**ROUGH BOUNDARY CALCULATION FOR PRESSURE REQUIRED TO COLLAPSE TRAILER**

Robert Swaim, April 24, 2023
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Failing lithium ion (Li-ion) batteries may release hydrogen gas which is flammable and can become explosive in a confined space. Utilizing data developed during an aircraft accident investigation the amount of potential force which an explosion could deliver is the subject of this paper. This is a rough estimate and a more accurate estimate would require testing to know the key value of minimum pressure required for a dry van trailer to explode.[1]

BIRMINGHAM TRUCK STOP EXPLOSION

A powerful explosion destroyed a box trailer at a truck stop on March 31, 2023, near North Birmingham, Alabama.[2] The trailer contained sealed 55 gallon (210 L) drums and reportedly at least 25 full of Li-ion batteries were being transported to disposal. The force of the explosion blew away the walls and roof and had enough force to deform the structure beneath the flat portion of the trailer down to the ground. Witnesses stated that the metal roof reached about 70 of height. Photographs showed only one or two barrels burning near where the rear door had been and the rest appeared to have remained sealed.

(Photo by Birmingham Fire and Rescue Service)

Fig 1.

[1] Whether the batteries were packaged in accordance with appropriate regulations and best practice are not addressed in this paper.
[2] Truck explosion. https://cdllife.com/2023/truck-hauling-lithium-batteries-explodes-at-alabama-truck-stop/
https://www.lion.com/lion-news/april-2023/drums-of-lithium-batteries-destroy-truck-in-alabama

(Photo by Birmingham Fire and Rescue Service)

Fig 2.

(Photo by Birmingham Fire and Rescue Service)

Fig 3.

(Photo by Birmingham Fire and Rescue Service)

Fig 4.

## LESS FORCEFUL EXPLOSIONS

The truck stop explosion was significantly more forceful than Li-ion batteries which exploded in other trucking incidents when the rear door were blown off of trailers, but the trailers were otherwise intact. Firefighters responding to smoking or burning Li-ion battery failures in garages have experienced explosions in which the garage doors have blown out after the doors were opened. In each of these events, while opening the door added oxygen to the space and enough pressure developed to blow out the door, the rest of the structure and trailers remained intact.

In one event, firefighters were reportedly either near or inside of the garage when the explosion happened.[3] The garage door was thrown about 30 feet and there was relatively little other damage to the house.[4] The firefighters in this and other events near the explosion survived with relatively minimal injuries which may provide an estimated maximum pressure. It is documented that 2.4-12.2 psi results in 1-90% eardrum rupture among exposed populations. Values of 14.5-29 psi result in 1-99% fatalities among exposed populations due to direct blast effects.[5]

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[3] Jeep explosion https://www.outtherecolorado.com/news/jeep-battery-explodes-in-colorado-sending-debris-toward-firefighting-crew/article_9a49232c-d94f-11ed-b41d-936c11cee396.html
[4] https://kdvr.com/news/local/jeep-wrangler-4xe-battery-explodes-smoking-fire/
[5] https://response.restoration.noaa.gov/oil-and-chemical-spills/chemical-spills/resources/overpressure-levels-concern.html

Numerous videos have captured the dynamics of smoke igniting when released by failing batteries. The following example of an electric scooter battery failure shows that the smoke has not fully distributed in the room, implying that the hydrogen gas has not reached an even distribution through the space.


Fig 5. Expanding smoke from battery failures have been found to contain about 36% hydrogen.

Once ignited, the expanding flame has unfilled space to expand into, decreasing the resultant final pressure as shown below.

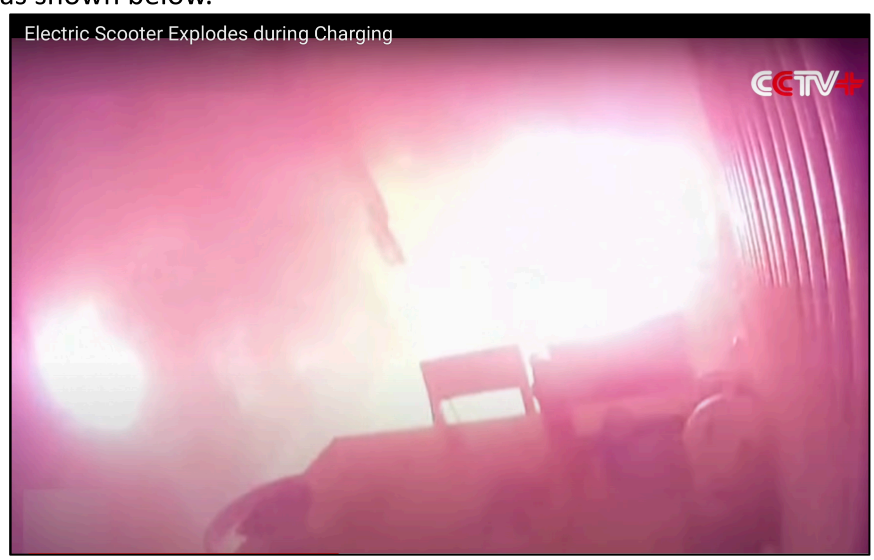


Fig 6. Upon ignition the room has sufficient open space to not be pressurized as evidenced by the relatively light objects remaining on the table in the fore ground.

