Analysis of a Large Hydrogen Balloon Explosion Incident

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Abstract

On December 19, 2017, a large balloon containing about 22 thousand cubic meters of hydrogen was deliberately torn open to initiate deflation at the completion of a filling test. An inadvertent ignition occurred after about two seconds and caused an explosion that produced extensive light damage to a large building near the balloon test pad. The analysis described here includes an estimate of the buoyancy induced mixing into the torn balloon, and the blast wave produced by assumed constant flame speed combustion of the 55% to 65% hydrogen-in-air mixture. Comparisons of calculated blast wave pressures are consistent with estimates of the pressure needed to cause the observed building damage for flame speeds in the range 85 m/s to about 100 m/s.

1.0 INTRODUCTION

Small hydrogen balloon ignition incidents are reported periodically in the news media. The media often call these incidents explosions, but the detailed description usually reveals that the event was a flash fire without any indication of pressure development. One example is the November 2020 incident in which a hand-held bunch of small hydrogen-filled balloons was deliberately ignited in an elevator, causing burn injuries to the five elevator occupants.[1]

Inadvertent ignitions of much larger hydrogen-filled balloons and airships sometime result in explosions, but are more likely also to be fires. A compilation of brief accounts of hydrogen inflated airship fire incidents from 1908 to 1937 [2] indicates there were a few explosions, but most were fires. The most infamous of these was the 1937 Hindenberg airship fire.

The World View large hydrogen balloon incident described and analyzed in this paper is a bona fide rare example of an unconfined accidental explosion. As such, it provides us with a rare opportunity to analyze how the hydrogen-air mixture was formed and to estimate the flame speeds and blast wave pressures that resulted from the subsequent mixture inadvertent ignition.

2.0 WORLD VIEW BALLOON INCIDENT

2.1 Site Description

World View Enterprises, Inc. develops and operates large balloons and other products for accessing and investigating the stratosphere. In December 2017 the company used a site near Tucson, Arizona called the Tucson Spaceport for balloon tests and launches. The Spaceport site, as shown in Fig. 1, consisted of a 137 m diameter flat concrete test/launch pad with its southern edge about 68 m north of the World View staff building. The site, including the building, was leased by World View from Pima County, the local governing agency. The immediate surrounding area is flat southwest U.S. rural terrain.

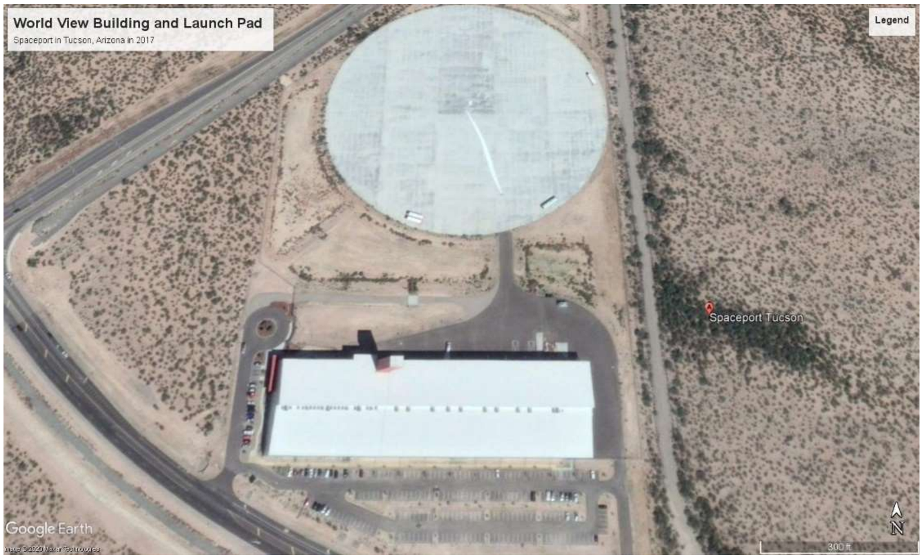

Figure 1. World View Tucson Spaceport 2017 site (from Google Earth)

2.2 Balloon Filling

World View teardrop shape stratospheric balloons are typically about 30 meters in diameter and have a volume of about 22,000 m^3[3]. Most of the World View flights are conducted with helium filled balloons, but in late 2017 the company was testing hydrogen inflation as a less expensive alternative to helium. The polyethylene balloons were filled on the test pad from hydrogen tube trucks via hoses and fill tubes as shown in Fig. 2 [4].

