Batteries in Recycling Transport Explosions

How, Why, Prevention, Mitigation

Drums of hydrogen in an enclosed space.
What could go wrong?

Robert L. Swaim

NTSB Engineering National Resource – Retired

Founder and Contact: www.HowItBroke.com

301-359-1399

HowItBroke.com

Monthly Li-Ion Battery Transport Fire/Explosion Losses

2023 explosion examples

Birmingham, AL, 3/31/23

Germany, 6/5/23

Livermore, CA, 12/23

Norfolk, VA, July 19, 2023

HowItBroke.com

Recycling Related Lithium-Ion Fire Losses Occur Daily

Fires Vastly Outnumber Explosions

Trash trucks and collection point fires experience fires daily

California found 65% waste facility fires started by lithium-ion batteries.

Seattle FD responded to 79 lithium-ion fires in the last two years.

Result: In January 2024 Seattle joined others banning **all** batteries in trash.

Staten Island, NJ. 3/17/22

Ventura, Cal. 9/9/23

Modesto, Cal. 5/3/23

Mis-Use of HMR 173.185 in Marking and Packaging

Shippers cite the following as the basis for the lack of internal protective packaging:

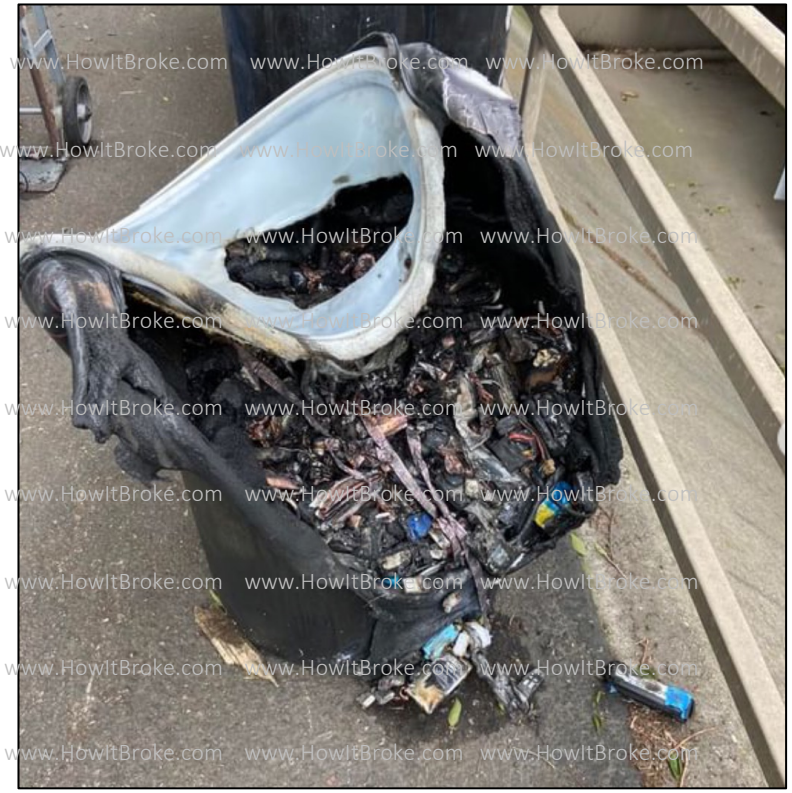
HMR 173.185

(d) Lithium cells or batteries shipped for disposal or recycling. A lithium cell or battery, including a lithium cell or battery contained in equipment, that is ***transported by motor vehicle to a permitted storage facility or disposal site, or for purposes of recycling, is excepted—***

(1) From the testing and record keeping requirements of paragraph (a) and the UN performance packaging requirements in paragraphs (b)(3)(ii), (b)(3)(iii) and (b)(6) of this section, when packed in a strong outer packaging conforming to the applicable requirements of subpart B of this part; and

While neglecting

(2) From subparts C through H of part 172 of this subchapter when the lithium cell or battery ***meets the size, packaging, and hazard communication conditions in paragraph (c)(1)–(3) of this section***.



Modesto, Cal. 5/3/23

What is being missed is that 173.185(c)(1)-(3) cites:

Maximum size and weight limits which are far less than being transported

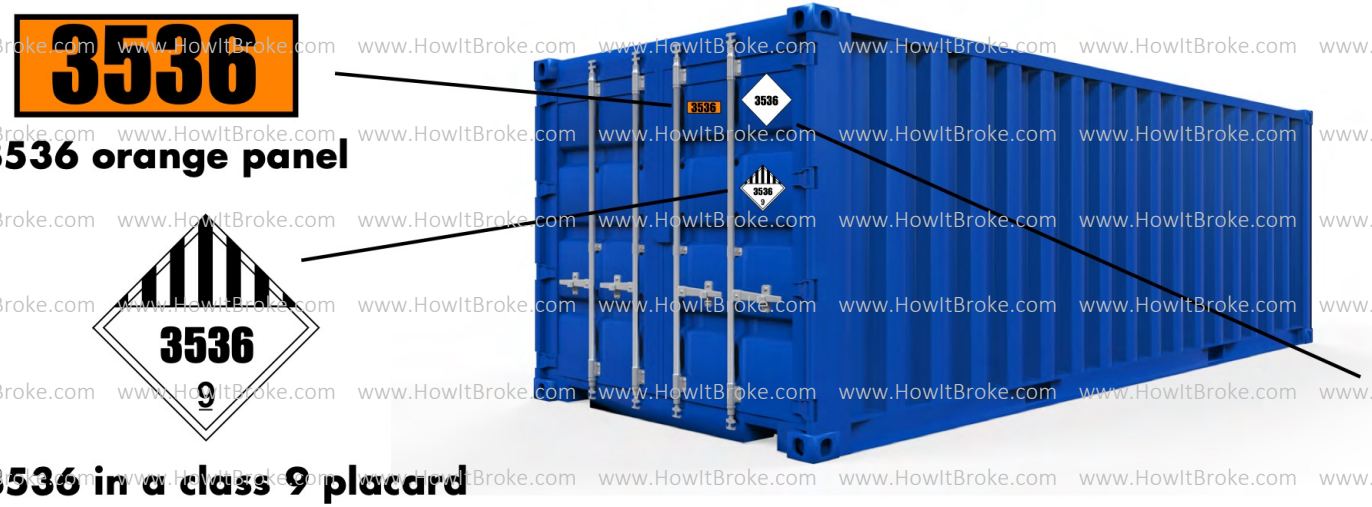
Ref. https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/2021-09/Lithium-Battery-Guide.pdf Guide 10

External Markings Not Applied To Inform Firefighters

Required Hazard Communication - § 172.102, Special Provision 389 (see Guide 10 diagram for additional details):

- The batteries inside the cargo transport unit are not subject any marking or labeling requirements.
- The cargo transport unit must display the UN ID number (3536) on an orange panel, white square on point, or a Class 9 placard. The three options for displaying the UN ID number are displayed in the diagram below.
- The cargo transport unit must be placarded on two opposing sides with the Class 9 placard.
- Transportation by aircraft is forbidden, unless approved by the Associate Administrator.

PACKAGING AND HAZARD COMMUNICATION DIAGRAM



Individual packaging

https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/2021-09/Lithium-Battery-Guide.pdf Guide 10

Birmingham Dry Van (Box) Trailer Case Study

2023 explosion examples

Birmingham, AL, 3/31/23

Germany, 6/5/23

Norfolk, VA, July 19, 2023

Livermore, CA, 12/23

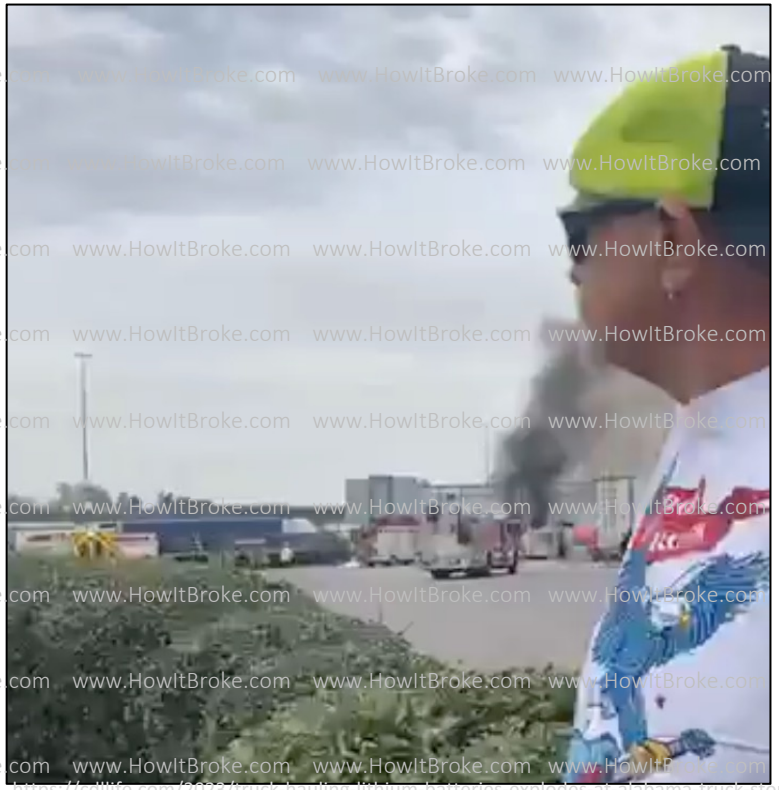
Birmingham Dry Van (Box) Trailer Case Study

Flying J Truck Stop, 3/31/2023

Source: Birmingham Fire and Rescue Service

Initial witness watches fire response arrive

Note confined fire/smoke at rear



https://cdllife.com/2023/truck-hauling-lithium-batteries-explodes-at-alabama-truck-stop/

Dry van (box) trailer contained barrels of batteries to be recycled

Driver drove about 1,800 miles from Las Vegas, NV

Parked two days before explosion to visit family

Witnesses reported roof reached 70 feet

Barrels of batteries found marked Class 9

Barrel contents found inadequately packaged

Birmingham Dry Van (Box) Trailer Case Study

Trailer details

Manufactured by Strickland

53 foot dry van, unvented box

4,035 cu.ft. interior volume

35,243 lbs weight, 33,753 lb net cargo

26 pallets loaded with 104 drums, 55 gallon

Interior length: 52’8”. (632”),
Interior width: 8.37’ (100.5”),
Interior height: 9.16’ (110”)

