bus project was performed by an extensive public/private partnership involving several leading technology and industrial organizations, mostly located in the Southeastern United States. Partners and their major roles in the project were as follows:

- Department of Energy — Project sponsor
- Westinghouse Savannah River Company — Prime contractor, metal hydride storage system, technical and safety analysis
- Southeastern Technology Center — Project management, public awareness/involvement services
- Georgia Tech Research Institute — Hybrid bus design, integration and testing
- Augusta-Richmond County Public Transit — Electric bus owner, transit operator
- Blue Bird Body Company — Electric bus manufacturer
- Hydrogen Components, Inc. — Hydride vessel construction, engine conversion
- Education, Research and Development Association of Georgia Universities — Contract administration

Other project participants included: Air Products and Chemicals, Inc.; Energy Research and Generation, Inc.; Power Technology Southeast, Inc.; Northrop Grumman Corporation; Air Liquide America Corporation; ElectroSource, Inc.; Neocon Technologies, Inc.

System Description

The H2Fuel Bus is a modified version of a an electric transit bus manufactured by Blue Bird Body Company of Fort Valley, Georgia. A photograph of the bus is shown in Figure 1. The bus is approximately 33-ft long and has a gross vehicle weight rating of 33,000 pounds. Bus features include electric air-conditioning and compatibility with the requirements of the Americans with Disabilities Act, including wheelchair access. There is space for 27 seated passengers plus standees.

The original electric bus was powered by four battery packs containing twenty-eight lead-acid batteries each. Two of the battery packs, weighing approximately 1,000 kg each, were replaced with metal hydride storage vessels. The bus employs a series hybrid electric power system, consisting of a hydrogen-fueled internal combustion engine and a Northrop Grumman electric drive train. The engine-generator set was installed in the rear compartment of the bus and connected to the hydrogen storage system and the electric drive train. The engine is a 7.5 liter V-8 industrial engine modified to operate with hydrogen fuel. A constant volume injection system provided by Hydrogen Components, Inc. is used to introduce hydrogen into the engine. The two remaining lead/acid battery packs provide peaking power capability and permit the hydrogen engine to be operated at peak efficiency and with minimal emissions. The IC engine/generator set produces up to 60 kW AC power, which is directed by a power controller for battery recharging or to help operate the high efficiency 170 kW AC induction electric drive motor. A regenerative braking system helps increase overall energy efficiency and significantly reduces brake wear. Electric operation provides noticeably quieter transportation, while matching the speed and acceleration performance of its diesel counterparts. The hydrogen hybrid design extends the useful operating range of the bus to over 200 km (nearly twice that of the battery-only version), permitting a full day of transit operation without mid-day refueling.

Hydrogen Storage

Hydrogen is stored onboard the bus at near room temperature and at low pressure in a safe, dry solid form through the use of metal hydride powder. Metal hydrides are intermetallic compounds that undergo reversible chemical reactions with hydrogen. They absorb hydrogen gas when cooled, and release it in a controlled manner when heated. The heating is accomplished onboard the bus by routing the engine cooling water through tubes located in the metal hydride storage vessels. A patented hydrogen storage device was developed by the Savannah River Technology Center (DOE Savannah River Site) to contain the metal hydride powder and to permit efficient hydrogen delivery to the engine. A schematic of a metal hydride storage vessel is shown in Figure 2. The cylindrical hydride vessels are made from thin wall, stainless steel tubes. The components inside each vessel include a porous stainless steel filter, aluminum divider plates, cylindrical aluminum foam pieces and a U-shaped water tube. The filter permits hydrogen to flow freely in and out of the vessel but confines the metal hydride powders in the vessel. The divider plates separate the vessel into short sections to prevent the metal hydride powders from shifting among the sections. The aluminum foam pieces with metal hydride particles in their pores improve the heat transfer between the hydride and the water tube. The engine coolant flows through the water tube to provide heat during desorption and to remove heat during absorption of hydrogen during refueling. The metal hydride vessels are manifolded together and contained inside an air-tight aluminum box. Two metal hydride storage assemblies, consisting of twenty-four individual tubular vessels each, are located under the floor of the bus. A photograph of one of the storage vessel assemblies is shown in Figure 3. These assemblies replace two of the four battery packs normally supplied with a battery-electric version of the bus sold by Blue Bird. The total weight of the two metal hydride storage assemblies is 1900 kilograms, approximately the same as the two packs of batteries they replaced. The hydrogen storage capacity is approximately 15 kilograms.

