Fuel Cell Mobile Lighting: A Fuel Cell Market Transformation Project

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Abstract

We report the results of a project aimed to introduce proton exchange membrane (PEM) hydrogen fuel cell technology into aviation ground support equipment (GSE) and rental construction equipment. The purpose of the project was to design, build, field-test and then commercialize fuel cell equipment that is superior to its diesel counterpart. The commercializing of this hydrogen-based technology will help to start the process of displacing diesel fuel use in aviation GSE and in mobile construction equipment. We describe a hydrogen fuel cell mobile lighting tower (H₂LT) that combines hydrogen stored as a high pressure gas, PEM fuel cell technology, and advanced lighting into a single unit with uses in aviation and construction. We assembled a project team of 15 institutional partners combining new technology expertise (hydrogen, fuel cells), equipment mass manufacturing capability (mobile light towers, lighting) and influential end-users to field test the H₂LT in real-world use in diverse environments. Seed funding provided by Boeing enabled additional funding from the U.S. Department of Energy (DOE) and a preponderance of in-kind contributions from the industrial partners. Prototype units were constructed and field tested in the entertainment industry, at the San Francisco International Airport, at the NASA Kennedy Space Center, with the California Department of Transportation (Caltrans), and with the Connecticut Department of Transportation. The goals of these approximately year-long field tests were to assess operation of the H₂LT technology in a wide variety of potentially corrosive environments (cold, wet, hot, humid, salty air) performing a wide variety of tasks, to reduce diesel emissions at these locations, and to help promote hydrogen PEM technology in new influential markets. The H₂LT proved to be exceptionally durable in these diverse environments, demonstrating the compatibility of PEM fuel cells and high-pressure hydrogen storage with the construction equipment application. Results from the field tests are discussed, including system performance (efficiency, duration, durability) and the efficacy of refueling the system by different methods (H₂ stations, mobile refueling). The H₂LT system is compared directly to a comparable diesel-fueled light tower with regard to size, performance and emissions. Overall, end users were pleased with the performance of the H₂LT, noting the lack of emissions and exceptionally low noise level. Recommendations for improvement were also collected and will be discussed. Two types of lighting used on the H₂LT (plasma, LED) were characterized by U.C. Davis in collaboration with Caltrans. LED lighting was found to be the most energy efficient and robust lighting technology for the highly mobile H₂LT application. The technical “lessons-learned” are reviewed, along with the plans for commercialization of the H₂LT technology by Multiquip Inc. Finally, the benefits to the industrial participants of the project organization are described.

Introduction:

This paper describes a project to bring hydrogen proton exchange membrane (PEM) fuel cell technology to aviation ground support equipment (GSE) and general construction equipment in the form of a hydrogen fuel cell mobile light tower (H₂LT). The project brought together new technology holders, mass manufacturing capability, and end-users to produce a superior zero-emissions commercial product that could be purchased, starting reductions in greenhouse gas (GHG) emissions in the construction equipment and aviation GSE realms.

Hydrogen fuel cell systems have the potential to provide high-efficiency and eventually low-cost power for portable equipment. Keller et al. has reviewed the attributes of hydrogen-based power for zero-emissions transportation technology [1], while also describing the history and worrisome magnitudes of the GHG emission and global climate change problems. PEM fuel cell systems and their use in automotive and portable power technology were recently reviewed by Klebanoff and co-workers [2]. The reader is directed to these references for a full description of hydrogen and PEM fuel cell technology and how hydrogen fuel cells can mitigate global climate change. The use of fuel cell portable construction equipment represents a good early market introduction of fuel cells, thereby supporting fuel cell market growth. The current diesel-based mobile light tower market is approximately 100,000 units in the United States, thus representing a niche market within the construction equipment realm, but a good starting point for introducing fuel cells into construction equipment and aviation GSE.

We begin with a discussion of how the project was initiated by The Boeing Company as well as the formation of the project team consisting of 15 institutional partners spread across industry, state government, and other entities. The elements of the H₂LT system design are described, and the H₂LT is directly compared to a comparable diesel-powered light tower with regard to size, performance and emissions. An account is then given of the field-tests in a number of challenging environments meant to test the physical durability and performance of the system, stimulate hydrogen fueling resources at the test sites, reduce diesel emissions at these locations, and promote fuel cell technology in new impactful markets. Finally, we review the design “lessons-learned” from the field-tests (which will fold into the final commercial design), discuss the reception and recognition of the H₂LT from industry, and the current plans to commercialize the H₂LT by Multiquip Inc. (MQ).

Project Origin:

In 2007, Sandia and Boeing collaborated on analyzing the utility of placing a PEM fuel cell on-board a commercial aircraft as a fuel cell emergency power system (FCEPS) [3]. The FCEPS system met the temperature, pressure, power, and volume requirements of the emergency power

application. Thus the FCEPS could serve as a relatively isolated (and therefore straightforward) point of introduction of fuel cell technology into the aircraft electrical infrastructure.

Following this FCEPS project, and anticipating barriers to getting a new power technology on-board commercial aircraft, Boeing felt it would be useful to gain experience with PEM fuel cells in a situation just off the aircraft, in a piece of aviation GSE on the tarmac. That way, Boeing could assess the technology for reliability, safety and infrastructure (fueling) requirements in an aviation environment not as challenging as the “on-board” aircraft applications. A number of GSE possibilities were discussed between Boeing and Sandia in March of 2008, with a decision made to focus on a piece of GSE that also had non-aviation uses in order to promote fuel cell use in a broader commercial market. Boeing noted that airline maintenance crews often used diesel-powered mobile lighting units to illuminate aircraft during ground service and maintenance operations, and thus would be a good candidate platform for replacing noisy, inefficient and polluting diesel technology with quiet, efficient and zero-emissions fuel cell technology. The mobile light platform was also attractive as it had a multitude of non-aviation uses such as in roadway construction, and other general-purpose security lighting applications. In addition, the power level of the mobile light platform was a modest 5 kW, which would make hydrogen storage easier and the overall system more feasible at the time. For these reasons, the decision was made to focus on developing a H₂LT, the basic idea of which is shown in Figure 1. Sandia performed an initial design of the H₂LT using high pressure (350 bar) storage of hydrogen, and a 5 kW PEM fuel cell.

Figure 1: General concept of the H₂LT. The H₂LT replaces a traditional diesel-powered light tower with a system that combines gaseous hydrogen (stored on the system), a PEM fuel cell, and an energy efficiency lighting (lamp) technology.

Assembling the Project Team:

The overall team-building strategy was to bring together new technology holders, mass manufacturing capability, and end-users to enable mass production of a zero-emissions H₂LT product whose design had prior input from end-users of the technology. The history of the team formation may be of interest to those contemplating similar hydrogen technology market transformation efforts.

Boeing and **Sandia** were the original project members, with Boeing providing the original seed funding. To seek further partners from the local hydrogen community, Klebanoff delivered a talk at the California Hydrogen Business Council on May 16, 2008. Two audience members expressed interest in the project: Bill Elrick from the **California Fuel Cell Partnership (CaFCP)** and Tom Damberger from **Golden State Energy**. Both the CaFCP and Golden State Energy became active project team members that evening.

Given the aviation origin of the project, it was desirable to have an airport involved as an end-user of the technology. Elrick, who had a prior experience in alternative fuel (natural gas) infrastructure development at airports, approached Roger Hooson, senior planner for the **San Francisco International Airport (SFO)**, and Derek Fliess, equipment manager for SFO. SFO is a leader amongst U.S. airports in exploring new energy efficient and low-emissions technology, and joined the development team. The team needed an institutional partner who could mass manufacture PEM fuel cells. Damberger had an existing relationship with **Altergy Systems**, a mass manufacturer of robust 5 kW PEM fuel cells used primarily as backup telecom power, and the only manufacturer of PEM fuel cells with a robotic assembly system capable of mass production. Altergy joined the project as the fuel cell manufacturer. Damberger also reached out to **Multiquip Inc. (MQ)**, a leading manufacturer of rental construction equipment, and a manufacturer of diesel-powered light towers. Torsten Erbel, Vice President for Product Development at Multiquip saw the zero-emissions fuel cell technology as a solution to the increasingly strict emissions restrictions being placed on diesel-based equipment. As a result, MQ joined the effort as the commercialization lead for the H₂LT. MQ would go on to create the first commercial construction technology platform based entirely on PEM fuel cells called Earthsmart™, for which the H₂LT was the first product.

The project had two important connections with the **California Department of Transportation (Caltrans)**. Tom Damberger knew Steve Prey, who was the Statewide Energy Program Coordinator for Caltrans, doing development work in the areas of H₂ and LED technologies. Prey provided early guidance and encouragement in pursuing a collaboration with Caltrans. Independently, on October 29, 2008, Randy Iwasaki, the Director of the Caltrans, visited Sandia management for a meeting to discuss areas of mutual research interest. Klebanoff presented the emerging H₂LT project, describing its potential for zero-emissions road construction use. Iwasaki directed the Caltrans Division of Research and Innovation (DRI) to engage in the project, with Randy Woolley from DRI being the Caltrans representative who would oversee

field-testing with Caltrans as well as fund a study of the lighting options for the technology. Caltrans engaged one of their university research partners, the Advanced Highway Maintenance and Construction Technology Research Center out of **U.C. Davis** to coordinate Caltrans field-testing of the H₂LT, and perform testing of metal halide (MH), plasma and LED lighting for the unit, which will be reported in detail elsewhere [4]. Caltrans and U.C. Davis became project partners in these capacities.

The project needed a mass manufacturer of lighting technology. With assistance from Mickey Oros of Alteryg, Tom Damberger contacted Thomas Skradski of **Lumenworks**, a lighting technology and design outfit in Oakland CA. Lumenworks joined the project, and recommended an emerging energy-efficient lighting technology (circa 2009) called plasma lighting [5] that could operate on the DC voltage provided by the PEM fuel cell. Plasma lighting is manufactured by **Luxim Corporation**, and fabricated into lighting fixtures by **Stray Light Optical Technologies**. When the project goals and aims were described to these companies, they joined the development team as well.