Birmingham Dry Van (Box) Trailer Case Study

Drum details

18 drums had fire damage
2 had sand in bottom with loose batteries undergoing thermal runaway on top
1 breached drum near door evidenced gas release

Batteries in most were loose packed

55 Gallons / 208 Liters / 7.345 ft^3
35 Inches tall
24 Inch diameter
16 ga Steel
380 in^2 lid surface area
Fail catastrophically at 14+ psi
Leak tests at 5 psi
Lids may bulge at 4 psi

Birmingham Dry Van (Box) Trailer Case Study

Damage found

Floor displaced downward to ground ahead of rear wheels

Right rear door separated

Aluminum roof separated into three pieces

- Aft third and mid landed to right of trailer
- Forward portion landed to left of tractor more damaged

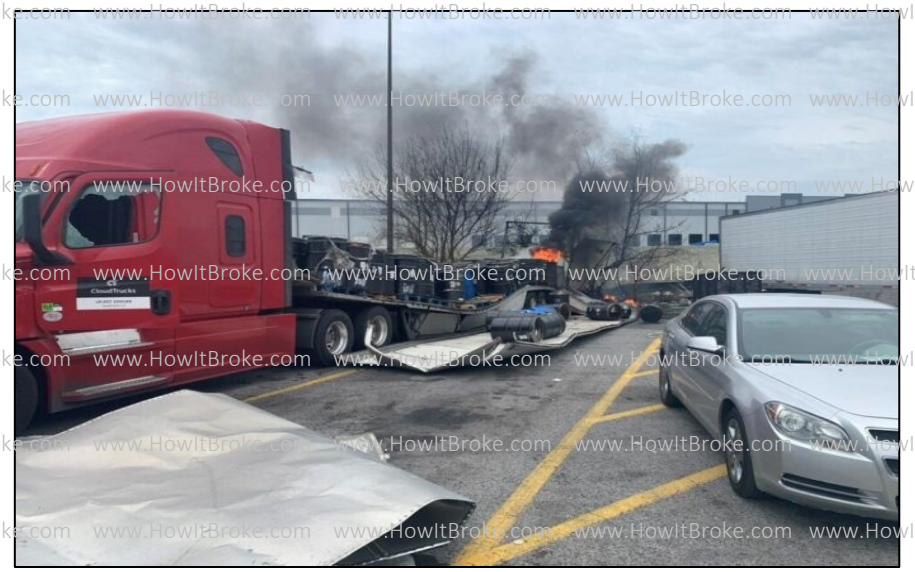
Left sidewall

- Total separation relatively intact
- Tearing from front ragged at front

Right sidewall

- Aft half folded down from top and remained attached
- Forward portions smaller and completely separated

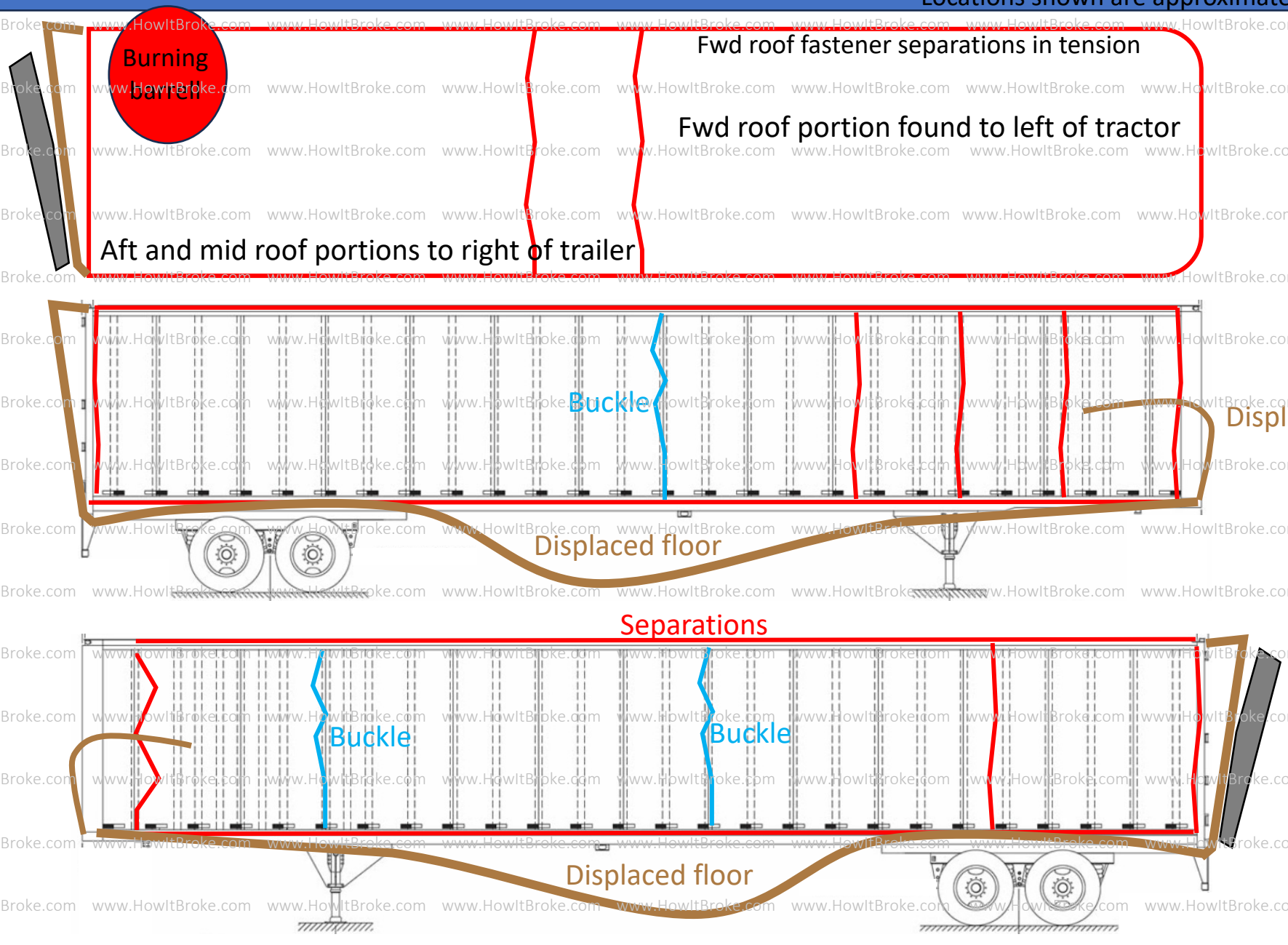
Front wall displaced forward into sleeper compartment of tractor with top folded aft



Some drums pulled during response

Damage to Trailer

Locations shown are approximate from photos



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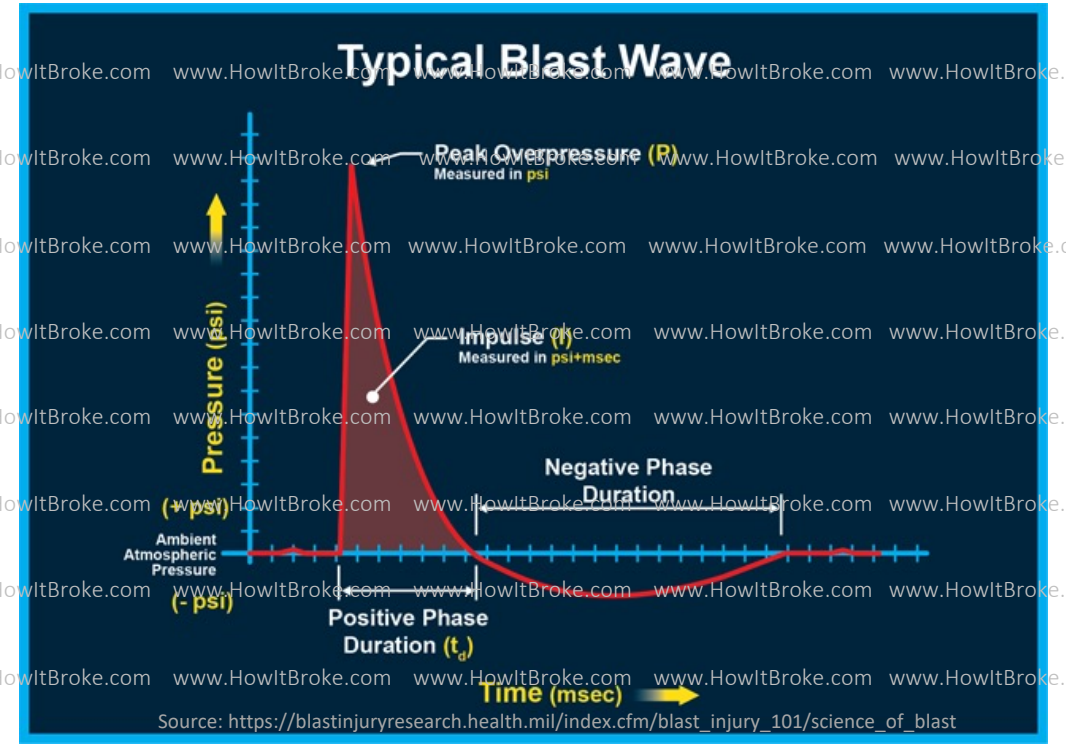
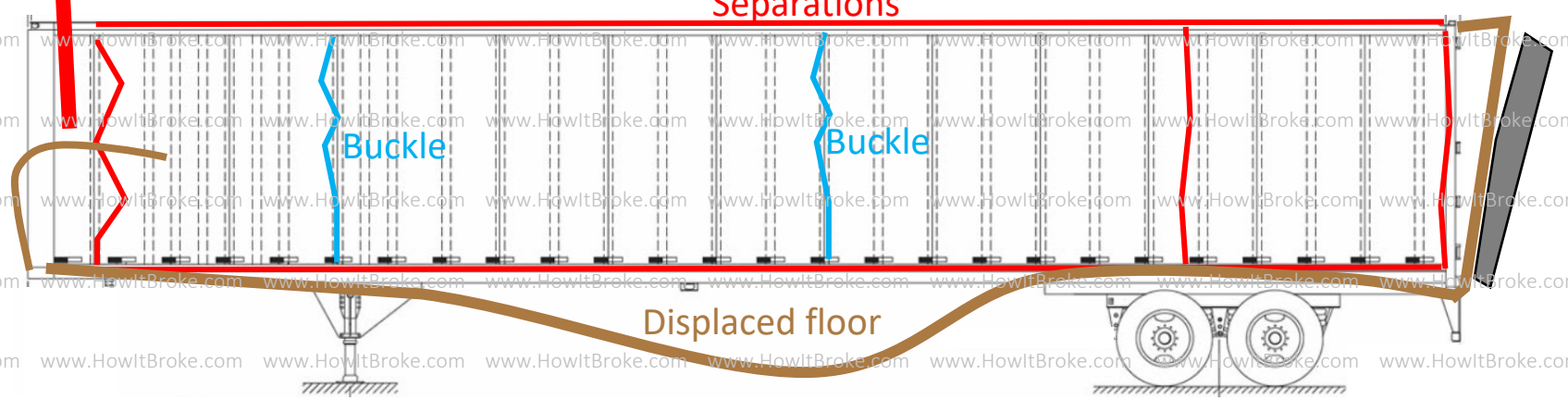
Evidence of Detonation – Negative Phase