Lanthanum-nickel-aluminum type material was selected as the storage medium on the bus. This material has been used extensively in defense work at the Savannah River Site for more than 15 years in various applications. It has been shown to have excellent chemical and physical stability, and the hydrogen absorption isotherm can be adjusted to give the desired operating temperature and pressure. In order to operate utilizing waste heat from the engine cooling loop and to recharge the storage beds with normal cooling water, an absorption pressure of 7 atmospheres at 30 degrees Celsius and a desorption pressure of 13 atmospheres at 60 degrees Celsius were selected. The hydrogen capacity on the hydride is approximately 1.27%. Although this weight density was sufficient to meet the design requirements for the H2Fuel transit bus, higher weight density metal hydrides could be utilized for light-duty vehicles and other applications. Satisfying the temperature/pressure limits, cycling lifetime, activation, oxidation/poisoning resistance, and cost requirements are the greatest challenges for selecting lighter weight hydrides.

Engine Design and Exhaust Emissions

The internal combustion engine was extensively modified in order to achieve extremely low nitrogen oxide (NOx) exhaust emissions. Hydrogen Components, Inc. of Littleton, CO performed the engine modifications and designed and built the emission control system. The results to date are based on engine tests prior to installation in the bus. Actual bus emissions data will be collected later this year. NOx levels measured during the engine testes were extremely low, indicating that this may be the cleanest internal combustion engine ever operated.

The engine is a Ford LSG-875 industrial engine. The original 7.5 liter Ford V-8 engine was extensively modified during conversion to hydrogen fuel. New heads and pistons were selected to increase the compression ratio for higher thermal efficiency. The heads have better flow characteristics to improve volumetric efficiency as well. A new intake manifold provides higher flow and accommodates the hydrogen injection ports. Hydrogen fuel is delivered through an HCI-patented Constant Volume Injection (CVI) system, a mechanical timing and metering device in phase with the intake stroke of the engine (i.e. sequential multiport injection). Operating on hydrogen, the engine is rated at 102 hp (76 kW) at 2450 rpm. The brake thermal efficiency of the engine is 31%.

The low NOx emissions were achieved through the use of a novel, high volume exhaust gas recycle system combined with a three-way catalyst. Although the system was designed by HCI, the original EGR/stoichiometric hydrogen engine concept was originally proposed by Dr. Michael Swain of the University of Florida. To achieve stable combustion and low oxides of nitrogen (NOx) emissions, hydrogen engines are typically run ultra lean, with an equivalence ratio of 0.5 or less. However, this results in surplus exhaust oxygen that precludes the use of a three way catalyst for final NOx reduction. The concept employed on the H2Fuel Bus utilizes high volume exhaust gas recycle (consisting primarily of nitrogen and water vapor) to dilute the air/fuel charge to provide slower flame speeds and lower peak flame temperature for stable combustion and lower NOx. This permits the use of a stoichiometric (or slightly rich) fuel mixture, allowing for the further catalytic reduction of NOx by the three way catalyst.

Before installation into the bus, several tests were run in which the exhaust was sampled, dried, and collected during engine operation at full speed (2450 rpm) and at various loads. In its final configuration, the engine's NOx emissions were so low that Hydrogen Consultants, Inc. was unable to detect any NOx in the vehicle exhaust with a 0-1000 ppm instrument. Measurements on bag samples at Honda Motor Company's laboratory in Denver, CO registered less than 1 ppm on their 0-30 ppm scale, as shown below. From the emissions concentration data, the brake specific emissions (BSE) can be calculated from hydrogen flow, engine brake power, and combustion stoichiometry. Tests were conducted at stoichiometric (equiv. ratio = 1.005) and fuel-rich (equiv. ratio = 1.04) conditions. The results are shown in Table 1.