Alteryg Systems had been in prior communication with Paramount Pictures in Hollywood CA on the topic of fuel cell power technology, and discussions continued with the H₂LT. On January 14, 2010, an early H₂LT prototype called the “Alpha System” was demonstrated inside Stage 17 of Paramount Pictures in Hollywood CA, at the invitation of Mark Bauserman, the Chief Engineer of Paramount at the time. The unit was demonstrated to representatives of Fox Studios, Universal Studios, Warner Brothers Studios and Paramount, amongst others and also to Saunders Electric Inc., the leading provider of diesel-based mobile power systems to the entertainment industry. Russell and Candace Saunders were impressed with the zero-emissions nature and how quiet the H₂LT technology was. **Saunders Electric** joined the development team at that time, and used the prototype Alpha H₂LT in their work at the 2010 Academy Awards on March 8, 2010. Prior to the 2010 Academy Awards, the project obtained funding support from the **U.S. Department of Energy (DOE)** Fuel Cell Technologies Office Market Transformation program, which allowed five additional near-commercial “Beta” units to be built with improved capabilities that could be field-tested in challenging environments.

With funding available from the DOE, the project team reached out to the **NASA Kennedy Space Center (KSC)** as an end-user of the H₂LT technology with a deep knowledge of hydrogen systems, as liquid hydrogen was used to fuel the Space Shuttle Orbiter and also the Saturn V launch vehicle used in the Apollo and Skylab programs. The NASA KSC location in southern Florida made it a perfect site to test the corrosion resistance and performance of the unit in a hot, humid and salty marine environment. KSC did not join the project as an official partner, but was a close collaborator during the nearly two-year deployment of H₂LT systems there. During the KSC field tests an H₂LT was used to support operations for the last Space Shuttle launch (Atlantis, July 8, 2011).

Although the initial H₂LT design employed Type III, 350 bar carbon fiber overwrapped pressure vessels (COPV) (i.e., “composite tanks”) as the chosen method of hydrogen storage, the project did consider the possibility that one day a metal-hydride tank could be used to store hydrogen for such an application. The project approached **Ovonic Hydrogen Solutions**, then a commercial source of interstitial metal hydride (AB₂) hydrogen storage systems. Boeing funded an analysis of the performance of such a tank for the H₂LT [6]. Ovonic joined the effort, although the project never did build a system based on interstitial metal hydride hydrogen storage because high-pressure gas storage seemed adequate to the task.

Taken together, this assembly of institutions formed the project team, shown in Figure 2. These institutions came together with a shared philosophy that commercially available fuel cell equipment that works better than their diesel counterparts needs to be created and disseminated, starting the transformation of the aviation GSE and construction equipment markets with fuel cell technology.

Figure 2: The H₂LT Project Team (known informally as the Circle of Love). Entities providing additional assistance to the project included the NASA Kennedy Space Center, and Paramount Pictures (not shown).

The team-building strategy for the H₂LT project can be summarized as follows. In order to design, build, field-test and commercialize this new piece of hydrogen fuel-cell-based equipment, we combined new technology holders (Sandia, Altery, Ovonic) with mass manufacturing capability in fuel cells (Altery), construction equipment (MQ) and lighting (Stray Light, Luxim, Lumenworks). To this group we added technically savvy and influential

end-users (Caltrans, Saunders Electric, SFO) who could field-test prototypes of the technology in challenging environments and provide feedback on how the unit performed and ways to improve the system.

Having a U.S. national laboratory such as Sandia leading the development effort proved to be especially beneficial. In the U.S., national laboratories are forbidden by law from competing with industry, and are motivated by the broader national and DOE interest in lowering barriers to commercializing fuel cells in early markets. Sandia's not-for-profit posture in this regard helped create a sense of safety and trust within the project that the interactions with partners would be unbiased and fair. Sandia's established and broad capabilities in hydrogen technology (e.g. hydrogen storage, fuel cells and engineered fuel cell systems) and role as "honest technical broker" helped ensure the project had a sound technical footing and direction and that technical transfer to industry was prompt and complete. Sandia's prior work in the hydrogen "codes and standards" community lent additional credibility for the H₂LT project in our briefings to emergency first responders, fire and safety professionals and law enforcement which were required for all of the field-tests.

Sandia adopted the management philosophy very early that the project would go in whatever direction the consensus of the group took it, without holding too tightly to the original concept of creating a piece of fuel-cell-based aviation GSE. This approach created a flexible and free environment in which collaborations flourished. Furthermore, management flexibility enabled the project to go in surprising and fruitful directions that ended up engaging a much larger and diverse community of end users and applications, better serving the fuel cell market transformation goals of the project. Boeing support for this management approach was invaluable.

The project was funded largely by in-kind contributions from the industrial partners. Boeing provided \$150K of seed funding. The U.S. DOE provided \$650K of project support for the construction of five additional H₂LT units and their field testing. Caltrans provided \$325K in support of field testing by Caltrans staff and lighting characterization studies by the U.C. Davis AHMCT. The other in-kind contributions from the project partners totaled \$1.22M, giving a total project value of \$2.35M. Thus, the Boeing and DOE funding spurred considerable investment from the other partners, which was required for a successful project.

Alpha H₂LT Design:

The H₂LT system is conceptually composed of three subsystems: fuel cell, hydrogen storage and lighting. The PEM fuel cell used for all of the H₂LT prototype units was the Altery Systems FPS-5 (5 kW) PEM fuel cell, shown in Figure 3. This fuel cell was chosen because of its appropriate power output, rugged design, its successful use as a backup power system in

hundreds of cell tower installations, and the fact that it could be mass manufactured by a robotic assembly line for use in the commercial H₂LT.

Figure 3: Altery Systems FPS-5 PEM Fuel Cell used in all H₂LT units for the project. The fuel cell has a maximal output power of 5 kW.

The H₂LT hydrogen storage system was comprised of Type III, aluminum-lined 350 bar COPV (e.g. “composite” tanks) with a capacity of 2.1 kg of hydrogen per tank. The tank chosen was the ALT 836U model from Structural Composites Industries (SCI). These tanks require a 350 bar source of hydrogen for filling. Our deployment sites were chosen to have access to high-pressure hydrogen, as will be discussed later in the section discussing the H₂LT field tests. We also considered using commercially available interstitial metal hydride hydrogen storage tanks available from Ovonic Hydrogen Systems. Such a tank was never used in a H₂LT system because the high-pressure gas storage functioned adequately with sufficient volumetric storage density. A metal hydride tank would offer better volumetric storage density, and importantly, could be refueled using low-pressure sources of hydrogen (e.g. 150 bar hydrogen cylinders). The design of an H₂LT system based on an Ovonic interstitial metal hydride hydrogen storage system was examined by Sandia, and will be described elsewhere [6].

The initial lighting used for the H₂LT systems was plasma lighting which in 2009 was an emerging high-efficiency lighting technology already used for stationary applications (arena lighting, street lighting, etc.). Figure 4 gives a brief description of the plasma light technology, with a more complete description given elsewhere [5]. Plasma lights operate by directing RF energy via a waveguide into a plasma light bulb, which contains a proprietary mix of metal salts and gases. The RF energy excites the salt/gas mixture, giving off light. The suitability of the plasma technology for a mobile application such as the H₂LT was not known at the beginning of the project, but there were some distinct advantages to plasma lighting such as a color rendering up to 96 CRI, a 50,000 hour bulb lifetime, an advertised high efficiency (lumens/watt) and compatibility with a DC voltage power source (i.e. the PEM fuel cell).

Figure 4: Schematic diagram of Luxim plasma light technology, with a photo of the plasma bulb shown.

The H₂LT system design and construction began with the “Alpha Unit.” The purpose of the Alpha H₂LT was three-fold. First, we wanted to design and build a limited H₂LT system (consistent with the Boeing seed funding) that would allow potential sponsors to see the unit and perhaps financially support its development. Second, the Alpha H₂LT would enable initial feedback from end-users, accelerating the feedback/re-design development cycle. Third, we wanted to start the process sooner rather than later of MQ gaining familiarity with the technology, namely learning the techniques for constructing an integrated system involving hydrogen storage tanks, fuel cell, manifolding, and the enclosure accommodating the essential fuel cell systems, as well as the process of flushing the system with hydrogen and leak checking the finished and hydrogen-charged H₂LT.

Prior to the Fuel Cell Mobile Light project, MQ had no experience with hydrogen, fuel cells, or high pressure systems. The philosophy we adopted in the project would be that with the exception of the first Alpha H₂LT, every subsequent system would be constructed and tested entirely by MQ personnel, enabling MQ to develop the necessary expertise. This was a critical “tech transfer” aspect of the project, and an important goal of both Sandia and the DOE. To support this tech transfer, MQ staff travelled to Altergy to receive instruction in hydrogen and fuel cell system safety (conducted by Sandia, Altergy and the CaFCP), and in the leak-tight construction of manifolds made of 316 stainless steel rated for 350 bar hydrogen (conducted by Swagelok), as shown in Figure 5.

Alpha H₂LT construction began with MQ shipping the base trailer to Altergy Systems. Altergy staff then installed the two ALT 836U hydrogen tanks and the 5 kW FPS-5 PEM fuel cell, as shown in Figure 6. Subsequently, the partially-assembled Alpha H₂LT unit was shipped to MQ in Boise ID for integration of the lighting and mechanical systems onto the unit, installation of the electrical control panel, and final assembly and pressure certification.

Figure 5: Bruce Coleman (left) and Jonathan Cuppett (right) of MQ learn the techniques for bending 316 stainless steel tubing for high-pressure H₂LT hydrogen manifold construction.

Figure 6: Build-up of the Alpha H₂LT at Altery Systems, September 4, 2009. Photos courtesy of Tom Damberger.

The completed Alpha system is shown in Figure 7. Within the white enclosure lies the two SCI ALT 836U hydrogen tanks storing 2.2 kg of hydrogen each at 350 bar (4.4 kg total hydrogen storage) and the 5 kW Altery Systems FPS-5 PEM fuel cell. The unit also has 8 plasma light bulbs located in 8 light fixtures located on a mast that can extend to 30 feet in height with full

360 degree rotation. The lighting system draws 2.1 kW of power from the fuel cell. Since the lighting drew significantly less than the maximum fuel cell power, the unit was also outfitted with a 1.5kW DC/AC inverter that could provide auxiliary 120VAC power to such items as power tools. The Alpha H₂LT could provide full lighting for 30 hours, less if auxiliary power was also used while the lights were on.