Locations shown are approximate from photos

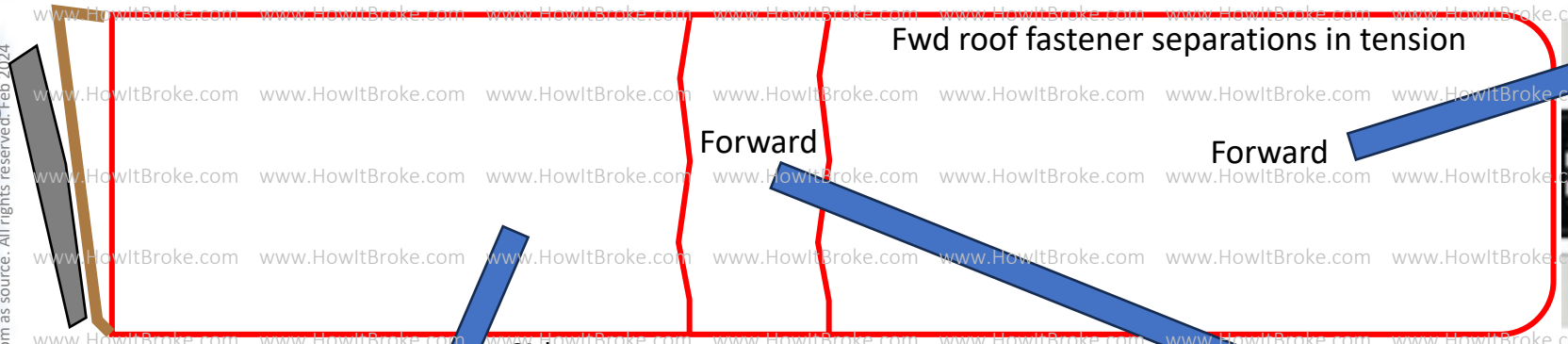




Top of left door separated

Evidence of Detonation – Roof Sections

Locations shown are approximate from photos



HowItBroke.com

Q - Why Didn't Birmingham Just Blow The Doors Off?

As in Livermore nine months later?

Answer:

Amount of fuel energy in the vapor cloud

Location of ignition

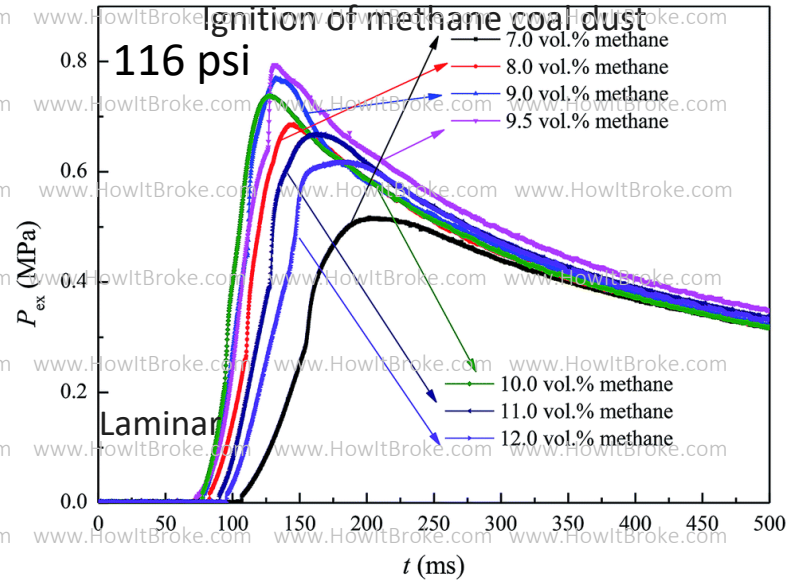
Vapor Cloud Detonations, Coal, Airline, Nuclear

Truck similarities to explosions in coal mines and airliners

Coal Mine Explosions

Air in a mine shaft can mix with methane gas and hydrocarbon volatiles from the surrounding coal.

Ignition results in a flame accelerating down the mine shaft to produce damaging overpressure.

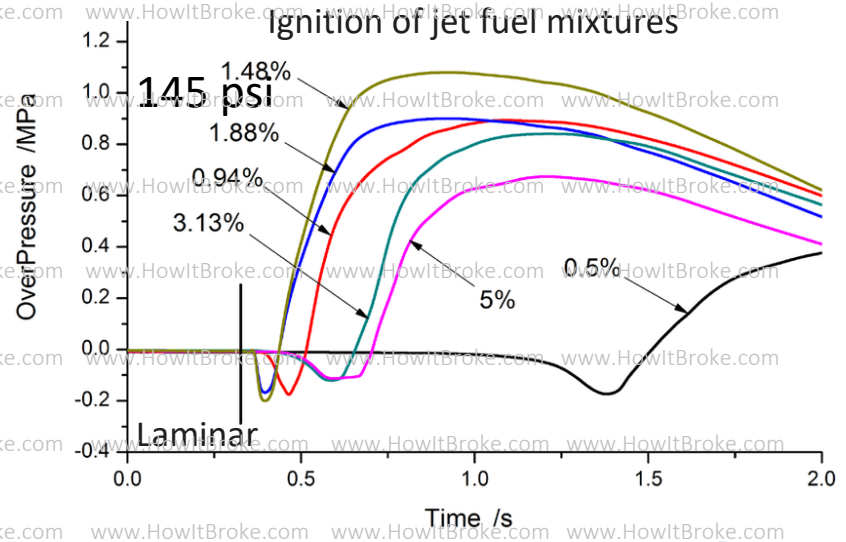


Airliner Fuel Tank Ullage Explosions

The vapor space above fuel has a limited range of flammability. (LEL and UEL)

Igniting jet fuel results in laminar flame fronts until encountering obstacles, then detonating.

Detonation impulse shatters structure.



HowItBroke.com

Three Mile Island Meltdown and H_2 Explosion Research

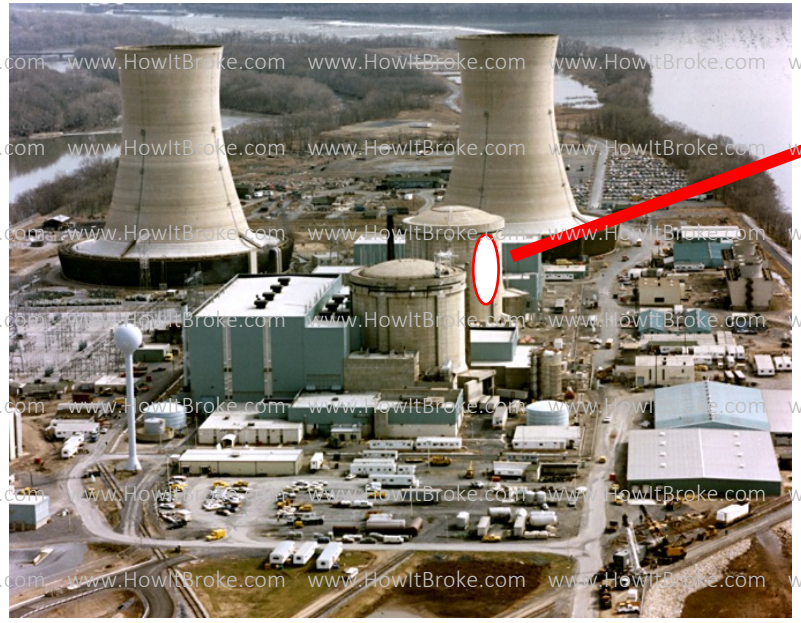
Deflagration to Detonation Transition (DDT) Near Miss Event

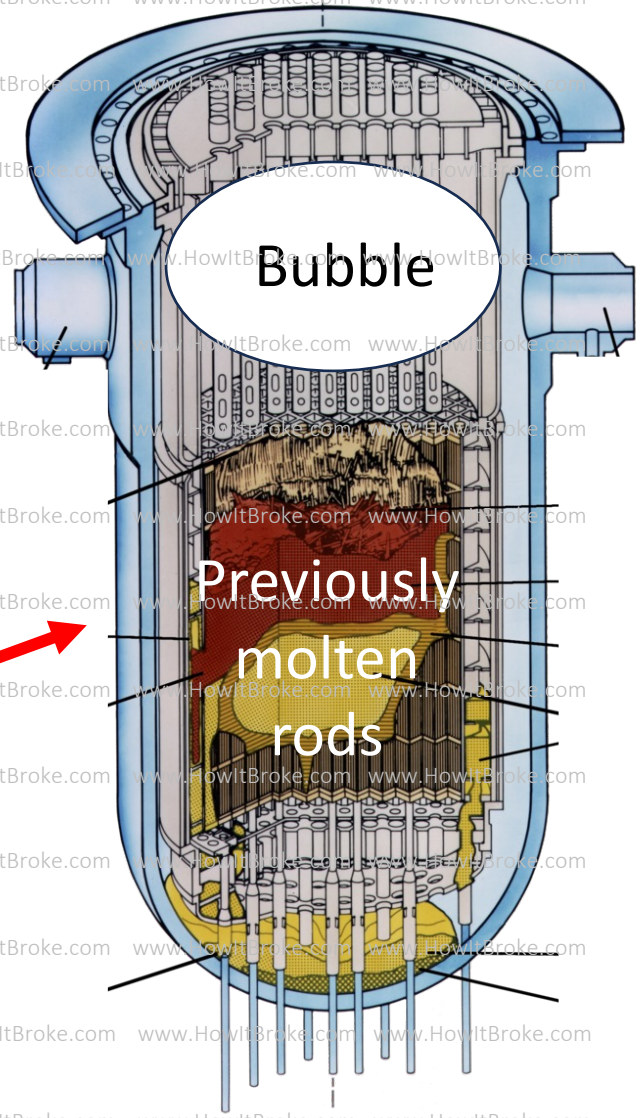
March 30, 1979 - Three Mile Island near Harrisburg, PA, experienced partial nuclear meltdown in TMI-2 reactor. TMI-1 resumed operation from 1985-2019.