Table 1. Exhaust Emissions for H2Fuel Bus Engine

NOx Emissions for Stoichiometric Operation:

LOAD	NOx (grams/hp-hr)	NOx (ppm)	NOx (grams/mile)*
90%	0.028	11.0	0.056
75%	0.019	7.0	0.038
50%	0.023	7.2	0.046

NOx Emissions for Fuel-Rich Operation (equiv. ratio = 1.04):

LOAD	NOx (grams/hp-hr)	NOx (ppm)	NOx (grams/mile)*
90%	0.0004	0.15	0.0008
75%	0.0005	0.18	0.0010
50%	0.0004	0.13	0.0008

*Note: "grams/mile" estimate based on average energy use of 2.0 hp-hr/mile. This represents total emissions for a fully loaded bus with 27 passengers. Appropriate corrections for passenger vehicles should be made.

Operating Results to Date

The H2Fuel Bus has been operated in a test mode in the City of Augusta since April, 1997. This testing has permitted several refinements and modifications to be performed to improve the bus operation and reliability. Key results to date include:

- Assembly of hybrid hydrogen/electric bus was completed successfully within GVWR limits
- Metal hydride storage vessels were constructed, installed and successfully operated. More than 20 refuelings have been performed.
- Safety analyses, liability insurance, codes & standards issues were resolved
- Refueling capability was established at an existing facility of the hydrogen supplier
- Road testing of approximately 1000 miles has been completed
- Energy efficiency was measured at 67 scf H2/mi or 7.5 mpg (exceeding goal). Energy consumption of 2,800 kcal/km compares to 6,000 kcal/km for diesel equivalent
- Near-zero NOx emissions were measured during engine testing (<0.2 ppm)

Current Year Accomplishments/Status:

During Fiscal Year 1998, the following additional accomplishments were achieved:

- Battery management system installed – significantly improving battery life & performance
- Final modifications completed in order to accept commercial passengers
- Hydrogen storage system modified to meet ASME Pressure Vessel Code requirements

- Engine/battery system operation optimized to permit smoother, more efficient operation
- Bus demonstrated at Eighth Annual U.S. Hydrogen Meeting in Vienna, VA
- Initiation of regular transit service in Augusta, GA planned for Spring, 1998

Conclusions

The H2Fuel Bus establishes the technical readiness of hybrid hydrogen electric buses. The performance, operating range, energy efficiency, and exhaust emissions all meet or exceed expectations. The metal hydride storage system has functioned flawlessly, and the advantages of this method of hydrogen storage have been verified. Insurance liability, licensing, refueling and other infrastructure issues have been successfully addressed.

The major area of difficulty with the technical operation of the bus was associated with the battery system. Hybrid electric vehicles are still in a developmental stage, and the design of charging and operating schemes to optimize battery performance, reliability and lifetime is still evolving.

Future Work

Future plans for the H2Fuel bus include:

- Perform final optimization and checkout testing
- Introduce the bus into regular transit service in Augusta, GA
- Collect and analyze data during transit operations
- Support DOE-EE efforts to transition the bus for continued testing

The H2Fuel Bus is a valuable national resource as a test-bed for hydrogen technologies. Potential future work associated with the bus may involve conversion to fuel cell operation, installation of an improved hydrogen storage system, or other modifications and demonstrations. The assessment of follow-on buses based on the H2Fuel Bus prototype are being discussed with the industry partners.

