ABSTRACT

Liquid hydrogen is increasingly being used as a delivery and storage medium for stations that provide compressed gaseous hydrogen for fuel cell electric vehicles. In efforts to provide scientific justification for separation distances for liquid hydrogen infrastructure in fire codes, the dispersion characteristics of cryogenic hydrogen jets from high aspect ratio nozzles have been measured. These nozzles are more characteristic of unintended leaks, which would be expected to be cracks, rather than conventional round nozzles. Spontaneous Raman scattering was used to measure the concentration and temperature field along the major and minor axes. Within the field of interrogation, the axis-switching phenomena was not observed, but rather a self-similar Gaussian-profile flow regime similar to high-pressure, room temperature hydrogen releases through round nozzles. The concentration decay rate and half-widths for the planar cryogenic jets were found to be nominally equivalent to that of round nozzle cryogenic hydrogen jets indicating a similar flammable envelope. The results from these experiments will be used to validate models for cryogenic hydrogen dispersion that will be used for simulations of alternative scenarios and quantitative risk assessment.

1.0 INTRODUCTION

Hydrogen is a carbon free fuel with a high gravimetric energy density, but the volumetric energy density, especially under standard conditions (atmospheric temperature and pressure) is low. Although the energy contained in 1 kg of hydrogen is roughly the same as the energy in 1 gallon of gasoline (120 MJ), a fuel cell electric vehicle (FCEV) can travel approximately twice as far on this amount of energy [1, 2]. High pressures and/or low temperatures can be used to improve the volumetric energy density of hydrogen. As a liquid at atmospheric pressure, hydrogen has approximately one quarter the volumetric energy density as gasoline. In other words, for the same number of FCEVs to travel the same distance as gasoline vehicles, a fueling station would need approximately twice the volume of liquid hydrogen as gasoline. At a storage pressure of 500 bar (at atmospheric temperature), a fueling station would need nearly 5 times the volume of compressed hydrogen as gasoline for the same criteria. For this reason (and reducing the frequency of deliveries), liquid hydrogen is the medium of choice for delivery and storage at large fueling stations serving many vehicles.

Continued research into the behavior of liquid hydrogen is needed to ensure safe handling of this fuel. The safety code that is most frequently used to govern the use of hydrogen in the United States is NFPA 2, Hydrogen Technologies Code [3]. In one section the minimum distances to exposures are listed for bulk liquefied hydrogen storage containers. These minimum distances are in many cases (e.g. minimum distance to air intakes) very large (23 m) and significantly larger than a comparable compressed gaseous system (10 m). The scientific justification for the minimum distance to exposures for compressed gaseous systems is documented in the annex of
NFPA 2, much of it based on work at Sandia National Laboratories [4]. A comparable analysis is needed for liquid hydrogen systems.

The basis for risk informed separation distances is validated physical models of hydrogen, especially unignited dispersion and flames. When these analyses are performed, models typically assume round releases of hydrogen. A real unintended release would be expected to have a much higher aspect ratio, for example, a crack in a hydrogen tube or leakage around a packing seal of a valve. It is therefore critical, to assess whether a round release has a similar behavior, or is at least the worst case assumption so that the risk is not underestimated. For compressed gaseous hydrogen, the unignited dispersion of hydrogen through high aspect ratio nozzles have been experimentally studied by Ruggles and Ekoto [5], who found that the centerline decay rate of hydrogen mass fraction was faster than for a round nozzle (i.e., the round nozzle was the worst case). Other than this study, there is scant experimental data specific to hydrogen dispersion through high aspect ratio slots.

Helium is often used as a proxy for hydrogen during experiments, as it is highly diffusive and buoyant. Li et al. [6] found a hyperbolic mass-fraction decay that was higher for high aspect-ratio slots compared to round nozzles for helium. Soleimani nia et al. [7] also used helium as a proxy for hydrogen and found the decay rate of concentration and velocity to increase with aspect ratio. Increased decay rates are attributed to higher entrainment rates due to increased mixing in the near field with high turbulent kinetic energy [7, 8]. Other experimental studies of air jets through high aspect ratio nozzles show similar trends (e.g. [7–10]).

CFD has been used to numerically study hydrogen concentration profiles through rectangular slots by Li et al. [11] and Makaraov and Molkov [12]. Both groups confirmed faster decay rates for rectangular jets as compared to round jets for high pressure releases. Li et al. [11] found this increase in decay rate to only occur at pressures above 3.7 MPa.