A radioactive hydrogen bubble was produced by reaction of Zircaloy cladding with super-heated water.

Despite extreme temperature, insufficient oxygen prevented ignition.

Realizing the potential failure mode led to extensive research into mechanisms for hydrogen detonations.





TWA Flight 800 Center Wing Fuel Tank (CWT) Explosion

July 17, 1996 Long Island, NY

SPORTS ★ ★ ★ ★ FINAL

DAILY NEWS

50¢ NEW YORK'S HOMETOWN NEWSPAPER Thursday, July 18, 1996

229 DEAD IN 747 FIREBALL

TRAGEDY OF FLIGHT 800

- TWA jet explodes in flames off Long Island
- Fiery plunge 10 minutes after leaving JFK
- No survivors found in massive rescue bid

FULL REPORT BEGINS PAGES 2 & 3

SPORTS ★ ★ ★ ★ FINAL

DAILY NEWS

50¢ NEW YORK'S HOMETOWN NEWSPAPER Friday, July 19, 1996

HORROR OF TWA FLIGHT 800

BLOWN APART

- Missile, bomb probed in 747 explosion
- Radar records viewed for telltale clue
- Some victims died in sea after plunge

THE FACES OF TRAGEDY


DEAD: Jody Loudenslager


DEAD: Richard Campbell


DEAD: Amanda Karschner


DEAD: Ludovic Chanson

20-PAGE SPECIAL REPORT BEGINS ON PAGES 2 & 3

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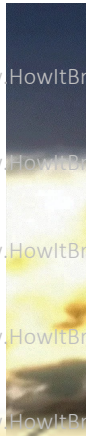
TWA Flight 800 Center Wing Fuel Tank (CWT) Explosion

July 17, 1996 Long Island,

Boeing 747-131, N93119



Parked at JFK through sweltering hot afternoon on July 17, 1996

230 passengers and crew on board

Fuel was in wing fuel tanks

- The “empty” center tank contained about 50 gallons (<2 inches)
- Air conditioning equipment heated vapors in center wing fuel tank

Departed for Paris at 8:19 p.m. FDR ends at 8:30 p.m.

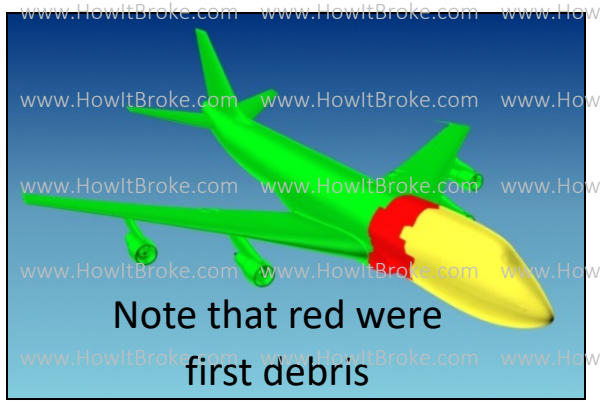
Routine Air Traffic Control Communication

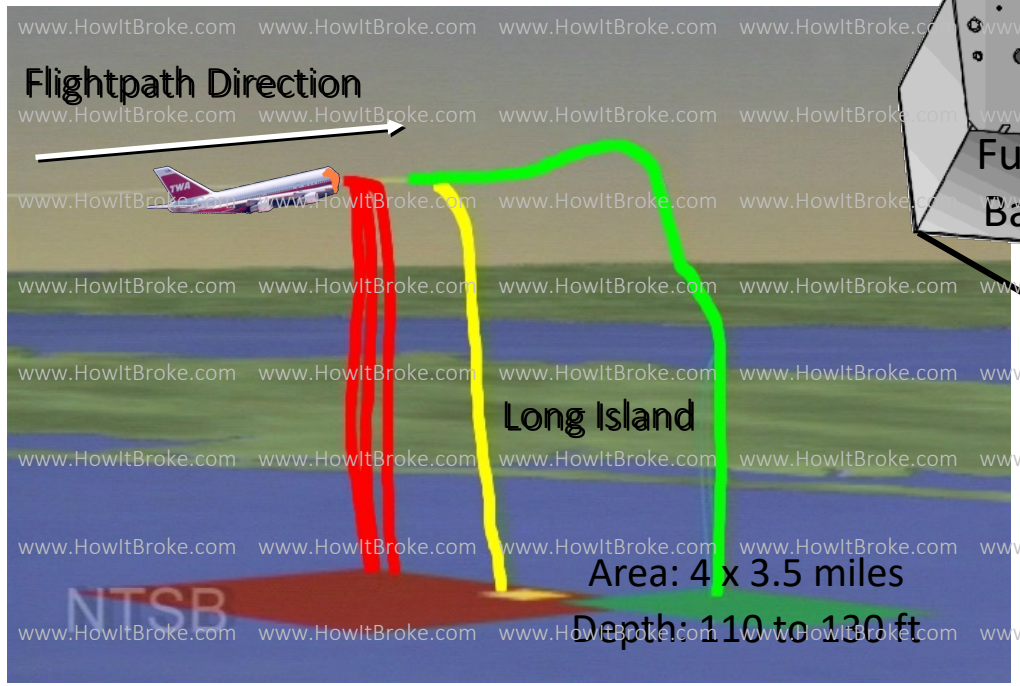
At about dusk the aircraft breakup began at 13,700 feet, 11 miles out

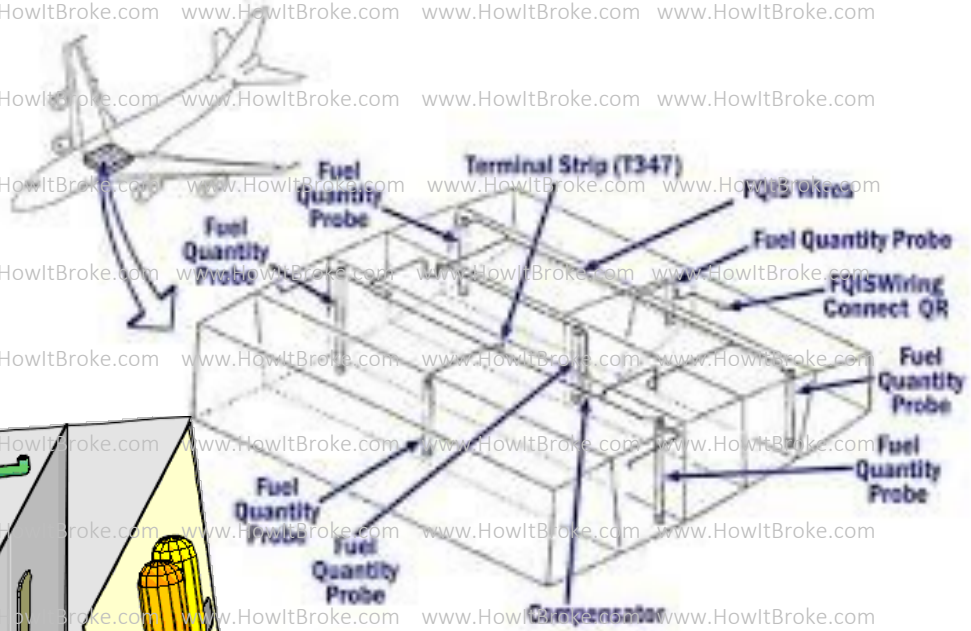
HowItBroke.com

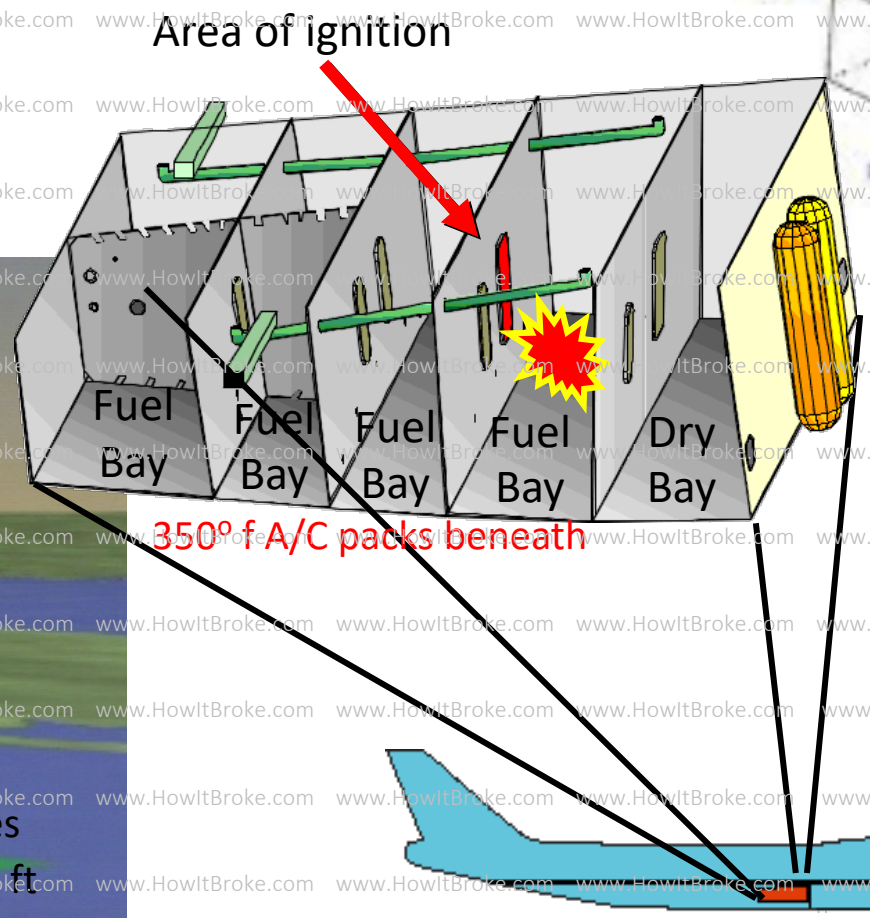
TWA Flight 800 Center Wing Fuel Tank (CWT) Explosion