Figure 2 Filling World View balloon with hydrogen (from Science News)

2.3 Incident Description

On December 19, 2017, World View was conducting a balloon hydrogen fill test on its Spaceport test/launch pad. According to the Incident Review Team Report [5], the fill was completed shortly before 12:48 pm, and the fill lines and associated equipment were removed in preparation for deflation. The deflation was then initiated by goring (piercing) the balloon to split it open along a line and vent hydrogen. This process is supposed to occur by the balloon film rapidly rolling back to allow an unimpeded vent flow. However, the Incident Review Team Report states that this goring event was different in that video recordings show the "fabric folding back in over the gore tear and constricting the gas flow out of the balloon."

At 12:48 pm, there was an ignition and explosion. The Incident Review Team Report states that the only credible ignition source is an electrostatic discharge associated with gas flow past the fragmented balloon fabric or inflation tube. Fig. 3 shows the flame within the torn balloon.

Figure 3 Flame within torn balloon during explosion (news media photo)

The explosion caused significant minor building damage that is described in the paper section on blast wave analysis. Three World View employees near the test pad perimeter experienced hearing issues and many others reported feeling a radiative heat pulse from the flame [5]. Firefighters, who had been stationed at the test pad as a precaution, waited for the descending burning balloon fragments to reach the ground, and then attended to the residual fire on the test/launch pad [5].

Repairs to the World View building cost just under $500K, and were completed, and the building restored to full operations by July 2018 [6]. There was also minor damage to nearby facilities as discussed in the blast wave analysis. The World View Independent Investigation Team made some operational and staffing recommendations that apparently have been implemented by World View [6].

3.0 Balloon Hydrogen Concentration Analysis

During the approximately two second interval between balloon goring and ignition, hydrogen escaped from the balloon and ambient air replaced it. The rates of venting and air replenishment depend on the location and size of the balloon open area, which are not known accurately and vary in time as the torn fabric reported flapped back over the open area. Fig. 4 is an image of the torn balloon about one second prior to ignition. It seems to show a vertical opening over most of the balloon length.

Figure 4 Torn balloon approximately one second prior to ignition (from xx)

Estimates of buoyancy induced hydrogen vent and air exchange flow rates have been made assuming there is a vertical opening, of area A_v, on the side of the balloon. The buoyancy induced volumetric flow rates of air and hydrogen through the open area are given by the following equations [7].

$$\dot{V}_{air} = C_d A_v \left[\frac{2H(\rho_a - \rho_h)g}{\rho_a} \right]^{1/2} \tag{1}$$

$$\dot{V}_h = C_d A_v \left[\frac{2H(\rho_a - \rho_h)g}{\rho_g} \right]^{1/2} \tag{2}$$

where $\dot{V}_{air}$ and $\dot{V}_h$ are the volumetric flow rates of air and hydrogen, respectively, C_d is the vent discharge coefficient, H is the height of the vertical opening, g is the acceleration of gravity, and ρ_a and ρ_h, are the densities of air and hydrogen, respectively.

The effective open area A_v is a transient value because of the observed balloon fabric flapping or folding back over the open area. Based on a review of the news media videos, the maximum open area appears to occur at the time shown in Fig. 4, and the maximum width, w_{max}, of the vertical opening at that time is estimated to be 3.6 m. Two different assumptions have been utilized to characterize the effective width, w, during the two-second interval in which w increases to w_{max}, and then decreases back to near zero. The assumptions are as follows:

Width Assumption 1: $w = w_{\max}\left(\frac{t}{1\sec}\right)$ for $t \le 1$ sec, and $w = w_{\max}\left[1-\left(\frac{t-1}{1\sec}\right)\right]$ for $2 > t \ge 1$ sec.