Liquid hydrogen is typically stored at low pressure (≤ 10 bar) so in this work we experimentally measure the dispersion of cryogenic hydrogen though high aspect ratio nozzles at pressures below 10 bar. This provides insight into whether observations for warm hydrogen and helium (and air), including the increased decay rates of concentration, also occur for cryogenic hydrogen releases through high aspect ratio nozzles. This data is critical to ensuring the safety of hydrogen infrastructure with liquid hydrogen.

2.0 EXPERIMENTAL DESCRIPTION

We measured cryogenic hydrogen dispersion through varied aspect ratio nozzles using the cryogenic hydrogen release platform at Sandia National Laboratories, described in detail by Panda & Hecht [13]. Briefly, gaseous hydrogen is cooled in a three-stage heat exchanger before flowing into the laboratory through a vacuum jacketed line. The pressure at the nozzle is controlled, and the temperature is measured. Temperature control at the nozzle is achieved by manually adjusting the flow of coolants (liquid nitrogen and liquid helium) through the heat exchanger. The hydrogen can be liquefied in the heat exchanger, but warms by the time it flows to the nozzle. A co-flow of air through a 19 cm diameter honeycomb at 0.3 m/s surrounded the cold hydrogen, to minimize the effect of any spurious room currents. A square 80 x 80 cm square hood located approximately 70 cm above the nozzle exhausts the gases. Typical exhaust volumes were 100 l/min, giving a face velocity of around 2–2.5 m/s.

The nozzles tested in this work had aspect ratios of 16 and 32, with an exit area equivalent to a 1 mm diameter round nozzle. Two and 4 bar hydrogen at around 50 K was released through these nozzles and the dispersion along the major and minor axes were measured, starting about 40 mm downstream from the nozzle.
Measurements were made using planar laser Raman imaging with a setup similar to that described in Hecht & Panda [14]. In these experiments, the third harmonic wavelength from a Nd:YAG laser (355 nm, 9 ns pulse, 450 mJ/pulse) was focused into an approximately 16 mm high sheet that illuminated a portion of the flow. A PIMAX ICCD with a gain of 255 and 4 × 4 binning was used to measure Raman light scattered off of nitrogen molecules, while a PIXIS 400B operated with 4 × 4 binning was used to capture Raman light scattered off of hydrogen molecules. Each camera was outfitted with a Nikon 50-mm lens, a Nikon 3T close up lens, and an OD 4, 355 nm, 17 nm FWHM notch filter to block out Rayleigh and Mie scattered laser light. The nitrogen camera also included two 387 nm, 15 nm FWHM, OD 6 fluorescence filters, while the hydrogen camera included two 420 nm, 10 nm FWHM, OD4 bandpass filters to capture Stokes-shifted spontaneous Raman scattering at 387 nm and 417 nm for nitrogen and hydrogen, respectively.

As described in Hecht & Panda [14], spontaneous Raman shifted scattering is proportional to the concentration of each gas and the intensity of the incident laser light. The proportionality constant is a function of the cross-section of the gas molecules as well as the collection efficiency and response of the camera and optics system. The response of the lens and camera systems were calibrated (such that the signals would be proportional to the amount of Raman light) by measuring the Raman signals from hydrogen or nitrogen for each binned camera pixel. A proportionality constant was found for each binned pixel to relate the observed counts for pure hydrogen to the intensity of light. This calibration process accounts for the unequal response for each binned camera pixel and any lens collection effects such as vignetting that was observed towards the edges of each image. A target was imaged by both cameras to find a mapping between pixels on the nitrogen camera to those on the hydrogen camera. Each image had approximately 2.5 pixels per mm after the binning and mapping process.