Wreckage was found in three areas called
Red, Yellow, and Green Zones









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TWA Flight 800 Center Wing Fuel Tank (CWT) Explosion

Theories about in-flight breakup included

1. Structural failure and decompression.

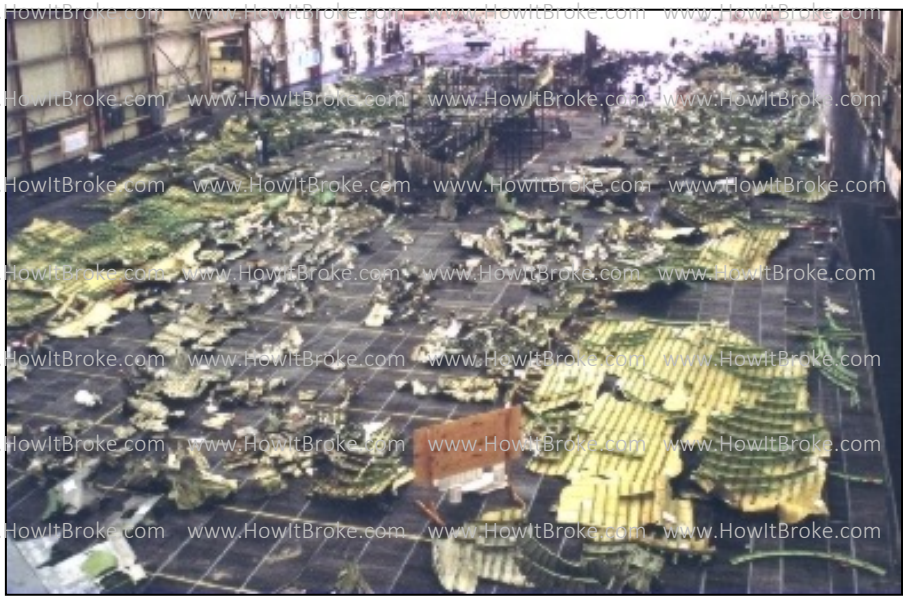
   No strutural failures found

2. Detonation of high-energy explosive device.

   No evidence of penetrations, bomb, or missile

3. Fuel/air vapor explosion in center wing tank.

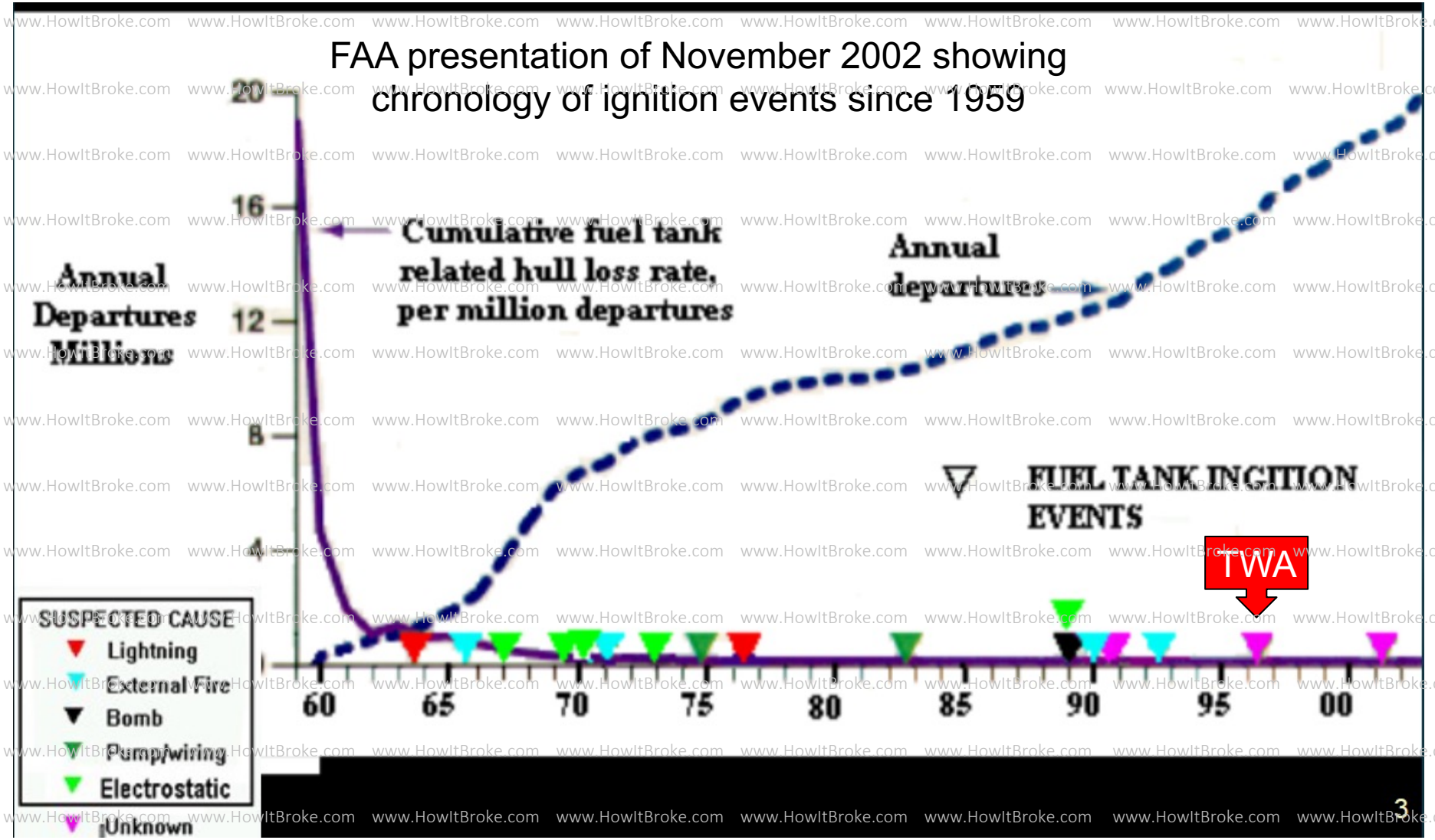
   Test program found explosive vapors and five potential ignition sources.



TWA Flight 800 Center Wing Fuel Tank (CWT) Explosion

Not until TWA800 was it realized that commercial aviation fuel tank explosion rate averaged about 52 months. Congress funded a major test program.

FAA presentation of November 2002 showing chronology of ignition events since 1959



TWA Flight 800 Center Wing Fuel Tank (CWT) Explosion

Fuel/Air vapor detonation research program used leased B-747 freighter

Fuels used:
- Jet fuel
- Propane
- Hydrogen

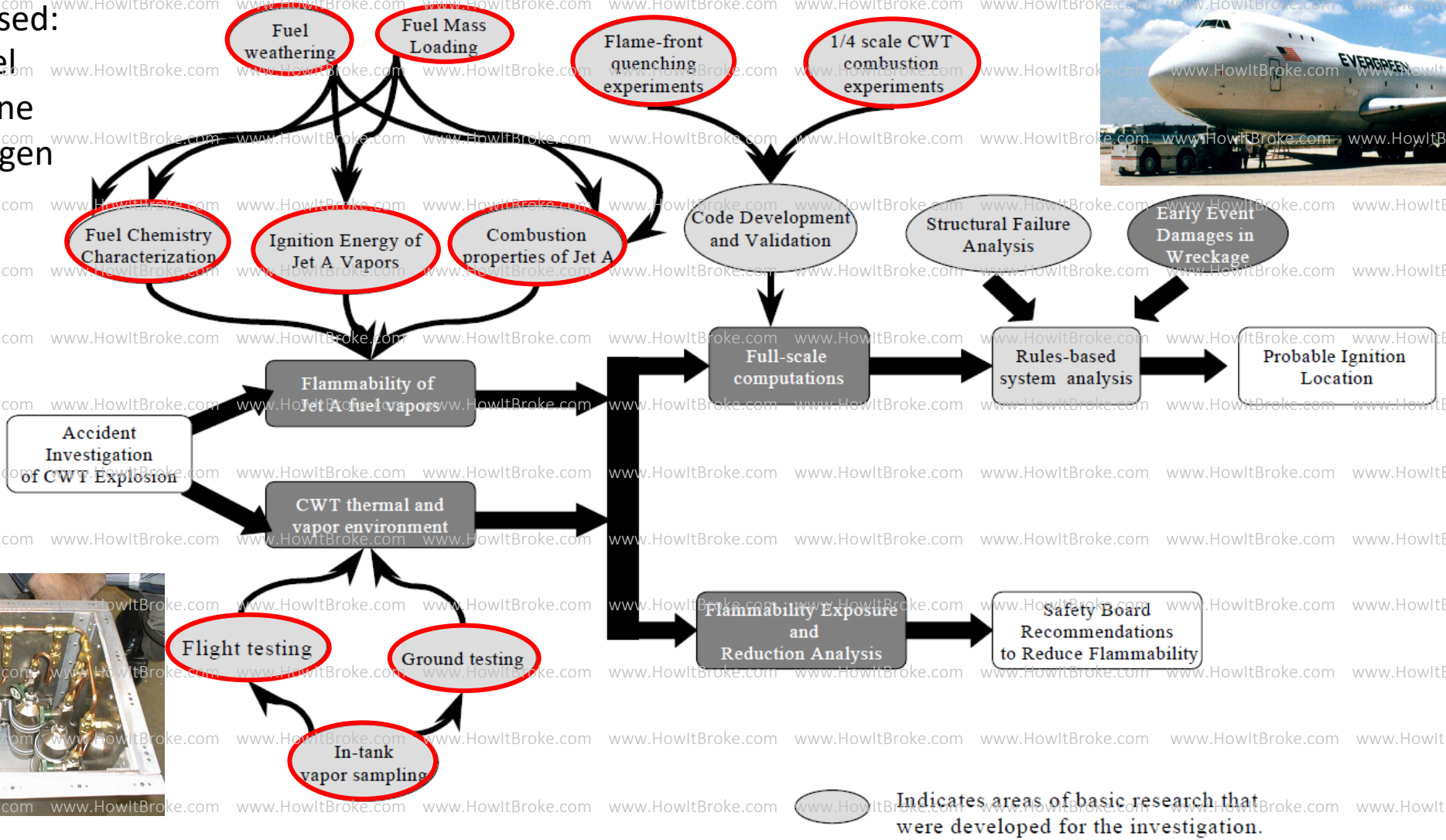
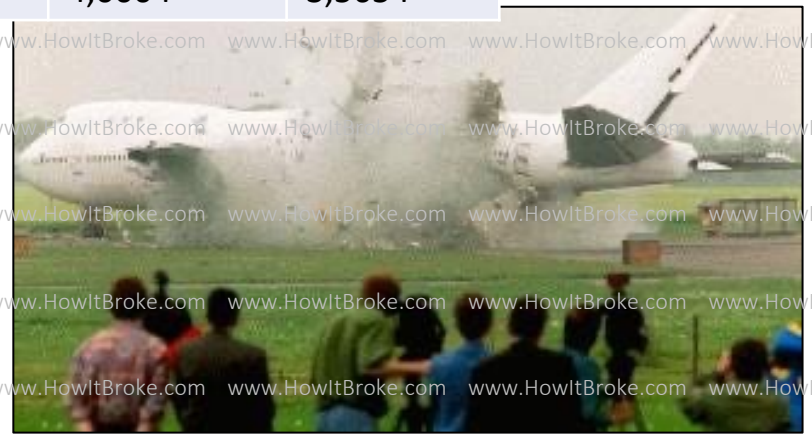


Figure 32. A flow chart of the fuel-related research conducted to support this investigation.