Caltrans challenged the team to build the Alpha H₂LT in time for display at the 2009 American Association of State Transportation Officials (AASHTO) meeting held in Palm Desert CA on October 23, 2009. The AASHTO meeting is an annual meeting of all the Departments of Transportation of the 50 U.S. states. Figure 8 shows deployment of the system at the 2009 AASHTO meeting. The left photograph shows that the H₂LT illuminates a fairly large area, approximately $\frac{3}{4}$ of a football field. The unit was measured to have a noise rating of 42 dB at 23 feet, which is much quieter than the corresponding diesel light towers (73 dB at 23 feet), with no attempt having been made to sound condition the Alpha H₂LT unit. The right photograph in Figure 8 shows the unit operating with several AASHTO attendees leaning on the unit, comfortably holding a conversation. The H₂LT's quiet operation was highlighted by many attendees as a particularly attractive aspect of the technology, although low-noise operation had not been a focus of the design effort.

Figure 7: Alpha H₂LT system, Palm Desert CA, October 18, 2009.

Figure 8: (L) Illuminated area of the Alpha H₂LT, with the Alpha H₂LT in the foreground, lower left. (R): Caltrans Director Randy Iwasaki (white shirt) holds a conversation with AASHTO attendees next to the operating Alpha H₂LT unit, indicating the low noise generated by the Alpha H₂LT.

In December of 2010, the project team (through Alteryx Systems) contacted Paramount Pictures in Hollywood California. The Chief Engineer of Paramount at the time, Mark Bauserman, was interested in seeing the H₂LT and arranged for a demonstration of the unit to lighting and power technology leads in the entertainment industry including Fox Studios, Universal Studios and Warner Brothers. A demonstration of the Alpha Unit was given on January 14, 2010 on Stage 17 at Paramount Pictures, as shown in Figure 9. Because the unit has zero emissions, it was allowed to be operated inside the soundstage. A crucial project contact with Saunders Electric took place during this demonstration. Saunders Electric is the leading provider of portable power to the entertainment industry, and provides diesel-based portable power to 58 award shows held annually in Los Angeles, including the Academy Awards (Oscars), the Screen Actors Guild (SAG) Awards and the Golden Globe Awards. Russ Saunders (see Figure 9 (R)) was impressed by the low noise and zero-emissions character of the H₂LT, and invited the project team to deploy the unit with Saunders operations at the 2010 Academy Awards held in Hollywood on March 8 of that year. This invitation commenced a 3-year period of field testing the H₂LT technology in the entertainment industry by Saunders Electric.

Figure 9: (L) Demonstration of the Alpha H₂LT inside Stage 17 at Paramount Pictures on January 14, 2010 to representatives of nearby studios and companies interested in clean portable power; (R): Russ Saunders of Saunders Electric (pointing) discusses H₂LT features with Mark Bauserman (pink shirt) of Paramount, while Chris Radley (blue shirt), Randy Woolley (Caltrans) and Candace Saunders look on. Note the lack of any sound conditioning in the steel enclosure of the unit.

Prior to use at the Academy Awards, the unit was demonstrated to members of the Los Angeles Fire Department (LAFD), and L.A. Building and Safety personnel. Approval from these departments had to be secured before use of the H₂LT in such a high-profile and high-security semi-public event as the Academy Awards. Figure 10 shows Chris Radley from Alteryx explaining some aspects of fuel cell properties to Eugene Andrews, the Fire Inspector for the Hollywood area, whose duties are to enforce the Municipal and State Fire codes as they pertain to public safety in all public assembly and special events (like the Oscars). This engagement with local fire and safety personnel was a continuing and vital component of the project activities wherever the unit was either displayed or used, and was an essential intrinsic component of the fuel cell market transformation process.

Figure 10: Chris Radley from Altergy discusses fuel cell technology with Chief Eugene Andrews of the LAFD.

During the week leading up to the 2010 Oscars, the Alpha H₂LT was used by the Academy of Motion Picture Arts and Sciences (A.M.P.A.S.) construction crews to build up the famed Red Carpet on Hollywood Boulevard in front of the Dolby Theatre (formerly the Kodak Theater). Figure 11 shows the unit being used by the A.M.P.A.S construction crews both at night and during the cloudy rainy days leading up to the event. The crews used the unit with no supervision, and were the first to use the H₂LT technology in real-world construction work. During the day of the Oscars event, the Alpha H₂LT was used to provide security lighting at the International Press entrance to the Red Carpet, with the on-board 1.5 kW auxiliary power unit providing power to a security metal detector that press representatives had to pass through. Feedback was collected from the A.M.P.A.S. construction crews on the H₂LT performance. After the awards ceremony, Russ Saunders presented a post-Oscars debrief attended by about 60 individuals comprised of vendors, producers, technicians, engineers, and Academy personnel. Saunders reported the debrief attendees were “quite excited at the H₂LT developmental prospects and have instructed me to use these devices at my discretion on all events associated with the Academy’s productions.”

Figure 11: (L) Use of the Alpha H₂LT by A.M.P.A.S construction crews on March 5, 2010 in the build-up of the Red Carpet at the 2010 Academy Awards. The H₂LT unit is in the lower left hand corner of the picture. Photo courtesy of Ron Roy Productions. (R) The H₂LT by the Red Carpet on March 6, 2010. Photo courtesy of A.M.P.A.S.

Hydrogen fuel (at 350 bar) for the 2010 Oscars deployment was provided by an Air Products Mobile Hydrogen Station which was located at the Saunders Electric yard for the duration of the event (see Figure 12). Saunders staff were trained in the use of the self-contained Air Products Mobile Hydrogen Station by Air Products staff, and performed all refuelings themselves.

Figure 12: (L) Air Products Mobile Hydrogen Refueling Station used to support use of the Alpha H₂LT by Saunders Electric staff at the 2010 Academy Awards. (R) Saunders Electric staff involved in the H₂LT use at the Oscars. Russ Saunders is standing on the left.

With DOE funding, the project embarked on a significant expansion which allowed second-generation “Beta” units to be constructed and field tested in a variety of types of work in different climactic conditions.

Beta H₂LT Design:

The Beta H₂LT system was designed to incorporate initial end-user feedback derived from the Alpha H₂LT, and to more closely resemble a real commercial piece of equipment. Steve Wingert of MQ performed the Beta design and assembly work. Figure 13 shows the Beta H₂LT during the initial assembly. As was the case with the Alpha system, the trailer is constructed from heavy duty steel channel. For the Beta unit, four SCI ALT 836U 350-bar composite tanks were installed, giving a system total hydrogen storage of 8.4 kg. This hydrogen storage capacity doubled that of the Alpha H₂LT, and increased the system run time (with plasma lights) to 60 hours. The hydrogen tanks are mounted with steel mounting brackets for firm seating, and are protected from impact threats by steel stabilizer bars. For additional safety the fuel cell is mounted to the back of the trailer, protected by a heavy duty impact channel.

Figure 13: Initial assembly of a Beta H₂LT unit: (Top) Mounting of four SCI ALT 836U composite hydrogen tanks on the Beta H₂LT; (Bottom) Mounting of both the 5 kW PEM fuel cell and hydrogen tanks. The “front” of the unit is to the left, toward the winch. Photos courtesy of Steve Wingert, MQ.

The H₂LT hydrogen manifold is constructed of 3/8" O.D. x 0.065 wall type 316 stainless tubing (ASTM 269) and Swagelok connection hardware rated for 442 bar (6500 psig) operation. Each composite tank has a temperature-actuated pressure relieve device (TPRD) and a multi-turn manual valve. The high hydrogen pressure of < 350 bar is reduced to a much lower pressure of < 3 bar at a regulator block before being directed to the PEM fuel cell. These features are shown in Figure 14. The manifold, connectors, valving, TPRD and pressure gauging have a temperature rating down to - 40 °F (- 40 °C). The H₂LT requires industrial grade (99.95% pure) hydrogen for operation of the PEM fuel cell.

Figure 14: H₂LT Manifold Design. Each composite tank has a TPRD and a multi-turn manual valve. The manifold is constructed of 3/8" O.D 0.065" wall 316 stainless steel tubing and Swagelok connectors rated to 442 bar (6500 psig) hydrogen pressure. Photo courtesy of Steve Wingert, MQ.

In several of the Beta Units, a 1.5 kW DC-AC inverter (Samlex model SA 1500) was installed, to provide auxiliary 120VAC power to tools. The inverter was mounted on top of the PEM fuel cell, as shown in Figure 15. On units with AC power, the power is available near the electronics control panel via a 15A/120VAC GFIC panel outlet.

DC-AC 1.5 kW Inverter

Figure 15: 1.5 kW 120VAC inverter (Samlex model SA1500) mounted on top of the PEM fuel cell in a Beta H₂LT. Photo courtesy of Steve Wingert, MQ.

The enclosure of the Beta H₂LT was constructed of powder-coated and painted sheet metal, and was designed to accommodate the larger volume of the four composite hydrogen tanks and manifolding, full integration of the fuel cell, inverter (if present) and the electronic control system. The enclosure also provided an integrated fueling panel containing the fueling port, pressure gauge and manifold ball valve. The completed enclosure and details of the fueling port and electronics control panel are show in Figure 16.

Figure 16: Beta H₂LT Enclosure, with Fueling Panel and Electronics Control Panel

The overall dimensions of the enclosure are 34.0" tall x 46.0" wide x 71.4" long. The weight of the Beta H₂LT unit is ~2500 lbs. All fuel tanks, refueling and control panel access doors are lockable for safety and security for access by authorized users only. The H₂LT unit can be towed behind a pick-up truck using standard hitch hardware (e.g. pintle or ball hitch).

Fueling is accomplished through an automotive style 350 bar TN1 connection port (WEH Products TN1 H2 (C1-31316-X1)) located on the fueling panel, with manifold pressure gauge and shut-off (fill) valve. The electronic control system allows one-button start-up of the fuel cell. Upon start-up, the PEM fuel cell undergoes a series of internal system checks, including a system leak check. After ~ 1 minute, power is available to the lighting system via 4 toggle light switches/circuit breakers. The Electronic Control panel provides a data information port to allow the PEM fuel cell system diagnostics to be accessed with a laptop computer. A green LED screen gives the status of fuel cell (active, undergoing leak test, in the process of shut-down, etc.). The PEM fuel cell possesses a hydrogen sensor, so that if hydrogen is detected within the enclosure, the fuel cell shuts down. Such a shut-down never occurred during the four years of field tests.

The lighting technology for the Beta units was either Plasma lights (as was used on the Alpha System), or LED lights from a couple of different manufacturers. The lighting technology will be discussed in more detail later.