Acknowledgments

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Awards:

- Federal Laboratory Consortium "1996 Southeast Regional Partnership Award"
- "Keys to City of Augusta" presented by Senator Sam Nunn to Mayor Larry Sconyers

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Figures

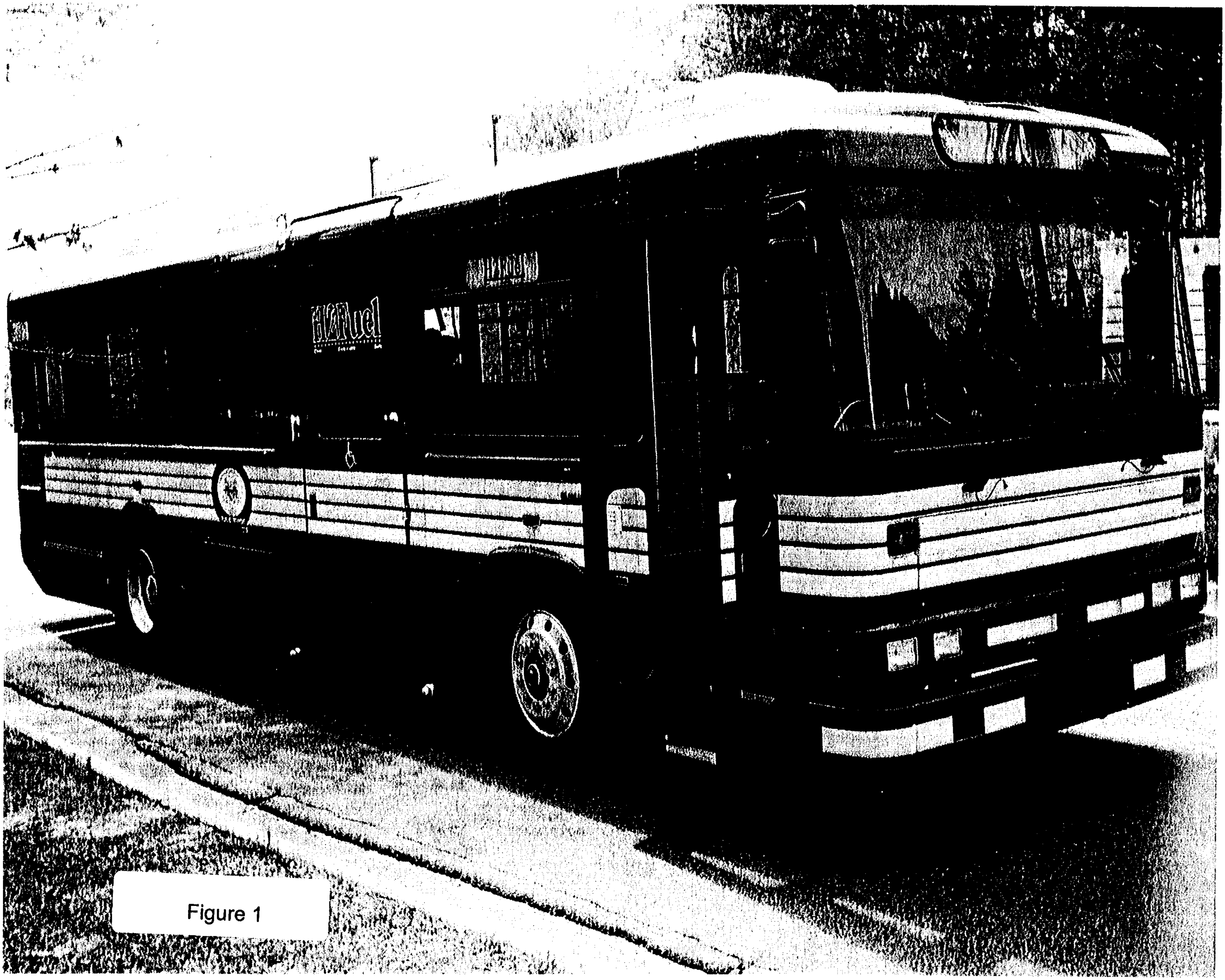