TWA Flight 800 Center Wing Fuel Tank (CWT) Explosion

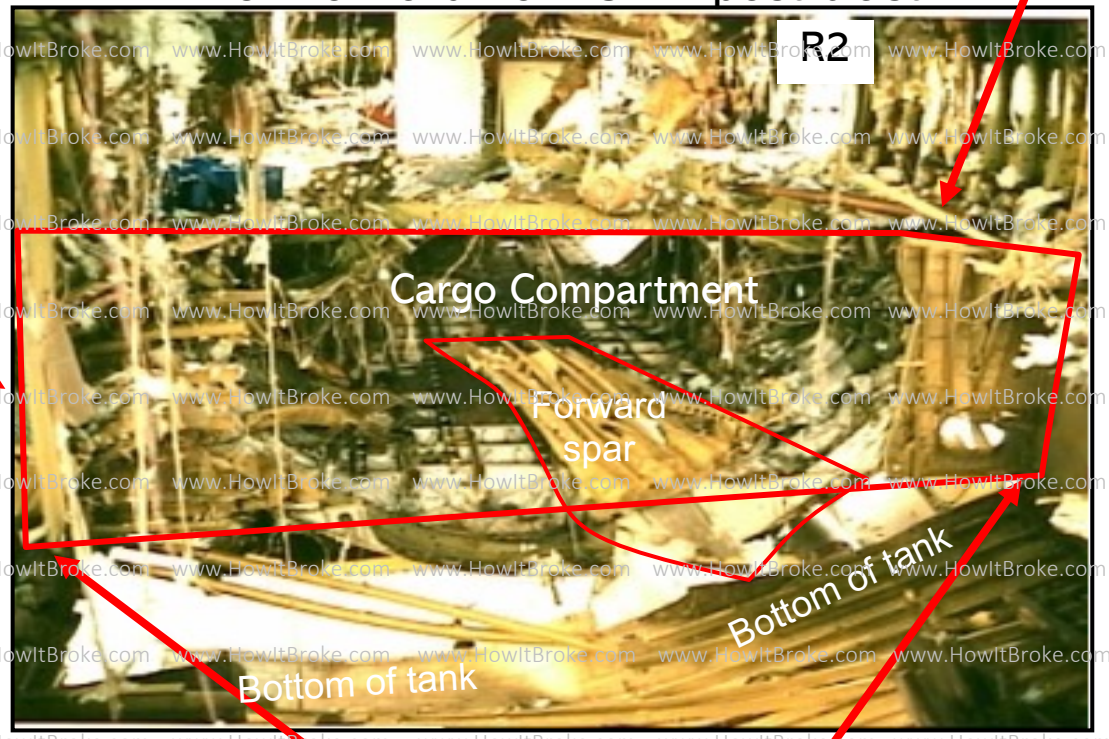
Quarter scale and other test explosions matched forward displaced SPWB #3 & Front Spar

	H_2	Propane
Energy content		73%
Flammability	4-75%	7-20%
Flame advance	200-300cm/s	30-40cm/s
Flame temp	4,000 F	3,565 F



View forward from CWT post-blast

Forward cabin floor

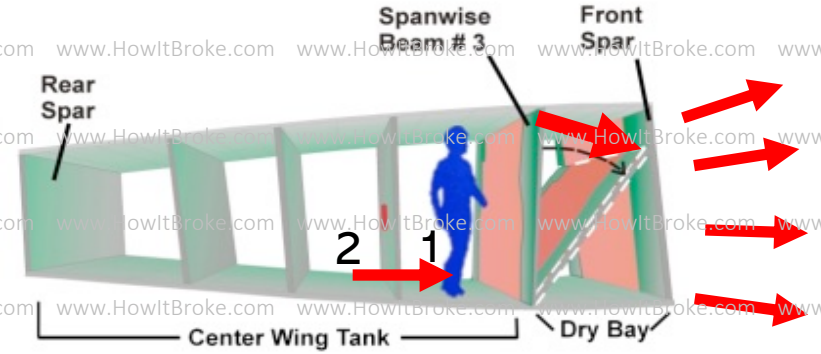


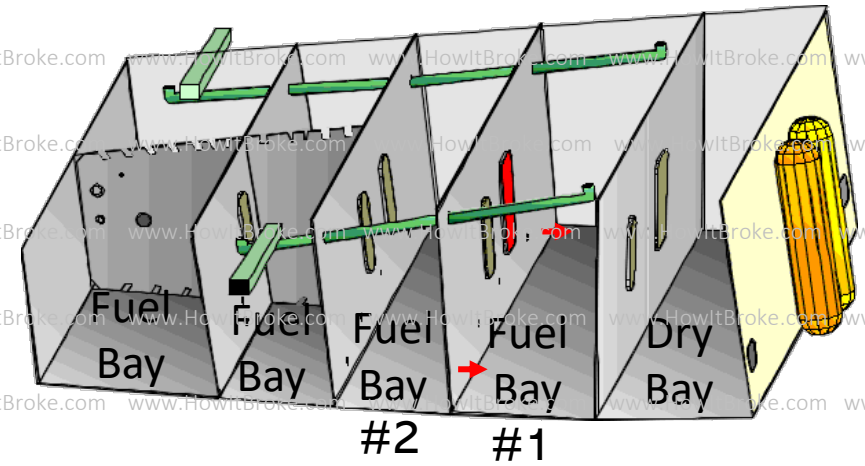
Fuselage fractures in TWA wreckage

HowItBroke.com

TWA Flight 800 Test Results

Center wing tank structure failed at 25 psi





Pressures in tank tests typically exceeded 52 psi progressing through bays

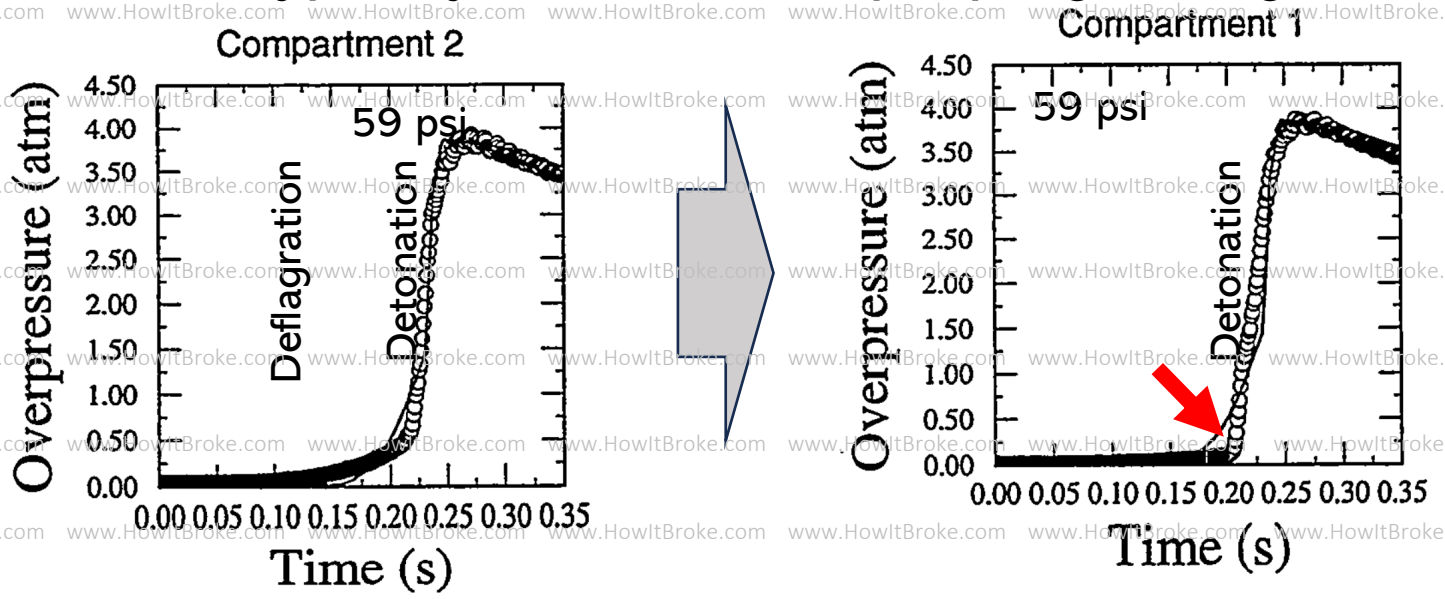
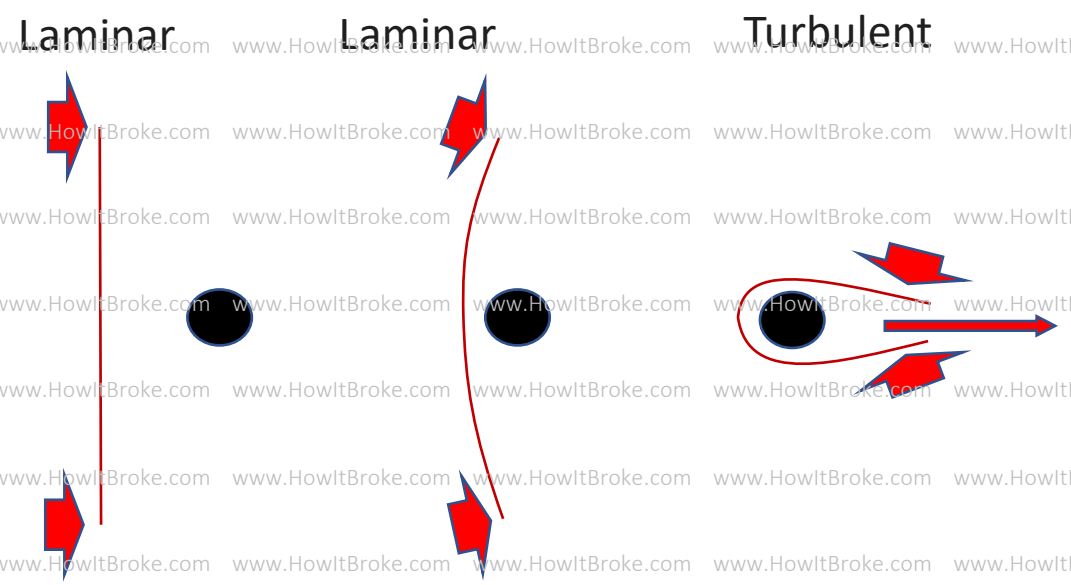


Figure 13. Overpressure versus time for Quarter-Scale Experiment 10.