After any H₂LT unit (Alpha or Beta) was constructed at the MQ Boise Idaho manufacturing facility, the unit was transported to nearby Norco Inc., a leading gas supplier in the U.S. Northwest. In collaboration with Norco staff, MQ staff pressurized the H₂LT manifold and tanks to 5500 psig with nitrogen and checked for leaks via bubble leak detection with soapy water. The required leak rate was no visible bubbles. After the 5500 psig nitrogen system leak check, the nitrogen charge was vented to 30 psig, and the system tanks and manifold were pumped out and then filled to 2800 psig of hydrogen (99.995% pure). After the hydrogen charge, the entire system was leak checked again with combustible gas detector and bubble leak checked. The required leak rate at any line or fitting was no visible soap bubbles and no sign of detection on the combustible gas detector. The system was then charged to 5,000 psig of hydrogen and leak checked again with combustible gas detector and bubble-check.

We measured the overall leak rate of the H₂LT manifold by valving off the hydrogen tanks, and observing the pressure decrease in the sealed-off manifold over time. Since the internal volume of the manifold is small (~ 150 mL), a very small leak from such a small volume can be detected as a pressure drop by the system pressure gauge. In one such test, the hydrogen pressure in the manifold dropped from 5000 psig to 4000 psig over the course of 10 days, corresponding to a system leak rate of 0.9 Ncc/min. The hydrogen community has established regulations [7] concerning acceptable leaks from hydrogen systems, and the maximal allowable loss from a hydrogen storage system is 150 Ncc/min for the stringent automotive application. The allowable hydrogen loss rate from any single leak is 3.6 Ncc/min. Thus the H₂LT manifolding is leak tight

to a level exceeding the required standards. These hydrogen leak and permeation standards are conservative numbers based on laboratory tests of the minimum hydrogen leak rate that can be ignited by a flame held over the leak. A 3.6 Ncc/min hydrogen leak is considerably less than that which can be ignited. A review of hydrogen safety codes and standards including allowed hydrogen leak and permeation rates for fuel cell vehicle storage technology has been given by Sloane [7]. Field testing of the Beta units showed that this excellent pressure integrity was maintained throughout the field testing, which included towing H₂LT units on all types of roads for in some cases several years.

One of the Beta H₂LT units was outfitted with a “cold weather package” designed and installed by Alteryg Systems. The concern was that if the H₂LT was left turned-off in a very cold (~ 25 °F, - 3.9 °C,) environment, the fuel cell would have trouble starting if some of the internal gas channels became blocked with ice. This freezing would be in spite of the fact that unit performs a stack purge with hydrogen before final shut-down, removing residual water. For this cold weather Beta H₂LT unit, the cold-weather package comprised of a heater and batteries were added to the system. The fuel cell software was modified such that when the fuel cell control system sensed the temperature was too cold, a pre-heat start up cycle would begin. During the ~ 10 minute pre-heat cycle, the batteries operate the heater in the enclosure, allowing the fuel cell to warm up to a safe starting temperature before normal system start-up. Once operating, the waste heat from the fuel cell allows the unit to operate continuously down to - 40 °F (- 40 °C). This cold weather package system was tested in an environmental cold chamber at Alteryg Systems, and found to allow fuel cell start up at temperatures down to about - 20 °F (- 28.8 °C).

Characterizing the Lighting:

The intrinsic energy efficiency of the lighting used on the Beta H₂LT has a dramatic influence on the overall system performance. Lighting technology most suited for the 28 VDC output of the PEM fuel cell is plasma lighting (already discussed) and LED lighting. LED lighting in particular made dramatic improvements in efficiency (lumens per watt of input power) during the course of the project. The Caltrans DRI funded the U.C. Davis AHMCT to characterize the light output and illumination pattern on the ground for the H₂LT using either plasma or LED lighting, and to compare the illumination output with a standard diesel-powered light tower using metal halide (MH) lighting. Some results are shown in Figure 17. Both LED and plasma lighting have higher energy efficiencies than the standard MH lighting technology. However, on a per fixture basis, these newer technologies output less overall light. Thus, more “fixtures” are required to equal the output of a MH light/reflector assembly. For an H₂LT outfitted with LED lights, substantially less fuel energy is required to produce the same light output as a diesel light tower with MH lights, due to the increased energy efficiency of both the LED lights and the PEM fuel cell. An in-depth discussion of the lighting tests will be given separately [4].

Light Type	Fixture Power Consumption (W)	Efficiency (lm/W)
LED	408	54.3
Plasma	476	38.4
Metal Halide	1392	35.0

-- results for one fixture each:

Figure 17: Test results for illumination (measured LUX versus ground-plane x-y location) pattern from LED, Plasma and Metal Halide Light fixtures. The LED “fixture” consists of an array of four individual Grote Trilliant 24V LED fixtures. The plasma and Metal Halide results are for single bulb fixtures of these technologies.

The observed difference between LED and MH lighting efficiency (lumens/watt) for any two systems can vary greatly due to differences between lighting manufacturers, but also due to the rapid decline in MH output with lifetime. At 10,000 hours, metal halide lights have lost ~ 50% of their original efficiency, whereas LED lighting can maintain ~ 95% of their original output. So the actual difference observed in the field between light towers using the two different kinds of lights can vary dramatically. The results of Figure 17 were acquired on new LED fixtures and “used” MH lights with unknown history. We suspect that these results were for MH lights with 10,000 hours of service or more.

Comparing the Beta H₂LT and a Diesel MQ LT-12D Light Tower:

The environmental benefits of the H₂LT technology relative to current diesel-fueled mobile lights have been calculated [8] by the U.S. DOE Fuel Cell Technologies Office (FCTO). The diesel unit used for the comparison is the Multiquip LT-12D light tower, shown in Figure 18.

Figure 18: Multiquip diesel mobile light tower model LT-12D

There are many choices and manufacturers for LED lights, and they have varying energy efficiencies which determine H₂LT duration and environmental performance. We will assume LED lighting comprised of Grote Trilliant 24V lamps, as characterized in Figure 17. A light tower can be configured based on the Grote Trilliant LEDs such that the total light output will be 177,600 lumens, consuming 3264 W of fuel cell input power. This light output would be about the same as a 4 lamp metal halide diesel light tower also characterized in Figure 17. This is a considerable light output; with 177,600 lumens output, one could read a book in otherwise pitch darkness at 150 yards distance from the H₂LT.

The results of the comparison are given in Table I. Both mobile light units are assumed to output 177,600 lumens, with Grote Trilliant LED lights used for the fuel cell systems and metal halide lights for the diesel-based LT-12D system [8].

Table I: Annual emissions and energy consumption savings associated with using one H₂LT unit in comparison to using a diesel fueled LT-12D light tower.

Annual H ₂ LT Benefits (per unit)	Renewable H ₂	NG-derived H ₂
Diesel Fuel Displaced per Year (gallons)	970	970
H ₂ Consumed per Year (kg)	375	375
CO ₂ (eq.) Savings per Year (kg)	11,292	7,055
(NMHC + NO _x) Savings per Year (kg)	68	68
PM Savings per Year (kg)	3.6	3.6
Fuel Energy Savings per Year, LHV (MJ)	86,917	86,917
Total Energy Savings per Year, LHV (MJ)	33,735	83,972

Notes: NMHC stands for non-methane hydrocarbons; PM stands for particulate matter.

Renewable H₂ is produced by wind-based electrolysis of water; NG-derived H₂ is produced by steam reforming.

The benefits shown in Table I depend on how the hydrogen is manufactured, either via reforming of natural gas (NG), or by renewable (wind-based electrolysis) methods. These results assume a H₂LT is used for 180 days a year for 10 hours a day. One H₂LT unit fueled with renewable H₂ reduces CO₂ (eq) emissions by 11,292 kg per year, with concomitant savings in other criteria pollutants. Using an H₂LT unit displaces 970 gallons of diesel fuel per year, and saves 83,972 MJ of total energy if the hydrogen is produced by steam-methane reforming of NG and 33,735 MJ if the hydrogen is produced by the renewable, but more energy-intensive, wind-based electrolysis of water.

One can compare the physical dimensions of the Beta H₂LT and the current diesel light tower LT-12 D to reveal the differences in stored deliverable energy densities. These comparisons are shown in Table II.

Table II: Comparison of Physical Parameters of the Beta H₂LT and LT-12D mobile lights. The Beta H₂LT stores 8.4 kg of hydrogen; the LT-12D stores 30 gallons of diesel fuel.

Physical Attribute	Beta H ₂ LT	LT-12D
Enclosure Dimensions (“h” x “w” x “l”, inches)	34 x 46 x 71.4	31 x 34 x 56
Enclosure Volume (L)	1829	967
Light Tower Mass, fueled (kg)	1132	786
Enclosure and Contents Mass (kg)	467	385
Duration at 177,600 lumens output (hours)	40.6	48
Engine Thermal Efficiency (%)	47	25
Engine Nameplate Power Output (kW)	5	6
Stored Fuel Capacity (kg H ₂ , or gallons diesel)	8.4	30
Stored Fuel Energy, LHV (MJ)	1005	4076
Noise Spec at 23 feet (dB)	42	73
DSV Electrical Energy Density (MJ/L)	0.258	1.053
DSG Electrical Energy Density (MJ/kg)	1.01	2.65
Refueling Time (no external cooling water)	10 mins	4 mins

Notes: Nameplate Power Output is equivalent to maximum rated power output. DSV stands for Delivered System Volumetric; DSG stands for Delivered System Gravimetric.

In Table II, the mobile light enclosures contain the fuel storage (H₂ or diesel), engine (fuel cell, diesel generator) and all required manifolding, valving, pumps and other B.O.P items. These enclosures are quite compact in their design, with little wasted space, thereby allowing a real-world practical estimate of the system volumetric and gravimetric deliverable electrical energy storage densities for these technologies. None of these enclosures are sound conditioned. Thus, the dramatically quieter (42 dB) H₂LT noise level reflects the intrinsically low-noise character of PEM fuel cells compared to diesel generators (73 dB). We see from Table II that the H₂LT possesses a smaller delivered system volumetric (DSV) electrical energy density of 0.258 MJ/L compared to that of the diesel-powered LT-12 D (1.053 MJ/L). For context, a typical 12-V lead-acid battery has a volumetric stored energy density of ~ 0.440 MJ/L [9].

