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LAWRENCE LIVERMORE NATIONAL LABORATORY

Commercialization of LLNL Zinc Air Fuel Cell Technology For Stationary And Mobile Applications And Electromechanical Battery For Mobile Applications Final Report CRADA No. TC-1420-97

F. J. Tokarz, J. F. Cooper, D. Haley

November 3, 2017

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Commercialization Of LLNL Zinc Air Fuel Cell Technology For Stationary And Mobile Applications And Electromechanical Battery For Mobile Applications

Final Report
CRADA No. TC-1420-97
Date Technical Work Ended: October 20, 1998

Date: June 5, 2001 Revision: 5

A. Parties

This project was a relationship between Lawrence Livermore National Laboratory (LLNL) and Power Air Tech Pty, Ltd.

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B. Project Scope

Utility deregulation is occurring throughout the world. Energy storage, peak demand leveling and power quality are becoming increasingly important. New, innovative cost-effective methods are critical to the financial success or failure of utility companies in the new free market environment.

The implementation of energy storage gives a utility the ability to better utilize existing generating capacity. Energy is stored in the periods of low overall demand and then the stored energy is connected to the power grid during peak demand periods. Storing energy in this manner will lead to significant economic benefits to utilities as well as their customers. Furthermore, because the utility's system is operated more efficiently there is a direct reduction in atmospheric pollutants including greenhouse gases.

This CRADA was to start a long-term partnership to towards the commercialization of LLNL's Zinc Air Fuel Cell (ZAFC) and Zinc Recovery Unit (ZRU) and Electromechanical Battery technologies.

LLNL's primary responsibility focused on research and development of ZAFC and ZRU. This included:

1. Identifying and solving technology issues
2. Designing, testing, building, and demonstrating a prototype for various selected ZAFC applications (both stationary and mobile)

PAT's primary responsibility focused on the cost effective manufacturing requirement to bring the ZAFC and EMB technology to commercialization. The business focus included identifying the markets, appropriate applications, customer interfacing, marketing plans, etc. The manufacturing responsibilities included identifying resources (facilities, people, etc.) required to extend prototype products to cost-effective, reliable, safe, etc., commercial products.

The original CRADA established the following six tasks:

Task 1
LLNL and PAT jointly established the Development Organizational Structure. LLNL identified internal resources required. PAT identified external resources required, and PAT provided the lead.

Task 2
LLNL and PAT together examined the stationary application of the ZAFC technology defined for electrical utilities. PAT was responsible for selecting the utility application and providing performance specifications to meet customer needs. LLNL had primary responsibility to determine the feasibility, configuration and parameters, and an appropriate development plan. PAT provided the lead.

Task 3
LLNL and PAT jointly developed an initial marketing plan that identified client areas, specific applications, scope of the market, competing technologies, industrial contacts, etc. This included the stationary and mobile EMB applications. Product delivery channels included large to small utility applications, heavy to light vehicle and other applications such as mining operations. PAT provided the lead.

Task 4
LLNL and PAT jointly produced a detail project management plan that covered the proposed project activities from the date of the CRADA to Year 2000 Olympic Games in Sydney, Australia.

Task 5
LLNL and PAT set up ZAFC/ZRU system demo for public access. LLNL provided the lead with PAT providing marketing assistance.

Task 6
LLNL and PAT determined next set of parameters and deliverables to meet overall goal of commercializing ZAFC/ZRU and EMB.

The Amendment to the CRADA modified the original work scope as follows: Task 1 and 5 were retained. LLNL's portion of Task 2 was completed. Tasks 3, 4 and 6 were eliminated with expectations that they would be addressed in the future. (Including all work associated with LLNL's EMB technology).

The amended scope was stated as follows:

Task I
LLNL and PAT will jointly established the Development Organizational Structure. LLNL will identify internal resources required. PAT will identified external resources required, and PAT provided the lead.

Task II
Set-up one (1) ZAFC/ZRU system demonstration for public access.

Task III
Modification of ZAFC Demo Units System's durability.

Note, the work associated with Tasks II and III included four (4) reconstructions of three (3) demonstrations of the 6-cell demo units and 12 test operations to generate data.