Deflagration to Detonation Transition (DDT)

Flame front Acceleration (FA) becomes turbulent leading to a supersonic shock wave

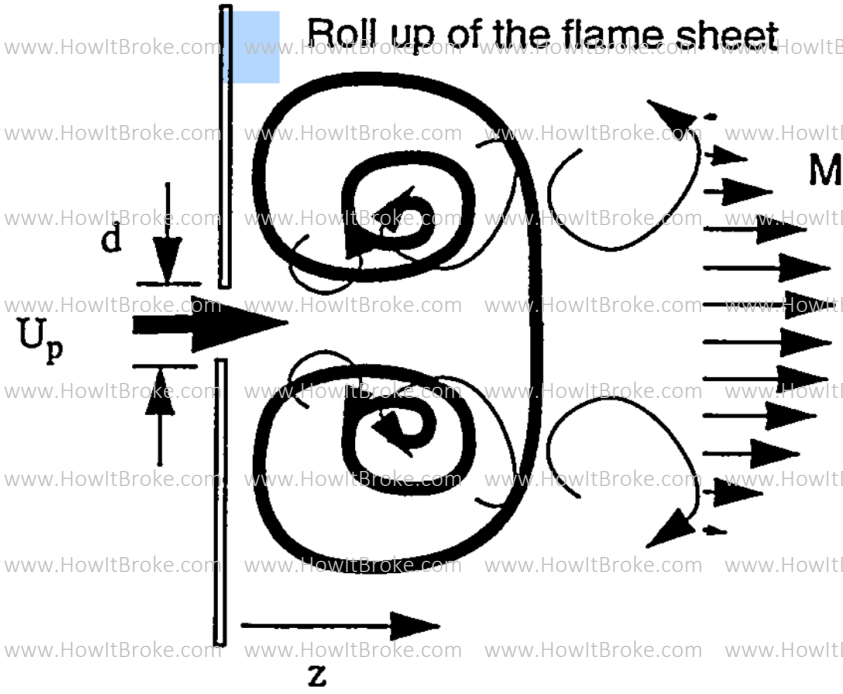
Two potential causes increase flame surface and turbulence



(Red) Laminar flame front approaches an obstruction at subsonic speed

Boundary wraps around obstruction

Collapsing flame front creates supersonic jet



Flame front passing through orifice becomes turbulent

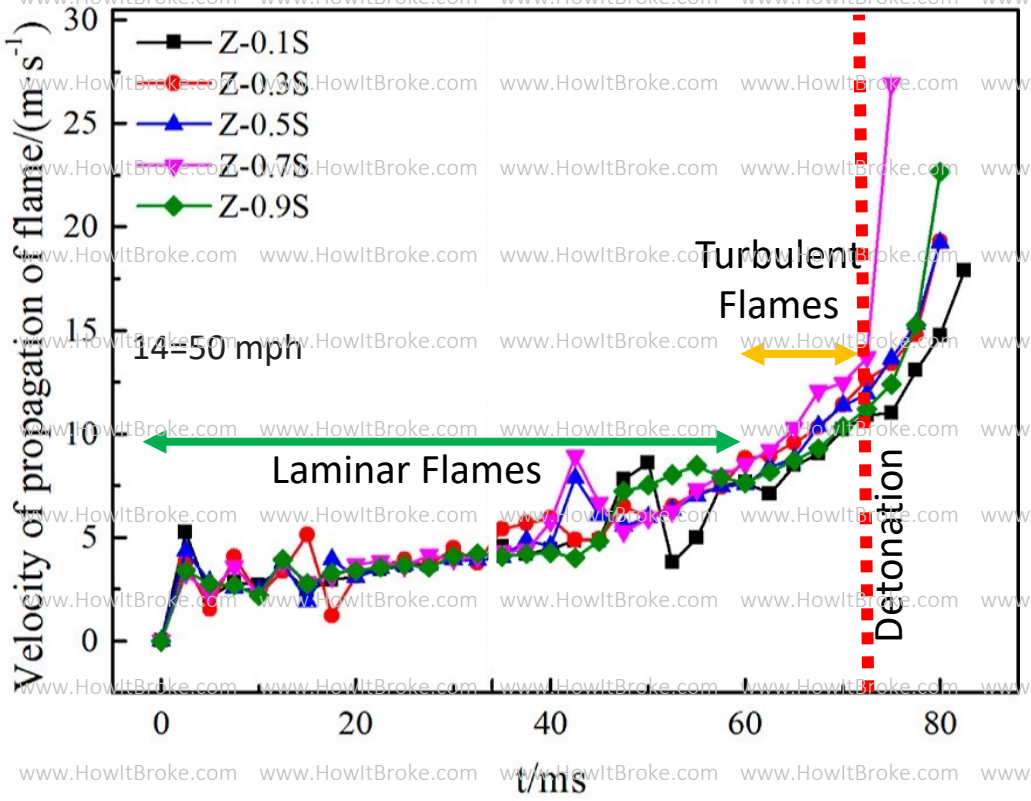
Various tests used jet fuel, hydrogen, and propane

Source: TWA Flight 800 Computational Fluid Dynamics (CFD) Report

More Recent Modeling Similar to TWA Results

Deflagration to Detonation Transition (DDT)

H_2 Burn velocity increases over time and distance



...the [laminar] self-accelerating expanding flame of stoichiometric hydrogen-air mixture is ... acceleration exponent of 1.22 ...

https://www.sciencedirect.com/science/article/abs/pii/S036031992032601X

Laminar through orifice

Turbulence developing

Detonation kernel

Turbulent Flow Formation

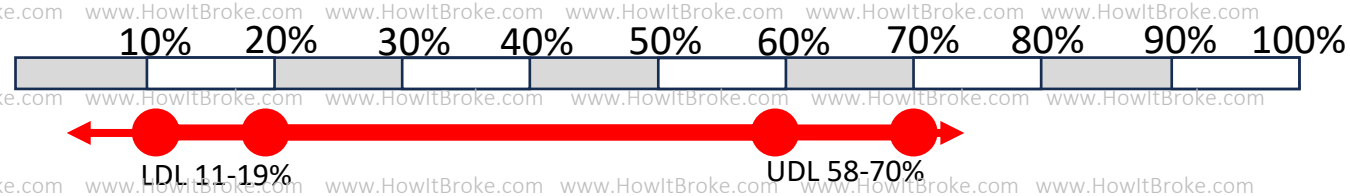
Source: https://www.slideserve.com/virote/flame-acceleration-and-transition-from-deflagration-to-detonation-in-hydrogen-explosions

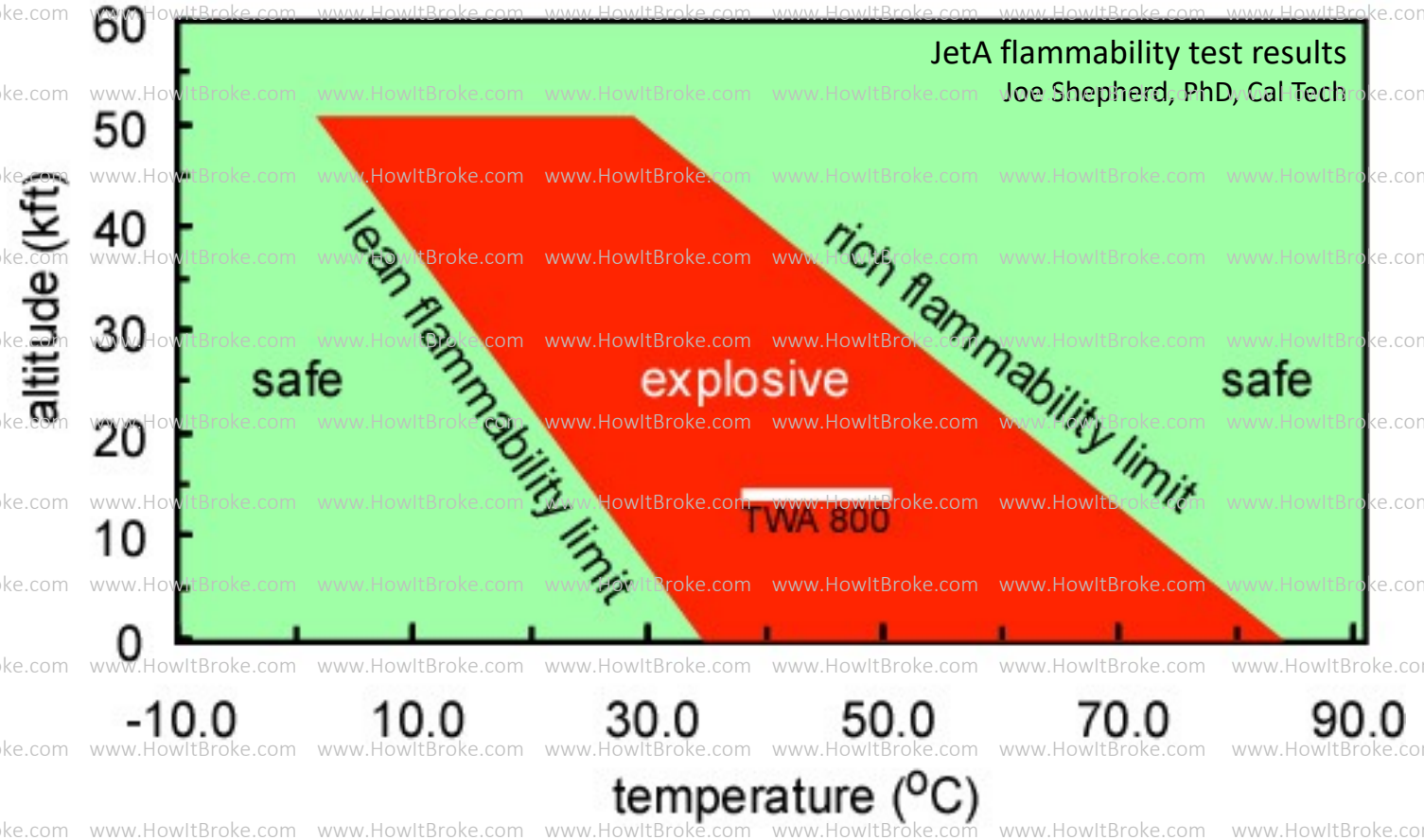
Velocity of explosion overpressure propagating in air is c = 350.88 m/s (785 mph)