To estimate the real-world practical gravimetric H₂LT and LT-12D deliverable electrical energy storage densities, we report the mass of the hardware within the enclosures, including the enclosures themselves in Table II. The H₂LT has a delivered system gravimetric (DSG) electrical energy density of 1.01 MJ/kg, whereas the DSG electrical energy density for the LT-12D is 2.65 MJ/kg. To give these gravimetric energy density numbers a context, a typical lead-acid battery has a stored gravimetric energy density of ~ 0.190 MJ/kg [9].

Field-Testing of the H₂LT

All users engaged in field-testing a H₂LT unit underwent in-person instruction on the H₂LT technology and hydrogen safety by project staff including CaFCP, Altery Systems, Multiquip and Sandia. In particular, end-users, their fire/safety personnel and in some cases first responders were instructed on all aspects of hydrogen properties and safety-related issues and procedures, as well as the PEM fuel cell technology used in the H₂LT. Any maintenance concerns arising from a H₂LT unit were referred to Altery Systems for initial evaluation, available on a 24-hour basis.

The field tests were conducted in a variety of locales chosen to challenge the technology environmentally and in terms of accomplishing a particular lighting task. The field tests were conducted from March 2010 until the project end on January 20, 2014. The field-test partners were:

1. Saunders Electric, who used the H₂LT (both Alpha and Beta systems) for many award shows and television production work in the Los Angeles area.
2. The NASA KSC, who used the Alpha and Beta units for security lighting, and also to support special events such as the final launch of the Space Shuttle Atlantis on July 8, 2011. NASA KSC used the H₂LT in the hot, humid marine air of coastal southern Florida, which represents a significant test of corrosion resistance.
3. Caltrans District 3, who used a Beta H₂LT unit in the snow of the Sierra Mountains near Lake Tahoe CA and in Sacramento CA for a variety of road construction and repair activities, cleaning debris from hillsides, and for bridge and overpass inspection work.
4. SFO, who used a Beta H₂LT for general area lighting, for lighting runway repair operations and a host of other maintenance procedures on the airfield.
5. The Connecticut Department of Transportation (ConnDOT), who used a Beta unit in support of the Q-Bridge construction project along I-95 in New Haven CT, the largest federally funded U.S highway construction project currently being conducted in the U.S.

The field testing of the unit in each of these venues will now be described.

Entertainment Events, Los Angeles CA:

Both the original Alpha Unit and a newer Beta H₂LT unit were used by Saunders Electric from March 2010 to the present at a number of award shows in Los Angeles and also used to provide

support for several television productions in the greater LA area. The units were used at the 2010, 2012 and 2013 Oscars, at the Screen Actors Guild (SAG) Awards in 2011, 2012 and 2013, and at the Golden Globe Awards in 2011, 2012 and 2013. For all of these shows, the units were used to illuminate construction work on the Red Carpet leading up to these events. As needed, the H₂LT system provided illumination of the Red Carpet during the event itself. Figure 19 shows the H₂LT providing illumination during construction of the Red Carpets at the 2011 Golden Globes, and at the 2012 SAG Awards. Introduction of the technology to the entertainment industry, through Saunders Electric and entertainment construction personnel, naturally leads to the development of the entertainment early market for this fuel cell mobile lighting technology.

Figure 19: (L) Fuel Cell Mobile Light (lower left in picture) Illuminating the Red Carpet construction work at the 2011 Golden Globe Awards, The Beverly Hilton Hotel, Beverly Hills California, January 14, 2011. (R) Two fuel cell mobile lights deployed for Red Carpet construction at the 2012 Screen Actors Guild Awards, Los Angeles Shrine Exposition Center, Los Angeles California, January 29, 2012. The Golden Globes photo courtesy of Ron Roy Productions.

Figure 20 shows Ms. Jae Je Simmons, Executive Director of the New York Division of the Screen Actors Guild, who received an informal briefing of the PEM fuel cell technology using a stand-alone 10 kW Alteryg Systems PEM power rack that was providing power for a security screening station at the 2012 SAG Awards.

Figure 20: Ms. Jae Je Simmons, Executive Director of the New York Screen Actors Guild with project team members Klebanoff (left) and Radley (right) at the 2012 SAG Awards.

From 2011 on, 350 bar hydrogen for the two H₂LT units undergoing entertainment field-tests was supplied free of charge by the Santa Monica Hydrogen Station. The longer duration of the Beta system (~ 60 hours) proved essential at these events since the H₂LT typically became “buried” in place in tight confines, surrounded by other equipment, and could not be removed for refueling.

NASA Kennedy Space Center, Cape Canaveral FL:

Deployment of initially the Alpha H₂LT (on loan from Saunders Electric), followed by a Beta H₂LT system began at the NASA KSC in May of 2011, and extended until September of 2012. Since Space Shuttle Operations use an enormous amount of hydrogen (mostly stored as LH₂), there was ample supply of hydrogen for this field test. The summer weather in Cape Canaveral Florida is characterized by high heat (average monthly high temperatures ~ 90 °F, 32.2 °C), very high humidity (~ 80%) and occasional torrential rains. Furthermore, the coastal location provides a salty marine air environment. Thus, the deployment at KSC was an excellent test of the durability of the system in strong weather, and the general corrosion resistance of the system.

As shown in Figure 21, the Alpha H₂LT system was introduced to KSC personnel on April 21, 2011. There was no need for a hydrogen safety briefing, as NASA KSC originated many of the best practices for storing and handling hydrogen, both as a gas and a liquid. Prior to use at the KSC, the H₂LT passed a thorough safety review by KSC safety subject matter experts.

Figure 21: KSC equipment, propellants and safety personnel briefed about the Alpha H₂LT operation. The Alpha H₂LT was used at the KSC until August 2011; thereafter a Beta H₂LT system was field-tested.

The systems were refueled to 350 bar using hydrogen available on-site, as shown in Figure 22.

Figure 22: Beta H₂LT system being refueled at the NASA KSC. Compressed gas is being provided at 350 bar. Photo courtesy of Rusty McGlaughlin, NASA KSC.

On occasion, the H₂LT was used for special events, one of which was the final launch of a Space Shuttle (Atlantis), shown in Figure 23. The Alpha H₂LT was used in the support of the International Press area operations, providing lighting at night. In addition, the DC-AC inverter on the unit allowed some auxiliary power functions, such as recharging camera batteries for several of the 1500 members of the international press corps in attendance. BBC radio conducted an interview with the project team about the fuel cell mobile light project.

Figure 23: Alpha Fuel Cell Mobile Light (H₂LT) in support of the last Space Shuttle launch (Atlantis), Kennedy Space Center, July 8, 2011. Photo courtesy of Steffan Schulz.

A month after the final Space Shuttle launch, the Alpha H₂LT unit was returned to Saunders Electric, and a year-long field test of the Beta H₂LT commenced at the KSC. The unit was used to provide security lighting for a new building on the site. After one year field-test, the unit was inspected on September 11, 2012 at the Institutional Support Contract (ISC) Generator Shop by two corrosion experts at NASA. A report of the corrosion findings and recommendations for how the system could be improved for corrosion resistance was forwarded to MQ so that the learning could be folded into the ultimate commercial design. In general, the corrosion experts reported that the unit looked good despite being exposed to outdoor conditions at KSC for 1 year. The H₂LT showed comparable signs of corrosion to similar types of ground support equipment that have been exposed for the same period. Most of the corrosion was in non-hydrogen parts of the system, for example the mechanical winch systems suffered corrosion, as did some cut corners in the H₂LT enclosure. However, the high-pressure hydrogen manifold (composed of 316 stainless steel) showed only superficial and spotty discoloration. Both the Alpha and Beta H₂LT performed without failure during the field tests at the KSC.

Caltrans District 3, Sacramento CA:

With coordination provided by Caltrans DRI and U.C. Davis AHMCT, a Beta H₂LT system was deployed with the road crews of Caltrans District 3 which encompasses Sacramento California

and the nearby Sierra mountains including Lake Tahoe CA. The unit was introduced on February 18, 2012 to the Caltrans District 3 Kingvale California yard located ~ 20 miles west of Truckee California, as shown in Figure 24. The field-testing was managed locally by Wil White of U.C. Davis. Refueling of the unit was performed at the hydrogen station operated by the CaFCP in West Sacramento, 95 miles from Kingvale. As a result, in the course of the deployment and for refuelings, the unit was towed up and down rough mountain roads over 1100 miles without a single occurrence of a system hydrogen leak. This was a strong test of the physical durability and stability of the hydrogen systems (fuel cell, tankeage, manifolding), as there is very little suspension on the H₂LT to cushion the ride as it was being towed. To our knowledge, fuel cells have never been exposed to the shock and vibration that occurred in the field-test with Caltrans. The fuel cell and hydrogen storage system and manifolding performed without failure, indicating the hydrogen systems and PEM fuel cell are sufficiently durable for the construction equipment application. The deployment was also a test of the endurance of the unit in cold weather. During the day, the unit was stored in a shed that had one side exposed to the elements, with no heating in the shed. At night, the unit was operated in sub-freezing temperatures. This particular H₂LT system was outfitted with the “cold weather” package described previously to allow a delayed system start if the temperature should ever reach below 25 °F (- 3.9 °C). Figure 24 shows the arrival of the H₂LT at Caltrans District 3 and its storage and use in winter weather.

Figure 24: Clockwise from lower left: Delivery of the Beta H₂LT to the Caltrans Kingvale, CA Yard on February 18, 2012; Storage of the H₂LT exposed to winter conditions; H₂LT illuminating a Caltrans chain control checkpoint along Interstate 80W in the snowy Sierra, March 16, 2012; Use of the H₂LT to perform bridge repair along Interstate 5 N in downtown Sacramento CA, September 20, 2012. Upper right photo courtesy of Tom Damberger, Golden State Energy. Upper left and lower right photos courtesy of Wil White, U.C. Davis.

In September of 2012, the unit was used to perform bridge repair along Interstate 5 N in downtown Sacramento CA (Fig. 24, bottom right picture). The Caltrans crews used the H₂LT to repair concrete spalls at the edge of the bridge expansion joints-- a task needing a lot of illumination. The crews also used the unit for bridge inspection work where the unit illuminated bridge structures underneath the road surface.