Deliverables:

Task 1: See Task I below

Task 2: A conceptual financial model for ZAFC/ZRU system for a 2 mega volt ampere (MVA) utility application

Task 3: A preliminary marketing assessment plan and applications specifications for ZAFC/ZRU and EMB development toward commercialization

Task 4: None

Task 5: See Task II below.

Task 6: None

Two deliverables were produced as the results of Tasks I, II and III:

1. A Development Organizational Structure Report
2. One (1) 6-cell demonstration ZAFC Units accessible to the public

C. Technical Accomplishments

In 1997, we began development of advanced zinc/air modules (6-cell stacks operating with an electrolyte storage tank and air and electrolyte flow subsystems), with the intention of testing the units under USABC protocols at an independent laboratory under DOE auspices. The same effort also provided designs for demonstration of the process under this CRADA, which supported construction, assembly, extended testing and post-test breakdown and analyses of these units at LLNL.

The cells constructed during this period were of the similar wedge-shaped configuration as developed for the 1995 6-cell tests on-board the Santa Barbara Bus. The cell was constructed of a plate (a copper-clad epoxy circuit board material with anode basket on one face and air-electrode assembly on the opposite face) and a frame (a plastic picture frame with windows to contain the hopper and the cell and with channels for air and electrolyte distribution).

The engineering advances at this stage included: (1) scale up from 250 cm^2 to 300 cm^2 per cell; (2) improved materials for the frame (polysulfone); (3) series connection of the cells through wrap-around junctions at the lateral edges of the plates; (4) development of a stamping technique where the anode basket and supporting ribs were pressed from a single sheet of Exmet (expanded-metal copper or nickel mesh); and (5) the electrolyte storage tank was reduced in volume and placed below the stack. The module was conceived and assembled as a stand-alone battery, with the battery providing all power for air and electrolyte circulation through an external electronic controller. The tank is fabricated from stainless steel. A composite epoxy/glass "strong back" is provided to compress the stack of 6 frames and 7 plates. Current collection is from the terminal (ending) plates only.

The sizing of the expanded metal used in the anode basket was chosen for providing maximum access of the anode fuel to the cathode by minimizing the "Faraday cage" effect of an equi-potential screen. This requires that the open spaces in the screen be large in comparison with the size of the zinc particles. Despite its name ("basket"), the primary function of the anode screen basket is to collect current from the zinc at a point as close as possible to the surface of the inter-electrode separator in order to minimize IR losses. The basket is not intended to contain zinc particles.

Units such as this were used in the press release and demonstration (September 1997) and in visitors' day (October 1997). These tests yielded the cell discharge performance that was among the best ever seen by us. Typical voltage curves show total resistances of 1-1.8 ohm-cm^2 per cell.

Work in this time frame did not include any new construction or testing of a zinc recovery unit (ZRU), as the cells were designed to use commercial cut zinc wire anode material.

D. Expected Economic Impact

D.1 Specific Benefits:

Benefit to Industry

Establishing a long-term partnership between PAT and LLNL resulted in progress towards the commercialization of LLNL's ZAFC/ZRU and EMB technologies.

Benefit to DOE

This project resulted in major benefits to DOE, DP, and LLNL. This project continued the DOE's firm commitment to develop technology capable of improving energy conversion efficiency and to limiting U.S. dependence on foreign energy resources. This commitment has been demonstrated through continuing sponsorship of programs to research and develop of advanced energy storage devices for electric propulsion and for utility load-leveling, as well as fuel cell technologies for electric power generation, for emergency power and for various electric propulsion applications.

Between 1976 and the time of the CRADA, the U.S. Department of Energy has sponsored research and development in various primary and secondary zinc/air, zinc/bromine, zinc/chlorine, zinc/nickel-oxide and zinc/ferrocyanide batteries well as the advanced development of zinc electrowinning processes using hydrogen as a reactant. DOE consistently supported development of air electrode structures and catalysts essential to zinc-air and iron-air batteries as well as all fuel cell applications. The refuelable zinc-air technology of this CRADA has its origins in LLNL's internal research (LDRD, core competency energy research 1992-1994).

The participation in this CRADA provided LLNL scientists and engineers with experience and involvement in forefront research concerning energy storage. It updated and exercised our expertise in treating global problems of energy conversion efficiency, power distribution problems, global energy balance considerations, and energy-economy calculations. This was done in reference to specific adaptations of LLNL zinc/air technology to utility load leveling, emergency or standby power; portable power and efficient power production equipment for remote communities; and energy storage for large electric vehicles such as busses, delivery and passenger vans; and specialized military and industrial mobile and stationary equipment.