Figure 1

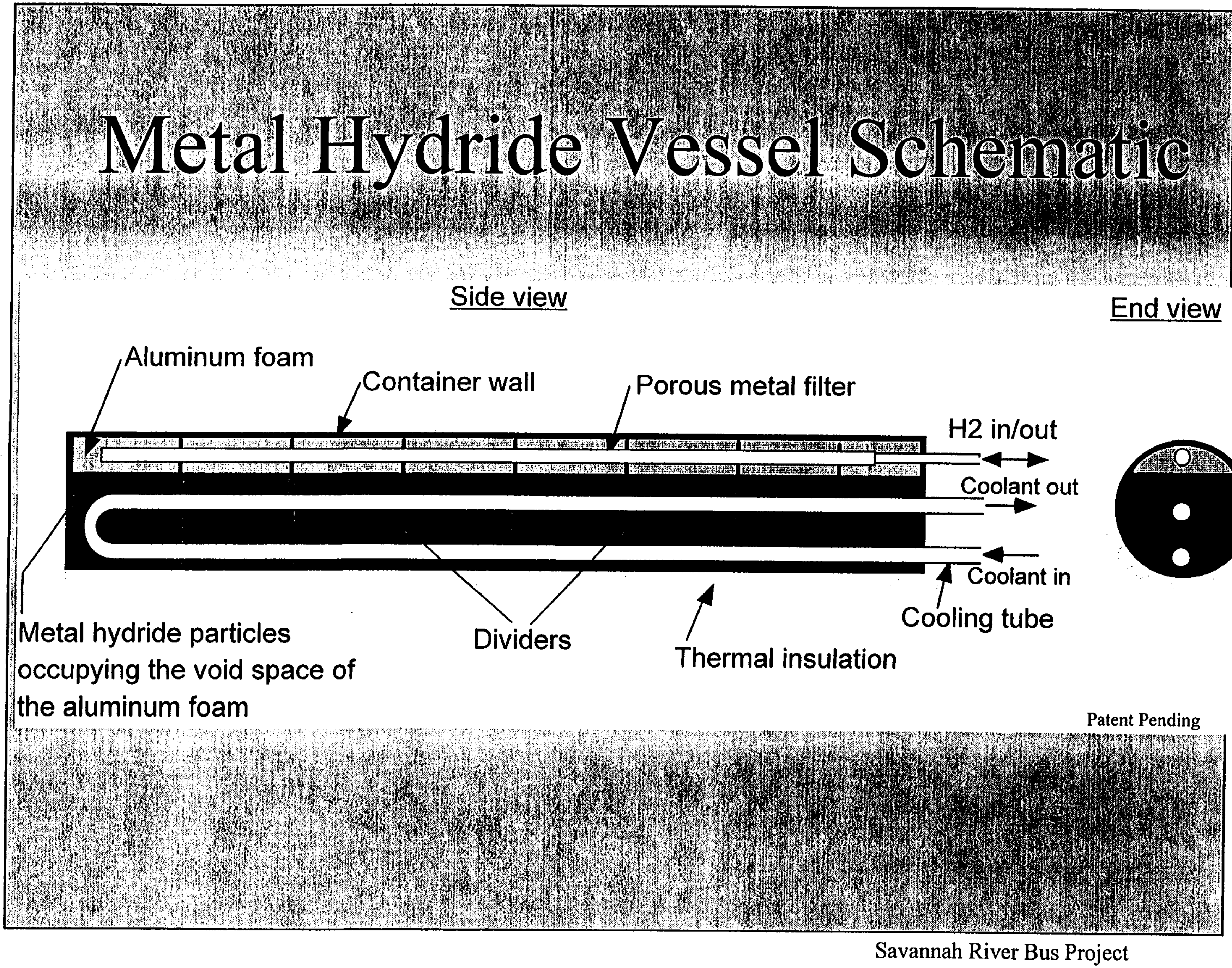
Metal Hydride Vessel Schematic
Side view
End view
Aluminum foam
Container wall
Porous metal filter
H2 in/out
Coolant out
Coolant in
Cooling tube
Metal hydride particles occupying the void space of the aluminum foam
Dividers
Thermal insulation
Patent Pending
Savannah River Bus Project