The San Francisco International Airport (SFO):

The H₂LT technology was field tested at SFO beginning in February 2013. SFO has been a national leader in exploring ways of reducing GHG emissions at airports. Deployment at SFO offered a way to evaluate the system for durability in a cold, wet and foggy marine environment and assess the use of the H₂LT in numerous aviation GSE applications such as aircraft maintenance, repair of land-based and water-based fire-fighting equipment, airfield plumbing repair, runway repair and general security lighting. As the H₂LT project began in March of 2008 with the H₂LT conceived by Boeing as a piece of aviation GSE, the deployment at SFO represents the closing of a conceptual circle for the project. At one time, SFO had considered building a hydrogen station just off the airfield to provide hydrogen for a future fleet of airport fuel cell vehicles. However, plans for that station were cancelled, although SFO maintains a strong interest in hydrogen fuel cell technology.

A Beta H₂LT system outfitted with Grote Trilliant LED lights provided by Stray Light Optical Technologies was introduced to the SFO Equipment and Fire & Safety Staff on February 27, 2013, as shown in Figure 25. SFO Fire and Safety staff fully approved use of the H₂LT for airport and airfield operations.

Figure 25: (L) Chris Radley explains H₂ physical properties to SFO Fire and Safety Staff as well as Equipment Staff, February 27, 2013.

The first SFO H₂LT hydrogen refuelings occurred at the CaFCP in West Sacramento, an hour drive from SFO which was subject to some difficult traffic delays depending on the time of day. In order to fill the unit more conveniently, an emerging supplier in mobile hydrogen delivery, IGX/GTM was contracted to deliver hydrogen to the H₂LT. IGX/GTM has developed a mobile refueling trailer (towed by pickup truck) with a capacity of 77 kg H₂ (99.95% pure) at 3600 psig. The provider of the hydrogen is Air Products.

Figure 26 shows a picture of the H₂LT in use at SFO.

Figure 26: The H₂LT illuminates the front of a United Airlines Boeing 747 parked near United's San Francisco Maintenance Operations Center at SFO.

The unit at SFO was used to collect refueling data during IGX/GTM fills and also on one occasion at a hydrogen station. An initial cascade refueling test of the H₂LT was performed on July 24, 2013, as shown in Figure 27, which was the first mobile refueling of an H₂LT “in place” without it having to be removed from the field-test site. The pressure in the H₂LT reached 3200 psig after about 10 minutes of refueling. Since this initial fill, IGX/GTM has become a certified vendor at SFO, making routine delivery of hydrogen to the H₂LT via cascade fill.

Figure 27: (L) Michael Koonce of IGX/GTM explains the mobile hydrogen refueling capability to SFO equipment staff. (R): The H₂LT being refueled by cascade fill from the IGX/GTM in the SFO equipment yard on July 24, 2013.

During the second refueling of the system on October 3, 2013, data was collected to record the change in system pressure and temperature as the cascade fill proceeded. The temperature of the manifold dropped as hydrogen gas expanded (and cooled) into the H₂LT tank volume. The results for the refueling are shown in Figure 28. During the cascade fill, the H₂LT reached a pressure of 3150 psig in ~ 10 mins, corresponding to the transfer of 5.8 kg of hydrogen. The manifold temperature dropped quickly to 19 °F (- 7.2 °C), due to cooling by the cold gas, but started to warm up thereafter due to compressive heating. At all times the temperature of manifold and valving remained above the - 40 °F (- 40 °C) minimum temperature limit of the hardware.

Time (AM)	H ₂ LT Pressure (psi)	Valve Temp. (°F)	Manifold Temp. (°F)	Tank Temp (°F)	Cascade Tank No. (on trailer)
9:34	30	57.7	71.7	---	---
9:35 start fill					1
9:38	1350	32	19	---	1
9:42	2200	39.4	38.4	----	2
9:44	2700	48.3	48.4	----	3
9:48	3000	57.7	56.9	97.3	3
9:49 Stop fill	3200	64.2	58.3	97.9	---
9:52 top off	3150	74.1	62.7	99.1	4
9:57	3150	82.3	65.7	94.0	---

Figure 28: Measurements of H₂LT hardware temperature and pressure during cascade fill of the system from the IGX/GTM mobile refueler. Conditions of the fill are as follows: Ambient air temperature ~ 68 °F (20 °C), hydrogen temperature in the trailer ~ 68 °F. Initial hydrogen pressure in the H₂LT = 30 psig. All four hydrogen tanks were open during fill. Five minutes of refueling trailer preparation time were required prior to the fill.

On one occasion, a Beta unit was filled at the A.C. Transit Hydrogen Station in nearby Emeryville California, which employs a SAE J2601 fill [10]. This particular J2601 fill involved pre-cooling of the hydrogen to - 4 °F (- 20 °C) to reduce compression heating of the storage vessel. During this fueling ~ 5 kg of hydrogen was delivered in ~ 10 minutes from an initial H₂LT system pressure of 950 psig to 5,000 psig. Thermocouple temperature measurements were made for the H₂ Tank Valve and the Manifold as described above in Figure 28. Over the course of the fueling, the valve temperature dropped from 71 °F to 32 °F (21.66 °C to 0 °C), and the manifold temperature changed from 71 °F to 6 °F (21.66 °C to -14.4 °C). Again, these temperature changes were above the - 40 °F (- 40 °C) minimum temperature limit of the hardware. The lowest temperature was reached when the system was pressurized to ~3,000 psig. Thereafter, compressive heating associated with bringing the system pressure to 5,000 psig brought the valve and manifold temperatures to 39 °F (3.9 °C) and 31 °F (- 0.55 °C), respectively. It is worth noting that the Al-lined Type III SCI tanks used in this project have an upper temperature limit of 180 °F (82.2 °C), which is limited by the glass transition temperature of the

composite overwrap. Such high temperatures were never approached during use of the SCI tanks in the project.

Connecticut Department of Transportation, New Haven CT:

In May of 2013, the H₂LT was introduced to ConnDOT, as arranged by Greg Moreland, SRA International contractor to the DOE Fuel Cell Market Transformation Program. ConnDOT is engaged in the largest federally funded highway project currently being undertaken in the U.S, along Interstate I-95 at the intersection of I-91 in New Haven Connecticut [11]. ConnDOT was interested in field-testing a Beta H₂LT to reduce emissions and noise in the work zone, allow ConnDOT to gain experience with fuel cells, promote H₂ refueling in the area and display applications of fuel cells in transportation. On May 29, 2013, H₂LT project and H₂ safety seminars were delivered to transportation engineers in the ConnDOT Research Unit in Newington, CT, as well as to First Responders in the City of New Haven, as shown in Figure 29.

Figure 29: Mickey Oros of Altery Systems explains the H₂LT (outfitted with VisionX LED lights) to New Haven First Responders responsible for the I-95 construction project.

Later that same day, project descriptions were given to staff at the Proton SunHydro H₂ Station in Wallingford Connecticut, where the unit would be refilled (17 miles from the construction site). At that meeting, SunHydro personnel trained the contractor construction staff from O&G Industries Inc. on refueling the H₂LT. The overall field-test was under the local supervision of Rick Hanley of ConnDOT.

The Beta H₂LT was fitted with LED lights from VisionX that had the highest energy efficiency of lighting tested during the project. Figure 30 shows one of the eight VisionX fixtures used on the H₂LT. The fixture contains 30 individual LED bulbs, with reflector designed for a particularly forward-focused illumination pattern.

Figure 30: A VisionX LED fixture. There are eight such fixtures on the Beta H₂LT that was field-tested by ConnDOT in New Haven, CT.

The H₂LT was inserted into ConnDOT operations on the night of May 29, 2013 and was used in a number of different night construction operations including general area lighting, and lighting for a pile-driving operation.

On September 28, 2013, feedback was collected from O&G construction workers and inspectors who had been using the H₂LT. The workers found this particular H₂LT configuration lacking in a number of areas, including light output and distribution, the inconvenience of refueling at a remote site (the Proton On-site station), the weight/balance of the H₂LT and the absence of a 115V AC auxiliary power supply on the unit. The workers were impressed with the low noise of the H₂LT, and its zero-emission performance.

This particular configuration of LED lights was deemed insufficient by the end-users in this application. Although the energy efficiency of the VisionX lights was quite high (54 lumens/watt), there were an insufficient number of fixtures on the unit to provide light that was satisfactory to the O&G construction end-user. Furthermore, this particular LED reflector was designed to provide more forward-focused light, where in this ConnDOT application a wide illumination pattern was desired to illuminate a general work area (as opposed to a particular work task). After a couple of months of use, the unit was withdrawn from field-testing. The unit has since been re-directed to SFO for use, since SFO equipment staff had already evaluated this H₂LT Beta unit, and found the illumination pattern and output well-suited to runway repair work.

This difference between end-user requirements for lighting highlights the need for MQ to offer multiple lighting configuration options for the commercial H₂LT.

The official field-tests of the H₂LT ended on January 20, 2014, coinciding with the end of the project. However, two Beta H₂LT units will continue to be used and supported by SFO, with mobile refueling from IGX/GTM. In addition, the Alpha H₂LT and a Beta H₂LT will continue to be used and supported by Saunders Electric in their entertainment industry work. Thus, two enduring fleets of H₂LT units will continue in 2014 and beyond, reducing GHG emission in aviation GSE and construction equipment. MQ and Alteryx will continue to support these fleets as arranged by SFO and Saunders Electric.

Design Lessons Derived from Field Tests of the H₂LT:

During the ~ 3 years of field testing, the end-users provided valuable feedback on how to improve the H₂LT design. In addition, a number of maintenance issues arose that point to areas needing improvement to provide a truly robust commercial product. The largest of these “design lessons” are now reviewed.

One of the major issues that arose from the field tests is unreliability in the plasma light technology in applications where the lighting system is moving. Although the technology was known to be reliable in stationary applications such as street lighting, in the mobile H₂LT the plasma fixtures failed in unacceptable numbers. The cause of the problem is believed to be a motion-induced misalignment between the plasma in the plasma light bulb and the RF waveguide when the lamp is on, which causes RF energy to reflect back into the RF driver, damaging the driver electronics. The straightforward solution to this problem was to discontinue use of the plasma lights, and introduce LED technology in the latter stages of the project. LED lights have progressed enormously in the 3 year timeframe of the project, offer higher efficiency than plasma lights, instant on/off capability and are more robust. Our testing of the LED technology indicates it is sufficiently robust for the H₂LT application, consistent with LED technology already being used in mobile applications such as automobiles and other mobile equipment.