Mole fractions and temperatures for each pixel are calculated as

\[ x_{\text{H}_2} = \frac{I_{\text{H}_2} k_{\text{N}_2}}{I_{\text{H}_2} k_{\text{N}_2} + 1.28 I_{\text{N}_2} k_{\text{H}_2}} \]

\[ x_{\text{N}_2} = \frac{I_{\text{N}_2} k_{\text{H}_2}}{I_{\text{H}_2} k_{\text{N}_2} + 1.28 I_{\text{N}_2} k_{\text{H}_2}} \]

\[ T = \frac{I_0 k_{\text{H}_2} k_{\text{N}_2}}{I_{\text{H}_2} k_{\text{N}_2} + 1.28 I_{\text{N}_2} k_{\text{H}_2}} \]

where the mole fractions are denoted by \( x \), the temperature by \( T \), the corrected measured intensity by each camera by \( I \), and the subscript \( I_0 \) is the intensity of the laser sheet (which has variations over its height). The factor of 1.28 comes from the fact that air contains only 78% nitrogen. The factors \( k_{\text{N}_2} \) and \( k_{\text{H}_2} \) are found during the calibration process and were 1.28 · 295 K and 0.19 · 295 K, respectively, in the current configuration.

3.0 RESULTS AND DISCUSSION

This study focuses on understanding the structure and behavior of cryogenic hydrogen under-expanded jets from plane nozzles and compare the characteristics with round nozzle jets. In preliminary experiments, condensation of air at the exit of the nozzle was observed for release temperatures below 50 K which had a tendency to steer or split the hydrogen dispersion. To avoid such biasing on the results, the experiments were conducted for release temperatures above 50 K. Concentration measurements were carried out for hydrogen jets between 50 and 64 K and 3–5 bar

\[ \text{abs} \]

stagnation pressure. Two rectangular slot nozzles with aspect ratio of 16 and 32 have been used. The length and width of each slot nozzle was set such that the exit area was equivalent to that of a 1 mm diameter circular nozzle (the AR16 nozzle is 0.222 mm × 3.545 mm
Table 1. Experimental conditions.

<table>
<thead>
<tr>
<th>Experimental Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>pressure (bar$_{abs}$)</td>
<td>3 and 5</td>
</tr>
<tr>
<td>temperature (K)</td>
<td>50–64</td>
</tr>
<tr>
<td>hydrogen mass flow rate (g/s)</td>
<td>0.3 ± 0.02 and 0.475 ± 0.03</td>
</tr>
<tr>
<td>aspect ratio</td>
<td>16 and 32</td>
</tr>
</tbody>
</table>

and the AR32 nozzle is 0.157 mm×5.013 mm). This enables comparisons to the dispersion characteristics of the round nozzle jets studied by Hecht & Panda [14] for similar flow conditions. The experimental conditions investigated in this study are summarized in Table 1. Six to eight imaging areas were sampled, starting 40 mm downstream from the nozzle with successive areas imaged by traversing the nozzle assembly downwards in increments of 14 mm. 500 pairs of images were taken at each sampling window. Images at each height were stitched together to reconstruct the overall scalar field. For each slot nozzle, images were taken along the major as well as minor axis. Sample median profiles of hydrogen, nitrogen and temperature along minor axis (AR16) for 3 and 5 bar$_{abs}$ are displayed in Fig. 1. These images illustrate that the stitching is fairly smooth, being least smooth at location farthest from the nozzle. At locations further downstream of the nozzle, a higher amount of humid air is entrained by the jet which increases the background scattered light causing higher noise levels on the corresponding images. On average, both the jets have warmed by about 70 K and the concentration has decayed by approximately 30% at 40 mm downstream of the nozzle.

The nozzle pressure and temperature was continuously monitored as the 500 set of images were being acquired at the different distances from the nozzle. The variation of these parameters during data collection for AR16 (major axis) nozzle are shown in the left frames of Fig. 2. The variation of these parameters from the corresponding median values are represented by boxplots for the 25th and 75th quartile and whiskers extend to 5th and 95th percentage of the data. The pressure at the nozzle exit was the primary controlling parameter and it shows negligible variation during the data acquisition period. The temperature on the other hand, does not remain that steady and has some variation due to the manual control of this parameter. For both the 3 and 5 bar$_{abs}$ releases, the temperature varies not only at each image set, but also at different imaging heights. A drop in temperature increases the hydrogen density while the corresponding reduction in choked flow velocity, slightly offsets the variation of the mass flow rate. This unsteadiness in the flows adds error to the data, in addition to the errors associated with the noise on the cameras and data processing techniques.