Width Assumption 2: $w = w_{max}\sqrt{\frac{t}{1\sec}}$ for $t \le 1$ sec, and $w = w_{max}\sqrt{\left(1-\frac{t-1}{1\sec}\right)}$ for $2 > t \ge 1$ sec.

The transient balloon volume-average hydrogen concentration can be calculated as a function of time from the cumulative air inflow obtained from the numerically integrated flow rates based on Eqn 1. Results of calculations conducted using two different width assumptions and C_d=0.6 and H=30, are shown in Fig. 5. Since Width Assumption 1 produces a smaller width than Width Assumption 2, the air inflow rates are smaller with Width Assumption 1 and the hydrogen concentrations are higher. The final calculated hydrogen concentrations at two minutes are 67% for Assumption 1 and 55% for Assumption 2.

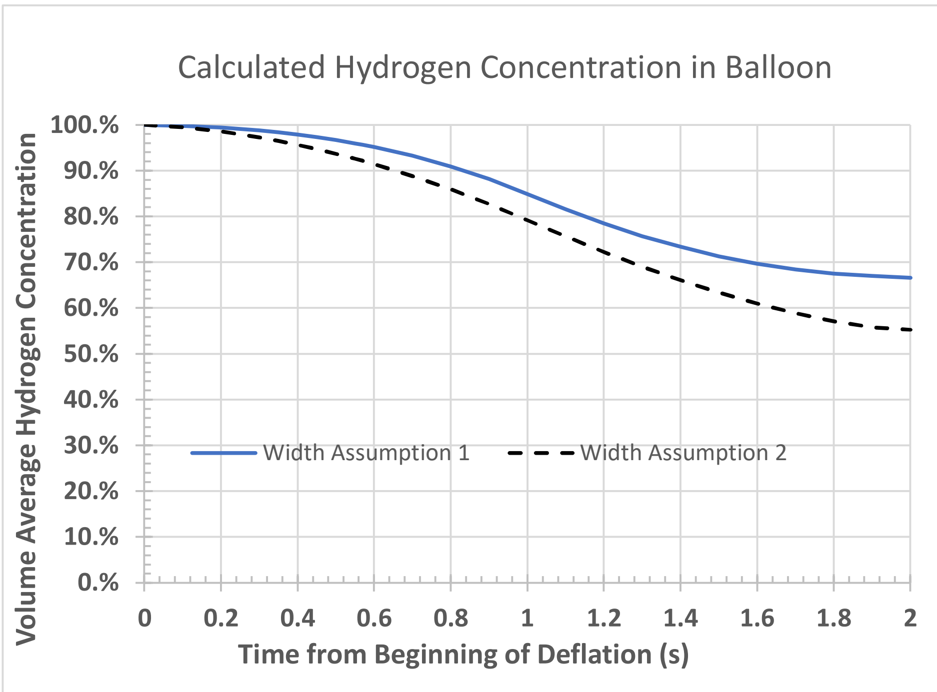

Figure 5 Calculated balloon hydrogen concentration as a function of time.

There is too much uncertainty in the input parameter specifications for the calculated hydrogen concentrations to be considered either accurate or bounding. However, the fact that the calculated concentration at the time of ignition is well below the hydrogen upper flammable limit of 75% to 77% (depending on the standard test method used) [8] is consistent with the observed occurrence of a hydrogen-air deflagration, rather than some near-limit combustion. Therefore, the calculated air inflow rates and corresponding concentrations appear to be at least consistent with the observed formation of a fuel rich flammable concentration.

4.0 Blast Wave Analysis

4.1 Applicable Analytical Blast Wave Models

Sochet [9] has reviewed a variety of analytical models and data correlations for calculating unobstructed vapor cloud explosion blast wave pressures. Three of those models/correlations have been used for this incident analysis.