Another major issue was the reliability of the manual multi-turn tank valves on the composite hydrogen tanks. Six of the 22 manual multi-turn tank valves on H₂LT units became stuck after 3 years of service. Typically the valve stem seized in the closed position. In two cases, the valves could be freed up, with the valve stem lubricated externally to prevent re-occurrence of the problem. However, in the other four cases, the valve could not be repaired in the field. These valve problems did not produce a hydrogen leak, did not involve contamination of the hydrogen fuel, nor had adverse impact on fuel cell integrity. However, these valve failures interfered with H₂LT refueling. A multi-turn valve is not needed for the H₂LT application, since only a 1/4-turn valve rated for 6500 psig hydrogen service is needed. MQ will be using a 1/4-turn manual ball valve such as that provided by Oasis Valve (Model T104) for the commercial H₂LT.

Table III summarizes additional reliability issues that surfaced during the H₂LT field tests, and the corrective action being undertaken for the commercial H₂LT design.

Table III: Additional reliability issues with the H₂LT, with design solutions.

The Problem	The Design Solution
1. Fuel Cell voltage tap connections can come loose with vibration.	The voltage taps on the Altergy PEM fuel cell were re-designed to make it impossible to shake loose with vibration
2. FC purge line pinched closed during enclosure assembly, which caused a fuel cell operating error.	MQ will position the purge line in the commercial H ₂ LT so it cannot be pinched closed.
3. Main winch severely rusted after 1-year KSC use.	Commercial H ₂ LT will have a more corrosion-resistant winch
4. On one unit, operating the AC Auxiliary Power led to a fuel cell shutdown.	Grounding issues between the DC/AC inverter and the fuel cell caused the problem and were resolved. The commercial H ₂ LT will incorporate the design change.
5. The H ₂ LT is so quiet that in some outside environments (city streets) workers forget the system is on during the day, wasting fuel	The commercial H ₂ LT will have a prominent “system power on” light to remind users the system is on in the daytime.
6. If the FC waste heat vent is on top of cabinet, snow can enter the H ₂ LT	The commercial unit will have the FC waste heat vents on the side of the enclosure.
7. The Beta H ₂ LT needs better balance to allow easier maneuvering	The balance issue will be addressed in the commercial H ₂ LT final design
8. The cabinet locks/keys were deemed insufficient to withstand cold weather conditions	More robust cabinet lock systems will be installed on the commercial H ₂ LT unit.

9. A pivot point on the H₂LT tower mast became corroded during 1-year field test at the NASA KSC

NASA recommends applying a zinc-based sacrificial coating to the frame under the black powder coating to prevent corrosion.

Relationship to Other Work and Products

During the course of this project, we became aware of related activities in the effort to bring fuel cell power to portable lighting. Recently, BOC developed a small fuel cell mobile lighting system using hydrogen as the fuel source [12]. The BOC product operates in a very different regime of power and lighting output than the H₂LT. The H₂LT has a 5000 W Altergy fuel cell, compared to the 150 W fuel cell in the BOC. The H₂LT stores 8.4 kg of hydrogen, compared to the 0.18 kg stored by the BOC hydrogen cylinder (which itself weighs 10 kg). Also, the H₂LT is designed to output the equivalent of ~4000 W of conventional lighting power for 66 hours, compared to the ~ 600 W of lighting power by the BOC unit which advertises duration of 24 hours. So, the two units are designed for very different tasks. The Multiquip H₂LT is designed for large area, long endurance lighting; the BOC unit for small area, shorter duration lighting. Since both are useful tasks, it is gratifying to see fuel cell proliferation in these different power regimes of portable equipment.

After our demonstration of the H₂LT at the 2009 AASHTO meeting, we became aware of unpublished work from 2006 in which Bowman and colleagues [13] at the Jet Propulsion Laboratory (JPL) proposed a fuel cell mobile lighting system for a U.S. Air Force demonstration. The proposed unit was based on a retrofit to a Unicore NF-2D Floodlight Set (i.e., a light cart), with a metal hydride hydrogen storage system storing 1 kg of hydrogen integrated to a 2 - 4 kW liquid cooled fuel cell. Such a system was demonstrated at Hickam Air Force Base in Hawaii by Hawaii Hydrogen Carriers LLC.

Next Steps Toward Commercialization:

With the field-tests results completed, and a wealth of information garnered from the end-user feedback across all 5 field-test sites, MQ is in the process of redesigning the commercial system to reduce cost while maintaining performance. With the rapid increase in the energy efficiency (lumens/watt) of LED technology, the commercial H₂LT system does not need a 5 kW fuel cell as it was configured during the project. A lighting power draw of ~ 2 kW should be sufficient for most lighting applications, indicating that unless an end-user needs large amounts of auxiliary power, then the system could be built using a less expensive ~ 2.5 kW PEM fuel cell. Sandia has recommended to MQ that the commercial system be based on 3600 psig hydrogen tank technology. Filling a unit to 3600 psig would provide 75% of the hydrogen storage

accommodated by 5000 psig storage technology. The duration of the Beta H₂LT equipped with the VisionX LED lights was typically ~ 85 hours when the unit was filled to 5000 psig. The runtime with 3600 psig hardware would be ~ 60 hours, still a very good duration. The cost of the system hardware (tanks, valves, etc.) for 3600 psig hydrogen service would be about half the cost of hardware rated for 5000 psig. By reducing costs for the fuel cell, and the hydrogen storage system, the price of the unit (including markup), originally estimated to be ~ \$50K, could be reduced to a more acceptable ~ \$35K per unit. Other approaches to reducing H₂LT system cost even further are currently being evaluated by MQ. In the course of showing the technology at trade shows, the system was quoted to hundreds of potential customers in the U.S. and Canada, but the ~ \$50K selling price was identified as a barrier to purchase.

By going to a system based on 3600 psig pressure, the H₂LT technology would not need to rely on the very few existing H₂ stations to be fueled. Such stations will be gradually coming to the U.S. as fuel cell electric vehicles (FCEVs) gradually roll out. Instead, the units could be very conveniently refilled today using the 3600 psig mobile refueling technology such as that developed by IGX/GTM, and which is now in routine use at SFO. Mobile refueling is the near-term future for a piece of fuel-cell-based portable equipment such as the H₂LT. Alternatively, the H₂LT unit could be fueled from commercially available (but more expensive) bottled hydrogen at ~2300 psig, with a booster pump increasing the pressure to 3600 psig.

The Fuel Cell Mobile Light project has shown that PEM fuel cells and associated hydrogen hardware are sufficiently robust for the mobile light application. The durability of the technology was unknown going into the project, as fuel cells had never before been subjected to the harsh conditions involved in the field-tests. The field-tests also revealed that the end-user enjoys how quiet the technology is, and its zero-emissions rating. The system can be used in a wide variety of applications from entertainment, to road construction, and many applications in-between. Commercializing the system will require getting the system cost down, with MQ's approach being to reduce the fuel cell power, and lower the system pressure rating. MQ must also find the right combination of LED lighting technology options that are flexible enough to meet the varying (and sometimes conflicting) demands of the customer on illumination pattern and total light output, while maintaining high lumen/watt energy efficiencies. The future looks bright as LED lighting technology continues to rapidly advance and come down in price as well.

Fuel availability is a commercialization concern for MQ, as neither mobile hydrogen refueling nor stationary hydrogen stations are currently widespread. Light-duty FCEVs are coming, and their introduction in large numbers will be a rising tide lifting all boats from a hydrogen availability and infrastructure point of view, allowing lower-cost mobile hydrogen refueling at 3600 psig as well. Even though the initial H₂LT units would be geared to mobile refueling at 3600 psig (to reduce costs), the H₂LT can easily incorporate higher-pressure composite tank technology (as was the case for the Alpha and Beta H₂LT units). With the move to 700 bar hydrogen stations to support FCEVs, when such stations became truly widespread, MQ would need to increase the pressure rating of its storage tanks beyond the 350 bar tanks used in this

project to fuel at such stations. Before the H₂LT can be truly sold on a wide scale, more hydrogen fueling (mobile, stationary) infrastructure will have to be developed. Multiquip is committed to commercializing the technology, but sales of the H₂LT limited to major markets only with current fuel availability is not sufficient for a successful product launch. In the meantime, in 2014, MQ will redesign the H₂LT system for lower fuel cell power and lower pressure rating, determine the most desirable LED lighting packages, while driving down the H₂LT system cost to as low as possible.

Reception of the Technology by the Construction Equipment Community

During the early phases of the field-testing, MQ showed the H₂LT technology to its power generation and construction equipment customers in order to gauge potential customer interest in the technology. The H₂LT technology was first shown at a power technology trade show on December 15, 2010 at PowerGen in Orlando Florida. Before the show, the Orlando Convention Center Fire Marshall was briefed on the H₂LT technology and the physical properties of hydrogen gas, by the CaFCP, Alteryg and Sandia. After the briefing, permission was granted to operate the unit indoors. The H₂LT was the only piece of power generation equipment allowed to run inside the convention center (diesel equipment is forbidden to be run indoors at such facilities). Figure 31 shows the operating Alpha H₂LT at this first trade show appearance.

Figure 31: The first appearance of Alpha H₂LT technology at PowerGen 2010, December 15, 2010, Orlando Convention Center in Orlando Florida.

Similarly, the Beta H₂LT was first shown at the World of Concrete Trade Show on January 19, 2011 at the Las Vegas Convention Center. Prior to the show, the Las Vegas Convention Center Fire Marshall was also briefed on the H₂LT technology and hydrogen properties as they relate to safety issues. After the briefing, permission was granted to operate the unit indoors. Figure 32 shows Torsten Erbel of Multiquip being interviewed about the Beta H₂LT technology at the World of Concrete show on January 19, 2011 in Las Vegas Nevada.

Figure 32: Torsten Erbel of MQ (left) being interviewed about the Beta H₂LT unit being shown for the first time at the World of Concrete Show, January 19, 2011, Las Vegas Convention Center, Las Vegas Nevada.

The reception given the technology at these shows by the all-important customer base was very positive. The H₂LT project and technology has received recognition from the rental and construction equipment industries, as well as from the DOE and from U.S. Federal Technical Transfer Organizations. These recognitions include:

1. 2011 Rental Equipment Magazine “Grand Prize” for Innovative Technology, December 20, 2011;
2. “Editor’s Choice Award” for Most Innovative New Product in “General Equipment,” World of Concrete 2011, February 15, 2011;

3. 2011 DOE Hydrogen and Fuel Cells Program R&D Award, “In recognition outstanding contributions to Fuel Cell Market Transformation Activities,” May 11, 2011;
4. 2012 Federal Laboratory Consortium (FLC) National Award for Excellence in Tech Transfer, May 3, 2012;
5. 2010 Federal Laboratory Consortium Award “Mid-Continent Region” for “Notable Technological Achievement”, September 2010.