For the AR16 nozzle, the variation of median centerline hydrogen mole fraction and temperature as a function of distance from the nozzle is shown on the right frames of Fig. 2. For some image sets, the maximum mole fraction and minimum temperature was observed to shift laterally due to ice buildup at the nozzle exit. Therefore, rather than extracting the values of mole fraction and temperature along the vertical axis corresponding to 0 mm (refer Fig. 1), the centerline mole fraction and temperature have been defined as the maximum average mole fraction or minimum average temperature at each vertical height. This approach enabled in reducing the variation in the centerline data where the different images were stitched together. However, some discontinuities are still observed for mole fraction and temperature at some heights where the images are stitched. This may be partially attributed to shifts in the centerline of the jet out-of and back into the laser-sheet plane. For the mole fraction data, a slight discontinuity is observed at 84 mm from the nozzle for the 3 bar$_{abs}$ release while at 96 mm for the 5 bar$_{abs}$ release. In terms of temperature, discontinuities are evident at the stitching location 96 mm and 110 mm downstream of the nozzle for 3 and 5 bar$_{abs}$ release, respectively. The overall trends
Figure 1. Mole fractions of hydrogen (top), nitrogen (middle) and temperature fields (bottom) along the minor-axis (the laser sheet is parallel to the minor axis) of the AR16 nozzle for 3 bar (left) and 5 bar (right) nozzle pressures.
Figure 2. Nozzle pressure and temperature during data acquisition (left frames), and median centerline mole fraction and temperature (right frames) as a function of distance from the nozzle, for the AR16 (major axis) slot nozzle. In the frames on the left, the dashed line connects the median values while images were taken at each sampling window, the boxes represent 25th and 75th quartiles, and the whiskers extend to the 5th and 95th percentage of the data. In the frames on the right, the median centerline mole fraction or temperature are shown by the solid lines, while the shading proceeds out to the dashed lines that capture the 25th and 75th quartiles of the data.
of the centerline data are as expected, decreasing mole fraction and increasing temperature. The centerline mole fraction for the 5 bar$_{abs}$ release was higher than the 3 bar$_{abs}$ release at all the vertical distances investigated in this study while the centerline temperature was lower, as expected for the same temperature release conditions. The shaded regions show the 25th and 75th quartiles of the mole fraction and temperature data. This spread can be primarily attributed to strong turbulent fluctuations in the flow in addition to some noise in the data which causes minor variation.

3.1 Concentration

The average centerline mass fraction ($Y_{H_2,cl}$) decays for the various nozzle aspect ratios and stagnation pressures are shown in Fig. 3. Although there is some scatter in the data, it is clearly evident that the inverse average centerline mass fraction increases linearly with downstream distance, which shows that the canonical hyperbolic decay law is also applicable to planar cryogenic hydrogen jets. In the left frame, the downstream distance has been normalized with the equivalent diameter which is the diameter of the round nozzle with an equivalent exit area. For a given pressure, the data for the two rectangular nozzle collapses to a single curve and the corresponding linear fit has been shown by a dashed line. Similar observations have been reported by Ruggles & Ekoto [5] for room temperature releases from rectangular nozzles with aspect ratios in the range of 2–8. In a recent numerical work by Li et al. [11], it has been shown that only at release pressures beyond 10 MPa is the decay rate affected by the nozzle aspect ratio. For the low pressure hydrogen releases studied in this work to simulate release from a liquid hydrogen tank that stores hydrogen in the range of 3–5 bar, the negligible effect of aspect ratio on concentration decay rate is apparent. The decay law of axisymmetric jets has been well documented in the literature [15–17] which show that by normalizing the downstream distance by an appropriate scaling factor, centerline concentration data collapses onto a single curve for various nozzle diameters and release pressures. The scaling factor is the effective diameter, $d\sqrt{\rho_0/\rho_a}$ where $d$ is the (equivalent) nozzle diameter, $\rho_0$ is the nozzle stagnation density, and $\rho_a$ is the density of ambient air. Based on the linear fit to our data, the decay rate is observed to be 0.2795. For releases at similar conditions from round nozzles, Hecht & Panda [14] had obtained a proportionality constant of 0.277, implying that the centerline mass fraction for slit nozzles is decaying at essentially the same rate. This is counter to the observations of Ruggles & Ekoto [5]
Figure 4. Radial mass fraction at selected downstream distances normalized by the centerline mass fraction for both high aspect ratio nozzle. Three fits are shown on each graph. The red line corresponds to the fit for each condition (at all heights), the dashed black line is the fit for all 4 releases conditions (for each nozzle), and the thick black line corresponds to the best fit for round nozzle jets \cite{14}.

and Makarov & Molkov \cite{12} that the concentration decay rate for slot jets is significantly faster relative to a circular nozzle of identical cross-sectional area, although those studies were for higher pressures.