The constant velocity expanding piston deflagration model has the following equation for the blast wave pressure, ΔP, in the acoustic zone at a location R far from the flame front and a time >> R/a_0, where a_0 is ambient air sound speed.

$$\Delta P = 2\rho_a \left(\frac{kS_u}{\alpha}\right)^2 (1-\alpha)\left(\frac{R_f}{R}\right) \tag{3}$$

Here $\alpha = \rho_f/\rho_a$, R_f is the maximum flame front radius, S_u is the gas mixture burning velocity, k is the empirical coefficient representing the ratio of the effective surface of the turbulent flame to the spherical laminar flame front.

Dorofeev [10] developed an unconfined hydrogen vapor cloud explosion blast wave model using the dimensionless Sach's scaling parameters, $\overline{R}$ and $\overline{P}$ defined as

$$\overline{R} = R\frac{P_0^{1/3}}{E^{1/3}}, \quad \overline{P} = \frac{\Delta P}{P_0},$$

where P_0 is atmospheric pressure, and E is the vapor cloud combustion energy. The nondimensional pressure is calculated as the minimum of $\overline{P}_1$ and $\overline{P}_2$, as given by the following equations.

$$\overline{P}_1 = \frac{0.34}{\overline{R}^{4/3}} + \frac{0.062}{\overline{R}^2} + \frac{0.0033}{\overline{R}^3} \tag{4}$$

$$\overline{P}_2 = \left(\frac{V_f}{a_0}\right)^2 (1-\alpha)\left(\frac{0.83}{\overline{R}} - \frac{0.14}{\overline{R}^2}\right) \tag{5}$$

The Baker Strehlow-Tang (BST) method [11] for estimating vapor cloud explosion blast wave pressures entails using the calculated nondimensional Sachs scaling positive pressure versus distance shown in Fig. 6 with flame speed Mach number curves. The methodology includes BST suggested Mach numbers for different categories of confinement, gas mixture reactivity, and congestion. A hydrogen vapor cloud would ordinarily be considered a high reactivity gas cloud, and the suggested Mach number for low congestion 3-D confinement/expansion would be 0.36. The suggested medium reactivity Mach number for this configuration is 0.11.

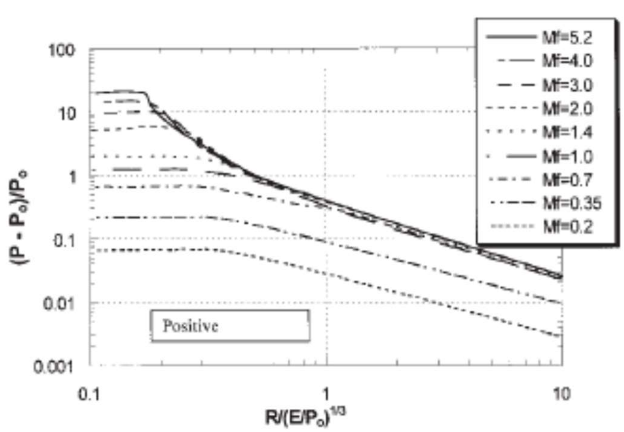

Figure 6 BST blast wave pressure versus nondimensional distance [11].

4.2 Calculated Blast Wave Pressures at World View Building

The three blast wave models described in 4.1 have been used to calculate the hydrogen-air balloon deflagration pressures at the nearest part of the World View building, estimated to be at a distance of about 122 meters from the centroid of the elevated filled balloon. The calculations were conducted for various flame speeds and results are shown in Fig. 7. The flame speed range of 25 m/s to 101 m/s corresponds to a Mach number range of 0.075 to 0.30.