Note that the pressure values which can lead to death are far less than the approximately 52 psi which the NTSB and Boeing found needed to destroy the center wing fuel tank of a Boeing 747.[6]

[6] Report NTSB DCA96-FA-070.

TRAILER VOLUME AND DRUM DATA

According to the manufacturer of trailers (Strickland) the dimensions and volume of a standard 53 ft dry van trailer are:
Interior length: 52'8". (632")
Interior width: 8.37' (100.5")
Interior height: 9.16' (110")
4,035 cu.ft. interior volume

Up to 104 55-gallon drums may fit in a standard 53 ft trailer. Estimating the number of drums on the accident trailer show approximately 17-20 rows of 4 drums for a total of about 68-80 drums. This equates to 500-588 cubic feet of volume. Ullage is the space by which a container falls short of being full so for these calculations the vapor space will be 4,035-588=3447 cu.ft.

While no steel drums fully collapsed, some had been slightly flattened or deformed. To collapse a 55 gallon drum has been documented to require a minimum of 9 psi.[7] Overpressure failures of 55 gallon drums have been documented to occur at 14-30 psi.[8] The issue with attempts to use the drums as a clue about pressure is that the contents are unknown and drums full of discarded batteries would not be able to collapse.

The drums would have acted as obstructions to the propagation of a flame front, preventing smooth spread once an ignition took place in the flammable gas.

TWA FLIGHT 800 ACCIDENT INVESTIGATION

In conjunction with Sandia National Laboratories and California Institute of Technology (Cal Tech), the National Transportation Safety Board (NTSB) conducted extensive testing and analysis following a July 17, 1996 center wing fuel tank (CWT explosion which destroyed a Boeing 747-131 operating as TWA Flight 800.[9]

The 12,890 gallon Boeing 747 CWT volume of 1,775 cu.ft. was about half of the Birmingham trailer (3,447 cu.ft.) after subtraction of the volume occupied by the drums. While assuming that the burst pressure of the trailer would be less than that of the Boeing 747 CWT, both are riveted aluminum construction and the weakest aluminum forward walls of the Boeing tank design are only about double the thickness of the dry van walls.[10]

The TWA accident investigation included computational fluid dynamics (CFD) modeling, instrumented ignitions in a quarter scale model, and detonation of the CWT in a retired Boeing 747. The fuel gases used to simulate the vapor in the nearly empty tank included hydrogen,

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[7] https://physicsforce.umn.edu/content/barrel-crush
[8] https://www.osti.gov/servlets/purl/1202902
[9] Report NTSB DCA96-FA-070.
[10] The Boeing surfaces are about .060-.080" thick while the dry van are estimated to be about .025"

propane, and Jet A fuel.[11] [12]The work was later used as part of efforts by the FAA into inerting aircraft fuel tanks.[13]

> "This modeling easily adapts to parametric and sensitivity analysis. Extensions of this prior work included incorporating a three-dimensional flame propagation routing for multiply connected regions with Jet-A fuel-air thermochemistry. This modeling in largely based on prior experimental studies which were successfully used in hazards analysis."

As discussed previously, when a flammable gas insufficiently fills a volume then pressure resulting from ignition has further volume to expand into. Conversely, pressure will increase when distribution is reached between the limits of flammability.

Hydrogen has a very broad flammability range of 4 percent (LFL) to 74 percent (RFL) concentration in air. The flame velocity of hydrogen is accepted to be 1.7-1.85 m/s.[14] "A flame can be defined as a subsonic combustion wave driven by a self–propagating exothermic reaction typically characterized by a localized reaction zone separating reactants and products (Barnard and Bradley 1985; Turns 1996). …. "turbulent flames are more complicated and the burning velocity is no longer a well–defined quantity"[15]

Previous work by Cal Tech had documented that flame propagation became turbulent and would pass the speed of sound (Mach) when encountering holes between compartments or obstructions within a compartment. When applied to the 747 investigation:

> "In the following sections, a model for flame propagation in a multiple compartment enclosure is described. This modeling is based on conservation equations approximated for the limit of small Mach number flow (flame speed/sound speed). At these conditions, the mean pressure is spatially uniform within each individual compartment. However, a

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[11] https://shepherd.caltech.edu/EDL/projects/JetA/documents.html

[12] "Tests at the CalTech facilities demonstrate that a mixture of hydrogen and propane with low pressure air can effectively replicate the turbulent flame propagation behavior of the light distil- late components of Jet A. Similar overpressure and burn velocities are observed. This greatly simplified experimental tests by avoiding the necessity of heating liquid Jet A fuel and provided a well-defined means for controlling the composition of the fuel air mixture."