The radial mass fraction concentration at several downstream distances for aspect ratio 16 and 32 are shown in Fig. 4a and Fig. 4b, respectively. The mass fraction is normalized by the centerline mass fraction and the radial coordinate is normalized by the corresponding axial distance, $\eta = r/z$. For both the rectangular nozzles, the mean radial profiles from several downstream distances collapse smoothly onto a Gaussian curve along the major as well as minor axis. The red line in each plot is the Gaussian fit for the release conditions at each frame. For both the nozzles, at specific release pressure, the widths of the Gaussian fits along the major and minor axis are very close. For instance, for AR16 nozzle at 3 bar$_{abs}$, the best fit along the major axis is represented by $Y_{H_2}/Y_{H_2,cl} = \exp(-54\eta^2)$ while the minor axis is best represented by $Y_{H_2}/Y_{H_2,cl} = \exp(-59\eta^2)$. The second Gaussian fit shown in both the figures corresponds to the best fit obtained for each nozzle at the two release conditions and across both the axes. The best fits obtained from the two rectangular nozzles are identical and correspond to $Y_{H_2}/Y_{H_2,cl} = \exp(-57\eta^2)$. The third line on the plots is the best distribution for round nozzle $Y_{H_2}/Y_{H_2,cl} = \exp(-49\eta^2)$ \cite{14}, which is slightly wider than the profiles obtained for slot nozzles, although this difference may not be significant, considering the noise on the measurements.

This behavior of the mean radial profiles for cryogenic hydrogen jets is contrary to observations by Ruggles & Ekoto \cite{5} and Li et al. \cite{6}. Both groups observed that the radial profiles at different distances from the nozzle never collapsed to a common curve along the major axis, and that the downstream profiles were wider than the upstream profiles. Along the minor axis, on the other hand, the profiles showed the opposite trend where the downstream profiles were narrower than the upstream profiles.

The variation of jet-half width (based on mass fraction data) is plotted as a function of the normalized downstream distance. The half-width was estimated by fitting a Gaussian curve...
Figure 5. Mass fraction based jet half-width plotted as a function of normalized downstream distance.

to the two-dimensional mass fraction data at each axial location, along both the major and minor axis for all the jets. As expected from the observations from Fig. 4, the half-widths along the minor and major axis are very close. There is some scatter in the estimate within \( \zeta = z/r_{\text{noz}} < 125 \) especially for the AR32, 3 bar\(_{\text{abs}}\) release condition (minor axis), but for all other conditions the half-widths along both the axes are shown to collapse fairly well against the normalized downstream distance. The slope of the best-fit line for all the data is \( \approx 0.06 \) mm. For round nozzles, the spread rate was found to be only slightly faster–around 0.071 mm. From the jet half-width estimates plotted in Fig. 5, it is clearly observed that for the cryogenic hydrogen jets studied in this work, the ‘axis switching’ phenomenon is not observed within the investigated field-of-view.

A plane hydrogen jet is often characterized by three regions–potential core, two-dimensional flow region, and an axisymmetric flow zone [12]. The ‘axis switch’ phenomenon is associated with the two-dimensional flow region. Owing to this phenomena, the plane nozzle jet provides faster mixing in the near field along the larger effective jet surface area relative to a round nozzle jet. Within their field-of-view, Ruggles & Ekoto [5] had observed the axis switch phenomena which was responsible for a faster concentration decay as well as a departure of the mean radial concentration profiles (along the major and minor axes) from a Gaussian distribution. This resulted in a lower hydrogen mass fraction at the downstream location where the axisymmetric flow zone begins (see, Fig. 3 in Ref. [12]) and consequently, an overall shorter flammable envelope. Within our imaging field-of-view, the axis-switching phenomena has not been observed and the flow exhibits an axisymmetric jet–like characteristics. In this work, our field-of-view is from 40 mm downstream of the nozzle to 122–152 mm. For similar flow conditions as a round cryogenic hydrogen jet [14], the concentration profiles and values are nearly identical for the rectangular nozzles studied in this work. This indicates that for the slot nozzles and pressures investigated in this work, the two-dimensional flow region (or axis-switch) does not lead to enhanced mixing and a smaller flammable envelope. In an additional work which has been submitted to this conference [18], visible flame lengths have been estimated for rectangu-
lar nozzles with aspect ratio up to 64. The aspect ratio has been observed to have a negligible effect on visible flame height for cryogenic releases at a given pressure and temperature. This indicates that for cryogenic releases the influence of axis switching phenomena is limited to a short region, even for an aspect ratio greater than 32.