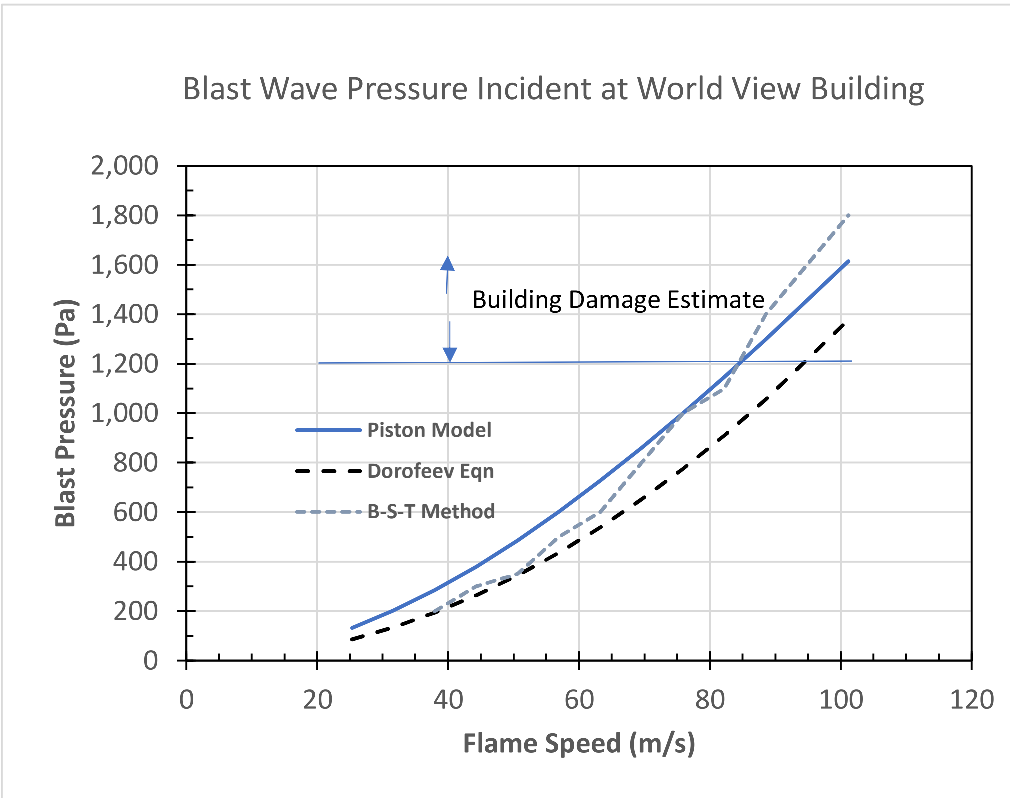

Figure 7 Calculated Blast Pressure at World View Building for different flame speeds.

The minimum flame velocity of 25 m/s shown in Figure 7 corresponds to a 55% hydrogen concentration (Fig. 5 calculated concentration at ignition using Width Assumption 2) burning velocity of 2.3 m/s, an expansion ratio of 5.5, and a turbulent flame augmentation factor, k, of 2.0. The maximum flame velocity of 101 m/s in Figure 5 corresponds to a turbulent flame augmentation factor of 8.

The distance from the filled balloon centroid to the northwest corner of World View building is about 170 meters. Using this furthest distance instead of the closest distance to the building facing wall, produces calculated blast pressures about 28% lower than shown in Fig. 7 for the piston model and the Dorofeev model.

The nearest neighboring buildings are at a distance of about 1200 m to the filled balloon. Calculated blast wave pressures at that location are under 200 Pa at flame speeds up to 100 m/s.

4.3 Blast Wave Pressures Estimated from Building Damage

World View headquarters building blast damage assessment reports were issued by the retained architectural firm [12], Pima County Facilities Management [13], and the retained structural engineers [14]. These reports provide detailed descriptions and photographs of the County/World View building damage resulting from the blast wave. The report concluded that there was no significant structural frame damage, but it listed numerous minor building components that were damaged. Examples of these are listed in Table 1.