[13] https://www.yumpu.com/en/document/read/20941137/evaluation-of-fuel-tank-flammability-and-the-faa-inerting-system-

[14] https://www.osti.gov/servlets/purl/1731098

[15] "A flame can be defined as a subsonic combustion wave driven by a self–propagating exothermic reaction typically characterized by a localized reaction zone separating reactants and products (Barnard and Bradley 1985; Turns 1996). …. "turbulent flames are more complicated and the burning velocity is no longer a well–defined quantity" https://shepherd.caltech.edu/EDL/publications/reprints/ramank.pdf

pressure gradient across the whole enclosure of the CWT takes place due to the presence of flow restrictions connecting compartments.

It was previously noted that the drums in the dry van would have been obstructions before a progressing flame front. An induced turbulent flow can be created when encountering an obstruction as the flame front collapses and wraps around the obstruction. (Fig. 7)

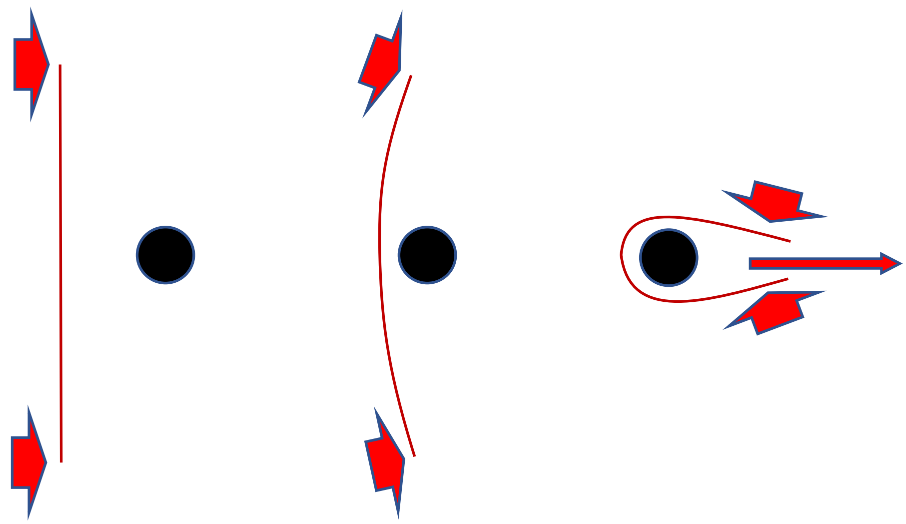

Fig. 7. From left to right, as a (red) flame front approaches an obstruction at subsonic speed the boundary is forced to wrap around the object until the boundary walls collapse. At this point the speed of the flame front becomes supersonic.

Detonation (aka explosion) is when a supersonic exothermic front accelerates through a medium that eventually drives a shock front propagating directly in front of it. The CFD report further states the following when the flame front reaches an opening rather than an obstruction:

> "Since gas motion is induced ahead of the flame, gas motion within each compartment takes place that is restricted by "orifices" connecting the compartments. The resulting flow at these locations induces localized jets that stir the unburned gases in the compartments, producing turbulence to enhance the rate of combustion. Empirical correlations based on existing literature data are used to specify the turbulent flame velocity of the gas mixture."