### 3.2 Temperature

The present diagnostic technique provides the opportunity to simultaneously measure temperature along with the concentration field. The variation of the normalized inverse average centerline temperature and half-width (based on the temperature field) are shown in Fig. 6 as a function of the normalized downstream distance. The spread rate based on the temperature half-width, 0.07 mm is slightly higher than the mass-fraction estimate (Fig. 5) of 0.06 mm. This half-width spread rate of temperature is also slightly higher than observations of the round nozzle, which was also sown to be 0.06 mm [14].

The normalized radial profiles of the temperature field at several axial locations are shown in Fig. 7. Similar to Fig. 4, three fits are shown in the plots. The red line represents the best fit corresponding to the specific release condition, the thick dashed line is the best fit curve for the specific nozzle (including both of the release pressures and both the major and minor axes) and the thin black line corresponds to the fit which was determined by Hecht & Panda [14] for round nozzles. The atmospheric temperature, $T_\infty$, was one of the fit parameters and the best fit values range from 289 to 299K, which is reasonably close to the average lab temperature of 295 K. The normalized temperature profiles are observed to be wider than the mass-fraction radial profiles. Similar to the mass fraction profiles, the temperature data along the minor and major axes, collapse on to a single curve. For each nozzle, the coefficients of the best fit of the data varies slightly with respect to release pressure or imaging plane (major/minor). Relative to round nozzle, the temperature profile for the slot nozzles are observed to slightly wider.
4.0 SUMMARY AND CONCLUSIONS

We used planar laser Raman imaging to measure the concentration and temperature fields of cryogenic hydrogen jets through two rectangular nozzles with aspect ratios of 16 and 32. The nozzles had an effective diameter of 1 mm and release pressures of 3 and 5 bar$_{\text{abs}}$ we reached cryogenic temperatures of 50–64 K. The centerline concentrations (mole or mass fractions) decayed hyperbolically and the centerline temperatures increased as a function of the distance from the nozzle. Normalizing the downstream distance by the effective diameter enabled all of the data for the inverse mean centerline mass fraction to collapse onto a single line, with a decay rate of 0.28. This decay rate is nearly equivalent to the decay rate for cryogenic hydrogen releases through round nozzles reported in the literature. The profiles of mean concentration and temperature were shown to be Gaussian, self-similar, and nearly equivalent along both the major and minor axes. The half-width of these profiles, and the spreading rate of the half width were also nearly equivalent to literature reported values for a 1 mm round nozzle [14].

The observations reported here are contrary to many observations of high-aspect ratio release experiments and modeling that often show two dimensional flow regions of non-Gaussian profiles along the major and minor axes, and centerline decay rates that are higher than round nozzles of the same effective diameter. However, these experiments and modeling efforts are for higher pressures than studied here. We did not make measurements near enough to the nozzles to observe the two-dimensional flow regions, and the pressures are likely too low to enhance the mixing significantly enough to increase the centerline concentration decay rates (and shorten the flammable envelope). The pressures reached in the experiments are representative of liquid hydrogen storage tanks, and the nozzle dimensions are characteristic of an unintended leak from this system. This work shows that by simulating a round release nozzle, risk assessments of liquid hydrogen infrastructure should be accurate, regardless of the actual leak geometry. Future experiments at higher pressures would be useful to extend the range of applicability to cryo-compressed hydrogen systems. These experiments would also elucidate whether the lack of aspect ratio effects are solely due to the low pressures studied here, or if the cryogenic temperatures also affect the mixing.
5.0 ACKNOWLEDGMENTS

The U.S. Department of Energy’s (DOE) office of Energy Efficiency and Renewable Energy’s (EERE) Fuel Cell Technologies Office (FCTO) supports the development of science-based codes and standards through the Safety, Codes and Standards program sub-element. The authors gratefully acknowledge funding from FCTO and the support of subprogram manager Laura Hill for this work. Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-NA0003525. This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

REFERENCES