Table 1. World View Building Damage Examples

Damage Description	Location
Rollup doors blown inward off their tracks	North Wall facing pad
Buckled tower wall panels	Tower above 2nd floor
Cracked drywall	Numerous
Windows: one broken pane and several popped gaskets.	North Wall facing pad
Interior walls bowed and cracked	Mezzanine south and east
Displaced ceiling tiles and light fixtures	Second floor rooms
Sprinkler piping displaced and leaking	Balloon Bay Tower
Roof panels lifted and damaged	Roof

Most of the damage in Table 1 can be generically categorized as limited minor damage, which has an associated side-on blast pressure threshold of 2-3 kPa [15]. However, the large wall facing the balloon would have experienced a partially reflected blast pressure, so that the estimated incident blast pressure was probably in the range 1.2 kPa to 1.6 kPa. This range is indicated in Fig. 7, and corresponds to a flame speed in the range 85 to 100 m/s.

There are no details of damage at any of the neighboring buildings. The lowest threshold pressure listed in [15] for “occasional breaking of large window panes already under strain” and “loud noise” is 0.2 kPa to 0.3 kPa. This could correspond to an incipient face-on blast pressure of 0.1 to 0.15 kPa, which are roughly the calculated pressures for flame speeds of 90 to 100 m/s.

5.0 Discussion of Results

Calculated blast wave pressures are consistent with the observed damage for the flame speeds shown in Table 2 for the three vapor cloud explosion models utilized. The Expanding Piston Model and B-S-T Model both produce the 1.2 kPa lower bound estimate at a flame speed of 85 m/s, while the Dorofeev Model requires a flame speed of 95 m/s. The upper bound estimate is produced at flame speeds in the range 95 m/s to 106 m/s using the three models. The turbulent flame speed/area augmentation factors corresponding to these speeds for a 55% hydrogen concentration (as calculated for Width Assumption 2) are in the range 6.7 to 8.4. The fact that there was a large turbulent flame augmentation factor is qualitatively consistent with the dimpled balloon surface seen in Fig. 3.

Table 2 Flame Speeds Corresponding to World View Building Damage

Blast Wave Model	Flame Speed (m/s) at 1.2 kPa	Flame Speed (m/s) at 1.6 kPa
Expanding Piston	85	100
Dorofeev	95	106
B-S-T	85	95

There is one well documented large hydrogen balloon explosion test in 1983 that was analyzed by Molkov et al [16] to estimate flame speeds and turbulent burning velocities. The test involved a near-stoichiometric hydrogen-air mixture in a hemispherical balloon with a diameter of 20 m. The maximum flame speed in that test was about 80 m/s, the peak turbulent burning velocity was 10 m/s to 13 m/s, and the flame front wrinkling factor calculated by Molkov et al. using their large eddy simulation was approximately 1.2. The peak blast wave pressure was about 6 kPa, and the pressure at a distance of 80 m from the balloon center was just under 2 kPa. Thus, the flame speeds and blast wave pressures in that test are comparable to the blast pressures and flame speeds calculated for the World View accidental balloon explosion, even though the estimated hydrogen concentration at ignition is significantly higher than the near-stoichiometric concentration in the balloon test.

The fact that minor but extensive building damage occurred in this incident involving a total of approximately 1800 kg of hydrogen within and around the torn balloon is consistent with the conclusion of Dorofeev [10] that the threshold mass of hydrogen to cause damage is about 1000 kg when released and ignited in the absence of confinement or an obstacle geometry. The Dorofeev conclusion resulted from his analysis assuming a hemispherical cloud with hydrogen concentration decreasing with distance from the cloud center. There certainly could have been a nonuniform concentration in this incident, but the more important parameter governing the blast wave damage potential is the effective flame speed when the cloud is ignited.

6.0 Conclusions

The December 2017 accidental large hydrogen balloon explosion near Tucson, Arizona has provided an opportunity to analyze air entrainment and mixing during balloon deflation, and flame and blast wave development associated with inadvertent ignition. The estimated volume-average hydrogen concentration produced by buoyancy induced air inflow into the torn balloon, and the time-varying open balloon area associated with the flapping of the torn balloon is in the range 55 v% to 65 v%. The un-reflected blast wave pressure estimated based on blast damage to the adjacent building is 1.2 kPa to 1.6 kPa. This blast pressure is consistent with three published constant flame speed vapor cloud explosion models providing the flame speed is at least 85 m/s, and no more than 106 m/s.

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