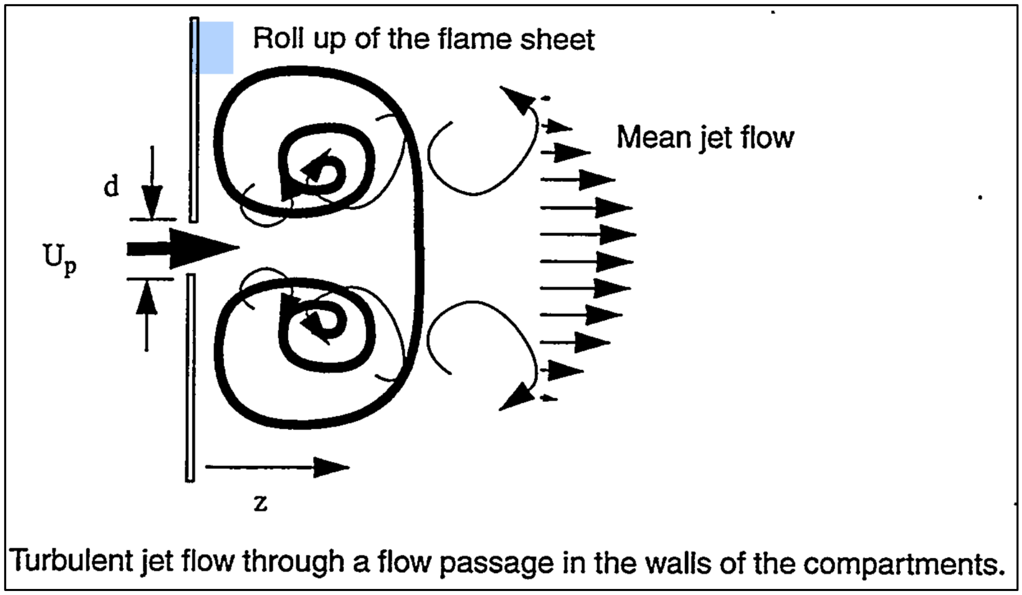


Fig. 8. Flame front becoming turbulent as shown in TWA CFD Report.

The Cal Tech test results found that the differential pressure in the Boeing 747 fuel tank repeatedly reached about 4 atmospheres as shown in the following graphics which compare calculated and test results.

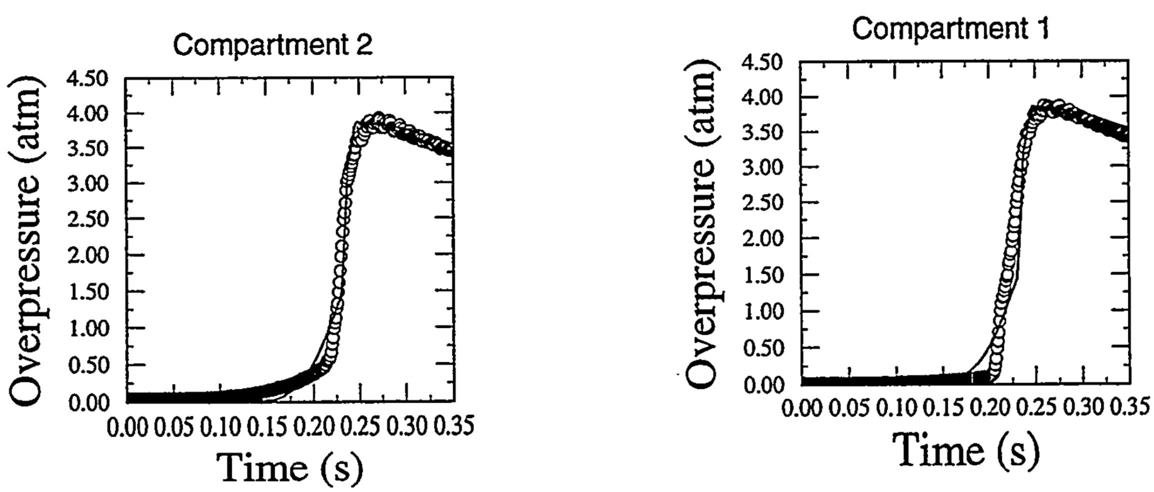


**Figure 13. Overpressure versus time for Quarter-Scale Experiment 10.**

Fig. 9. Graphics from Cal Tech CFD report, showing pressure rise over time in a quarter scale model of the Boeing 747 CWT. Note the accelerated rise in test rests (solid line) at about 0.25 seconds as the flow became supersonic.

## APPLICATION TO TRUCK IN BIRMINGHAM

The application of pressure would have been equal to all surfaces in the dry van, permitting a rough estimate of pounds force applied to the floor as an impulse.

The interior floor dimensions would have been 632” X 100.5” = 63,516 sq.in. (441 sq.ft.)

4 atmospheres X 14.7 lb/sq.in. = 58.8 pounds

58.8 X 63,516 sq.in. = 3,734,741 psi impulse on floor of van

This value would have been in addition to the weight of the cargo.

Again, this is based in the values found during investigation into a container (the center wing fuel tank) which would be stronger than the dry van trailer, so should be considered as the very rough estimate for an absolute maximum boundary condition.

## FINAL OBSERVATIONS

When later working with the FAA and Department of Defense, the NTSB found that the shock front propagated too quickly to be mitigated by “blow-out” (aka “gore”) panels before the supporting structure was also compromised.

Potential means of preventing this type of accident could include:

1. Require carriage of waste lithium ion batteries in well ventilated compartments. This could be accomplished by (A) carriage of the drums on an open flat bed trailer, (B) leaving the rear trailer doors off or open, or (C) forced ventilation. It should be noted that forced ventilation with fans should be upstream so that potentially leaking hydrogen gas does not saturate the fan.
2. Inerting, such as with nitrogen. The problem with this approach would be the wide range of flammability for hydrogen because reaching the lower flammable limit of 4% would be difficult to maintain. Coupled with the cost and potential rate of system failure versus low probability of need, this may be possible for special cases such as aviation but impractical for general road use.