Figure 2

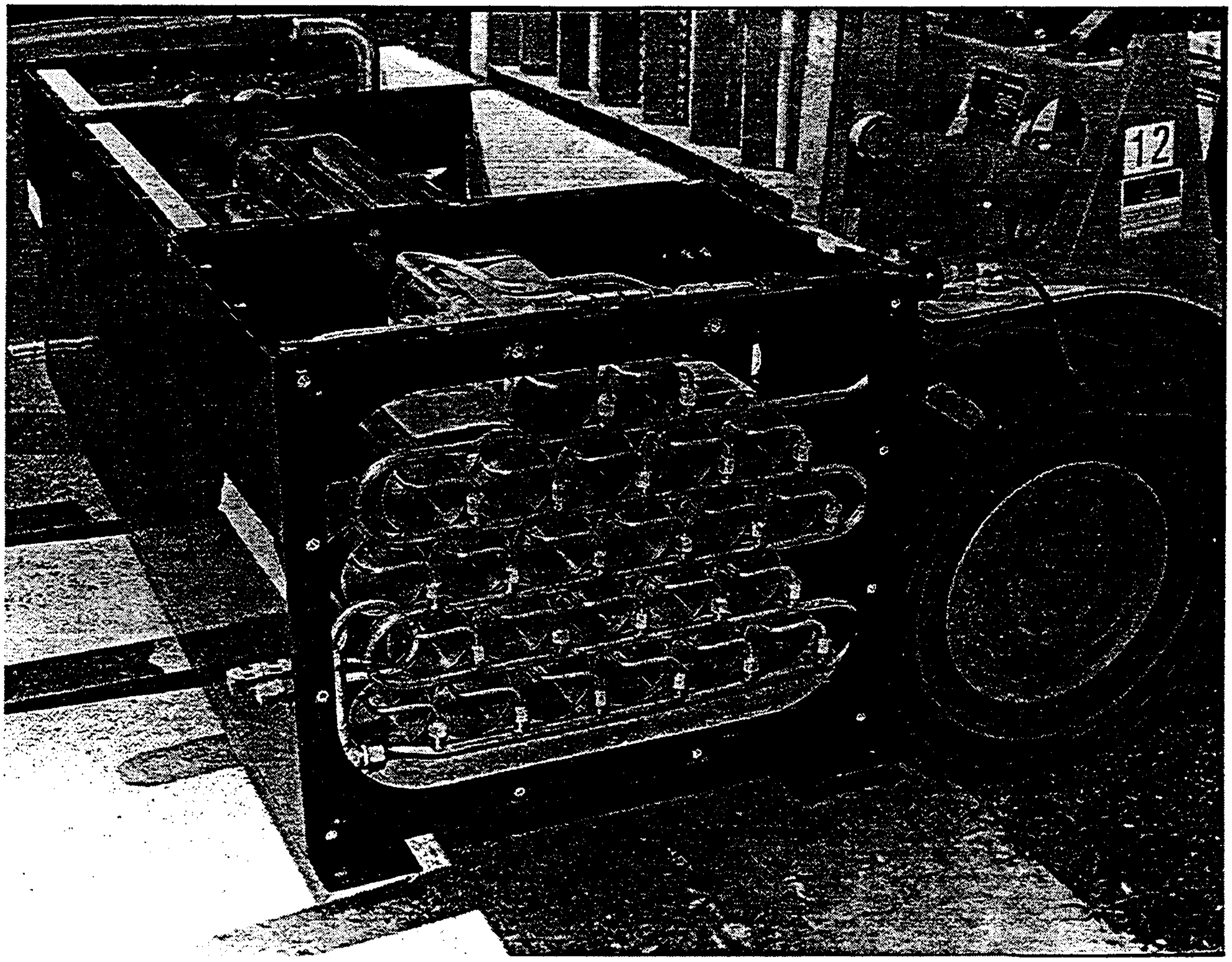

Figure 3