E. Partner Contribution

Numerous energy storage and peak shifting systems were available at the time of the CRADA. They used a variety of technologies to achieve utility objectives. Examples include hydroelectric pumped storage, compressed air energy storage and SMES.

LLNL's ZAFC technology had a unique advantage over existing technology options in that they:

1. Were free from negative environmental impact
2. Had no complex regulatory implications
3. Were inherently modular and may be installed on a distributed basis throughout a utility's system

The principals of PAT bring long-term experience in developing, marketing and starting up manufacturing of new products to the public utility industry. Their extensive prior involvement within the field provided a detailed understanding of the considerable potential available through the application of LLNL's ZAFC and EMB technology in the fields of energy storage, peak shaving and demand-side management.

PAT, by obtaining access to LLNL's ZAFC and EMB technology and providing further development, was able to broaden and strengthen their position in the utility field. This cooperative endeavor provided LLNL with the commercial introduction of the ZAFC and EMB technology into this important field.

F. Documents/Reference List

<u>Reports</u>

1. Cooper, Cherepy, Krueger and Tokarz, "The LLNL zinc/air fuel cell—design development and testing for commercialization in stationary and mobile power applications," UCRL-ID-140427 August 17, 2000.*
2. John F. Cooper and Roger Krueger, "The zinc/air battery: alternative zinc fuel morphologies and cell behavior," Paper presented to the 12th Annual Advanced Battery Conference, Long Beach CA Jan 14-17 1997; LLNL Report UCRL-JC-125729, January 15, 1997.
3. N.J. Cherepy, R. Krueger, J.F. Cooper, "A Zinc/Air Fuel Cell for Electric Vehicles," Proc. Annual Battery Conference, Long Beach CA January 1999. LLNL Report UCRL-JC-132975, January 11-14, 1999.
4. N.J. Cherepy, R. Krueger, J.F. Cooper, "A Zinc/Air Fuel Cell Modules for Electric Vehicles," Paper submitted to the Fall Meeting of the Electrochemical Society, Honolulu HA, October 1999; LLNL Report UCRL-JC-134327-SUM April 1999.
5. John F. Cooper, Roger Krueger, Ray Smith and Frank Tokarz CORE TESTING OF ZINC/AIR REFUELABLE BATTERY MODULES, Interim Report: April - September 1997; report to DOE, Office of Transportation.

*Contains proprietary data.

<u>Patent/Copyright Activity</u>

No patent or copyright activities were pursued by this project.

<u>Subject Inventions</u>

No subject inventions were made under this CRADA.

Background Intellectual Property

BIP was licensed to Power Air Tech, Inc., a wholly owned subsidiary of Power Air Dynamics LTD, (PADL).

Patent Number: 5,434,020
Date Issued: July 18, 1995
Title: Continuous-feed electrochemical cell with non-packing particulate electrode
LLNL Inventor: John F. Cooper

Patent Number: 5,578,183
Date Issued: November 26, 1996
Title: Production of Zinc Pellets
LLNL Inventor: John F. Cooper

G. Acknowledgement

Participant's signature of the final report indicates the following:

1) The Participant has reviewed the final report and concurs with the statements made therein.
2) The Participant agrees that any modifications or changes from the initial proposal were discussed and agreed to during the term of the project.
3) The Participant certifies that all reports either completed or in process are listed and all subject inventions and the associated intellectual property protection measures generated by his/her respective company and attributable to the project have been disclosed and included in Section E or are included on a list attached to this report.
4) The Participant certifies that if tangible personal property was exchanged during the agreement, all has either been returned to the initial custodian or transferred permanently.
5) The Participant certifies that proprietary information has been returned or destroyed by LLNL.

7/31/01

Dean Haley, Chairman and CEO — Date
Power Air Tech Pty Ltd (PAT) (now Power Air Tech, Inc.)

11/4/01

Dr. Frank J. Tokarz — Date
Lawrence Livermore National Laboratory

Attachment I – Final Abstract

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E. Project Dates:

March 20, 1997 – October 20, 1998