The H₂LT received a U.S. Patent in 2013 [14].

Impressions of this Fuel Cell Market Transformation Project from the Industrial Participants:

For many of the industrial participants, this project was a new experience, not only in a technical sense (creating a new product based on hydrogen fuel cell technology), but also in the way the project was organized, funded and executed. The industry partners found it to be a very effective way of partnering together. Alteryg’s experience was very positive, because the project had:

1. Top echelon partners in their respective field of responsibility
2. A very professional team with an open exchange of data
3. A “team first” approach philosophy within the group, with no guarding of turfs.

Alteryg would not have pursued fuel cells in the construction market were it not for this project, an indeed, the H₂LT platform opened up further product opportunities that were not originally anticipated.

From Multiquip’s perspective, the Fuel Cell Mobile Light project had a “profound” effect on the company. In particular, the project:

1. Exposed and entered the company into a technology MQ would not have otherwise pursued.
2. Created a new technology platform (Earthsmart™) within MQ.
3. Added new product lines to MQ’s offerings.
4. Generated acknowledgement from the construction field for innovative thinking.
5. Gave MQ the opportunity to work with leading companies and gain knowledge from their expertise. It was a wonderful experience for the company’s team members.
6. It broadened MQ’s view and exposed MQ to the benefits of working outside the company on a development project, gaining many new friends and business partners and an enormous amount of support.

We believe this project broke new ground on how a large group of entities with a shared genuine concern about GHG emissions can come together to accelerate the introduction of hydrogen fuel cell technology into new markets.

Conclusions:

A project was described to introduce hydrogen PEM fuel cell technology into aviation GSE and rental construction equipment. The H₂LT fuel cell mobile light tower combines hydrogen stored as a high-pressure gas, a 5 kW PEM fuel cell and advanced lighting into a single unit with uses in aviation and construction. A 15-institution project team was assembled, bringing together new technology expertise (hydrogen and fuel cells), equipment mass manufacturing capability (mobile lights, lighting) and influential end-users who could field test the H₂LT in real-world use in diverse environments and provide feedback for design improvement. Prototype units were constructed and field tested in the entertainment industry, with SFO, the NASA KSC, Caltrans, and with ConnDOT. These field tests allowed us to assess the durability of the H₂LT technology in a wide variety of potentially corrosive environments (cold/wet, hot/humid/salt-air) while performing a wide variety of tasks. At the same time the H₂LT reduced diesel emissions at the field-test sites and helped to promote hydrogen PEM technology in new influential markets. The H₂LT proved to be exceptionally durable in these diverse environments, demonstrating the compatibility of PEM fuel cells and high-pressure hydrogen storage with the construction equipment application. The field tests produced data on system performance (efficiency, duration, GHG reductions), the ease of refueling the system by different methods (H₂ stations, mobile refueling), and feedback assessing the H₂LT performance in different and often difficult lighting tasks. The H₂LT system was compared directly to a comparable diesel-fueled light tower with regard to size, performance and emissions. Overall, end users were pleased with the performance, noting the lack of emissions and exceptionally low noise level. LED lighting was found to be the most energy efficient and robust lighting technology for the H₂LT application. The technical “lessons-learned” are being folded into the final H₂LT design for commercialization by Multiquip Inc. The industrial participants found the project to be a very effective way of working together to reduce GHG emissions in the aviation GSE and construction equipment markets, and to accelerate the introduction of hydrogen fuel cell technology into these new markets.

Acknowledgements:

It is with great pleasure that the authors acknowledge the contributions of many who made this project possible. Very early encouragement of the project from Jay Keller, former lead of the Hydrogen Program at Sandia National Laboratories, was critical for the early success of the project. Continuing support and encouragement from Tom Felter and Joe Pratt at Sandia is deeply appreciated.

Partial funding from the Boeing Company is gratefully acknowledged via the Boeing/Sandia CRADA SC02/1651.14.00. Funding from the Fuel Cell Market Transformation program (led by Pete Devlin) at the U.S. DOE Fuel Cell Technologies Office was critical, making the broader and stronger development project possible, and specifically allowing the construction and field testing of five additional H₂LT units. In addition to funding, we appreciate the encouragement of Pete and his colleagues Nancy Garland and John Christensen in the Market Transformation program. Special thanks to Sunita Satyapal at DOE for supporting this work. The authors thank Tien Nguyen of DOE for providing an analysis of GHG emissions for the H₂LT technology, with the hydrogen derived from either steam reforming of natural gas, or wind-based electrolysis of water.

Jonathan Cuppett, Juan Quiros and Bob Apuzzo at MQ assisted with many of the field tests of the H₂LT, for which the authors are grateful. We acknowledge the superb support MQ received from Norco Inc. staff Ken Goicoechea and Roger Hudgens, both gas manufacturing plant operations managers with over 20 years' experience in the gas production business. Ken and Roger played a vital role in the system leak checking and final pressure certification of every H₂LT unit leaving the Boise Idaho MQ manufacturing facility.

The project would not have been successful without the participation of Caltrans. We thank Randy Iwasaki, former director of Caltrans, for providing wonderful encouragement and support of the work in its early phases, and offering resources of the Division of Research and Innovation at Caltrans (under the direction of Larry Orcutt) to be applied in support of the project. Larry Orcutt directed Nancy Chinlund of Caltrans to become involved. Nancy was very proactive in launching the project from a Caltrans perspective, which led directly to Randy Woolley's involvement in the project. The Caltrans partners aggressively challenged the project to build a prototype in a few months' time to be shown at the 2009 AASHTO meeting.

Caltrans provided considerable in-kind support through the donation of its own technical expertise, but also through its support of the U.C. Davis AHMCT for characterizing the lighting options for the H₂LT as well as supervising the Caltrans District 3 field test. We acknowledge the contributions of Gonzalo Gomez of Caltrans for discussions of lighting technology options for the H₂LT. Ben Creed, Lauren Miller, Sean Donohoe and Matt Jones at U.C. Davis provided many hours of night work characterizing the illumination provided by the candidate plasma, LED and MH lighting options. In a related activity, Ty Larson of Boeing performed checks that the glass covering the plasma lights was sufficiently absorbing UV radiation, which was very helpful.

The staff at Saunders Electric, including Ron Brewer, Frank Soggiu and Pat Hess were instrumental in the 3-year field tests of the Alpha and Beta H₂LT units used for the Los Angeles entertainment award shows and elsewhere in the entertainment industry.

The field test of the unit at the NASA KSC was an excellent example of cooperation between government agencies. We thank Chuck Griffin for providing local supervision of the project from the NASA KSC end, along with a lot of help from Melissa Clevenger of the propellants group and Ray Davis from operations. The KSC staff were extremely professional and helpful. We thank Pattie Lewis Burford (ITB Inc.) and Jerry Curran (EASI) for providing corrosion inspection of the Beta unit that was field tested at the NASA KSC for a year, and Randy Morris for extensive coordination.

A number of folks associated with ConnDOT and its contracting partner O&G Industries were instrumental in the field testing in New Haven CT. While Rick Hanley of ConnDOT oversaw the field test of the unit at the Q-bridge construction project along I-95 in New Haven, Joe Hudach was the lead engineer from O&G Industries managing the H₂LT use at the construction site. We thank Larry Moulthrop and colleagues at the Proton SunHydro H₂ Station in Wallingford CT for providing refueling services for the H₂LT during its deployment in New Haven CT.

A number of people and institutions facilitated various field tests during the project, in some cases donating needed hydrogen. We thank Polo del Toro and Bill Loper of the Sunline Hydrogen Station in Palm Desert CA for donating hydrogen in support of the 2009 AASHTO showing of the Alpha Unit. The authors thank Dan Rabun and Andrew Yulio of Air Products who provided refueling training to Saunders Electric staff during the early field-tests of the unit at the 2010 Academy Awards for which a mobile hydrogen station was rented and located at the Saunders Electric equipment yard in Arleta CA. Dan Poppe and the Burbank Hydrogen Station was a hydrogen vendor for several early entertainment field tests. Later, Rick Sikes and his staff at the Santa Monica Hydrogen Station donated hydrogen to the cause and provided refueling for the H₂LT field tests at many entertainment award events in Los Angeles, CA.

Nico Bouwkamp and Jordan McRobie of the CaFCP are acknowledged for connecting the project with the Sunline Hydrogen Station and the Santa Monica Hydrogen Station, respectively. During deployment of the H₂LT in Caltrans District 3, the H₂LT unit was refueled at the hydrogen station on the property of the CaFCP. We thank the refueling staff at the CaFCP for many trouble-free refueling events.

Special thanks are extended to Mark Bauserman, former Chief Engineer of Paramount Pictures. Mark “got” the H₂LT concept very quickly, and was instrumental in connecting the project to the entertainment world, and advising us on ways the technology could be most fruitfully used in that realm of application. Mark hosted the showing of the H₂LT on Stage 17 at Paramount on January 14, 2010, and arranged for Saunders Electric to attend, as well as many technology representatives from Hollywood studios.

Thanks are extended to Jaimie Levin (formerly of A.C. Transit), Steve Eckhardt (formerly of Linde) and Nitin Natesan of Linde for providing the SAE J2601 fill of the H₂LT at the Emeryville CA hydrogen station, and to DeLisa Leighton at IGX/GTM who coordinated multiple refuelings of the H₂LT units at SFO using the IGX/GTM mobile hydrogen refueler. We acknowledge many helpful conversations and excellent project support concerning the composite hydrogen tanks from John Coursen of Structural Composites Industries.

Finally, Lennie Klebanoff would like to thank Woody Clark for many interesting and supportive conversations concerning fuel cell technology and entertainment environmental activities. Woody also helped to promote the technology in his contacts and work in the Los Angeles area, which is very much appreciated.

Figure 33 shows some of the participants acknowledged above involved with the field-testing of the H₂LT. Unless indicated otherwise, all photographs appearing in this paper are courtesy of L.E. Klebanoff.

NASA KSC

Saunders Electric, Inc.

SFO

Caltrans District 3

ConnDOT

Figure 33: End-users who participated in the field tests of the H₂LT.

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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