HowItBroke.com

Flammability and Detonation Limits (LFL and UFL)

		Burn temp in air	LFL by Volume	UFL by Volume
Hydrogen	H_2	2483K = 4010F	4	75





LDL & UDL Source: https://hyresponder.eu/wp-content/uploads/2021/06/Lecture-10-slides.pdf

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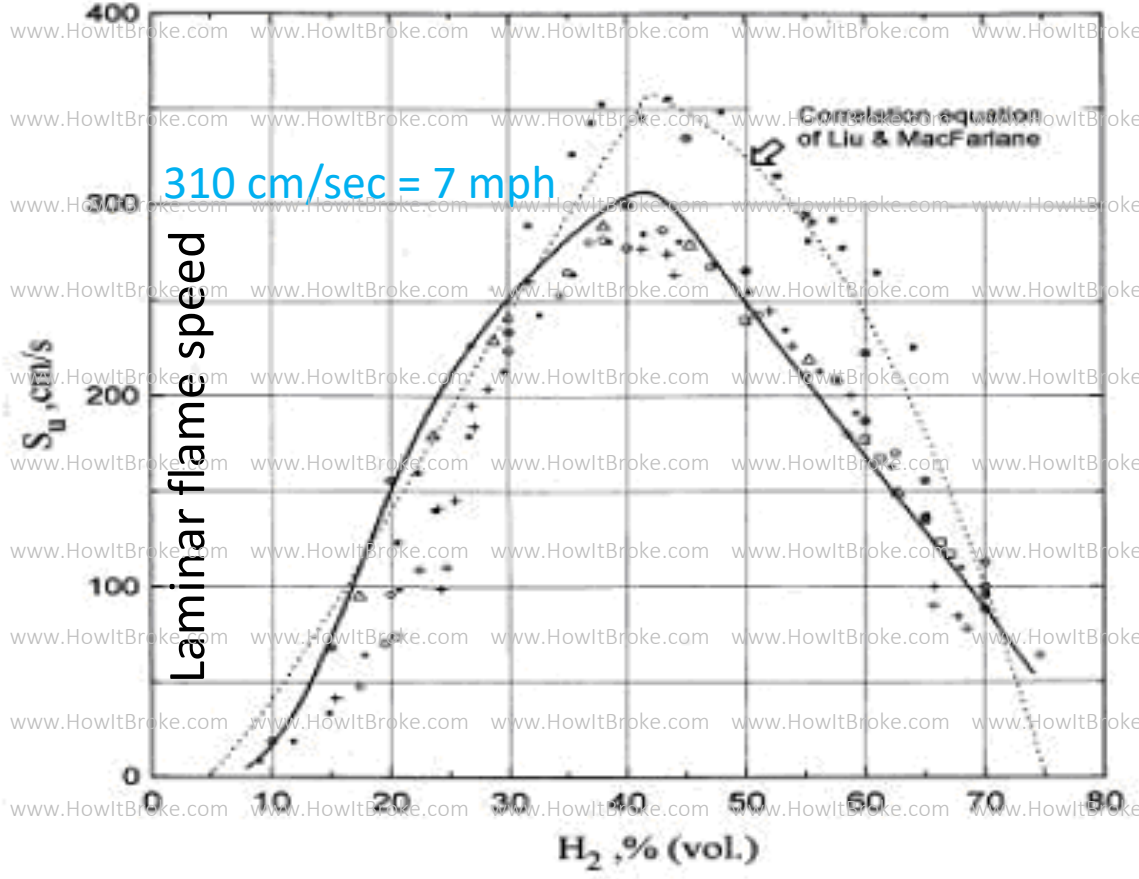
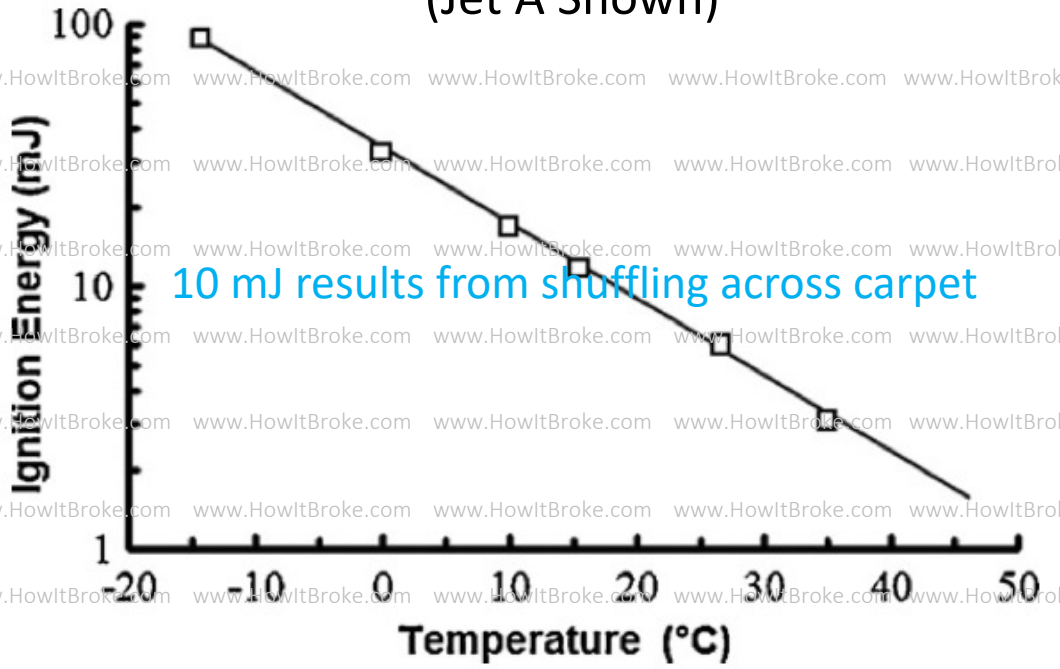
Mixture directly affects burning velocity

Mixture (Equivalence ratio) affects hydrogen flame speed and detonation distance



Flammability is also dependent on minimum ignition energy (Jet A Shown)



10 mJ results from shuffling across carpet

Dependency of ignition energy on fuel temperature for Jet A sprays [3].

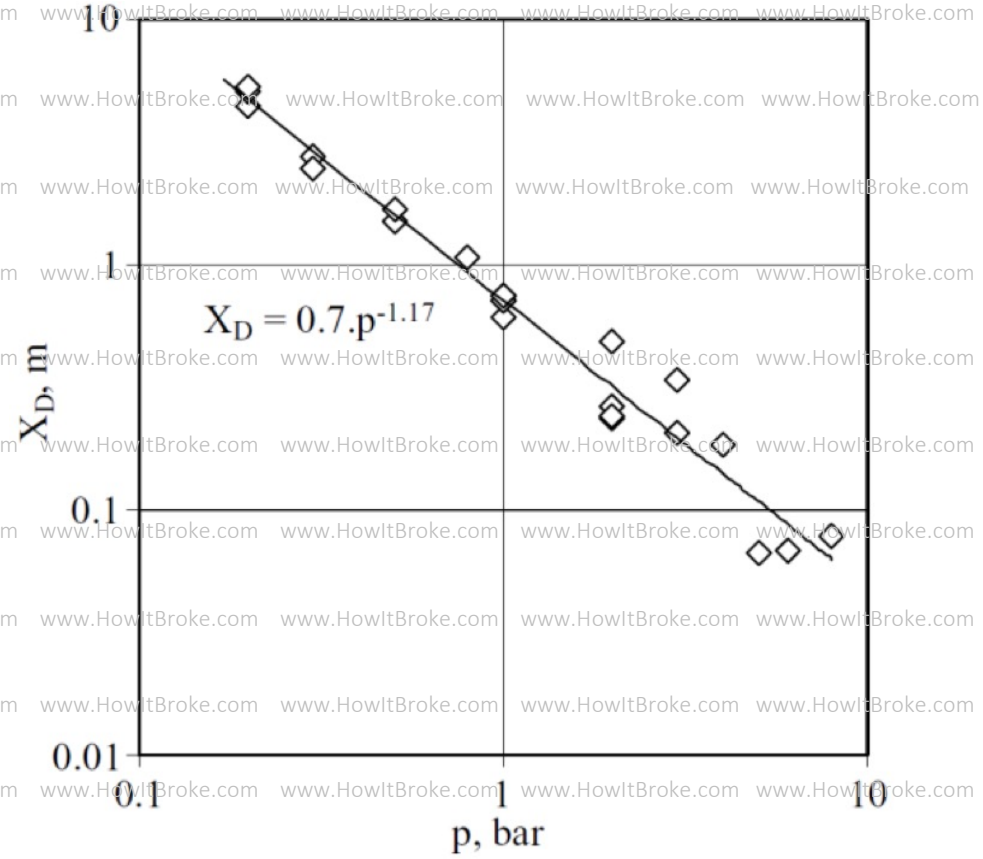
Run-Up of Deflagration to Detonation Transition (DDT)

Distance from ignition point to DDT is "Run-up distance" known as X_D

With optimum mixture and 200-300 cm/s flame advance distance is about 70 cm at 1 atmosphere (bar)

X_D decreases with pressure increase

Farther when mixture too rich or lean

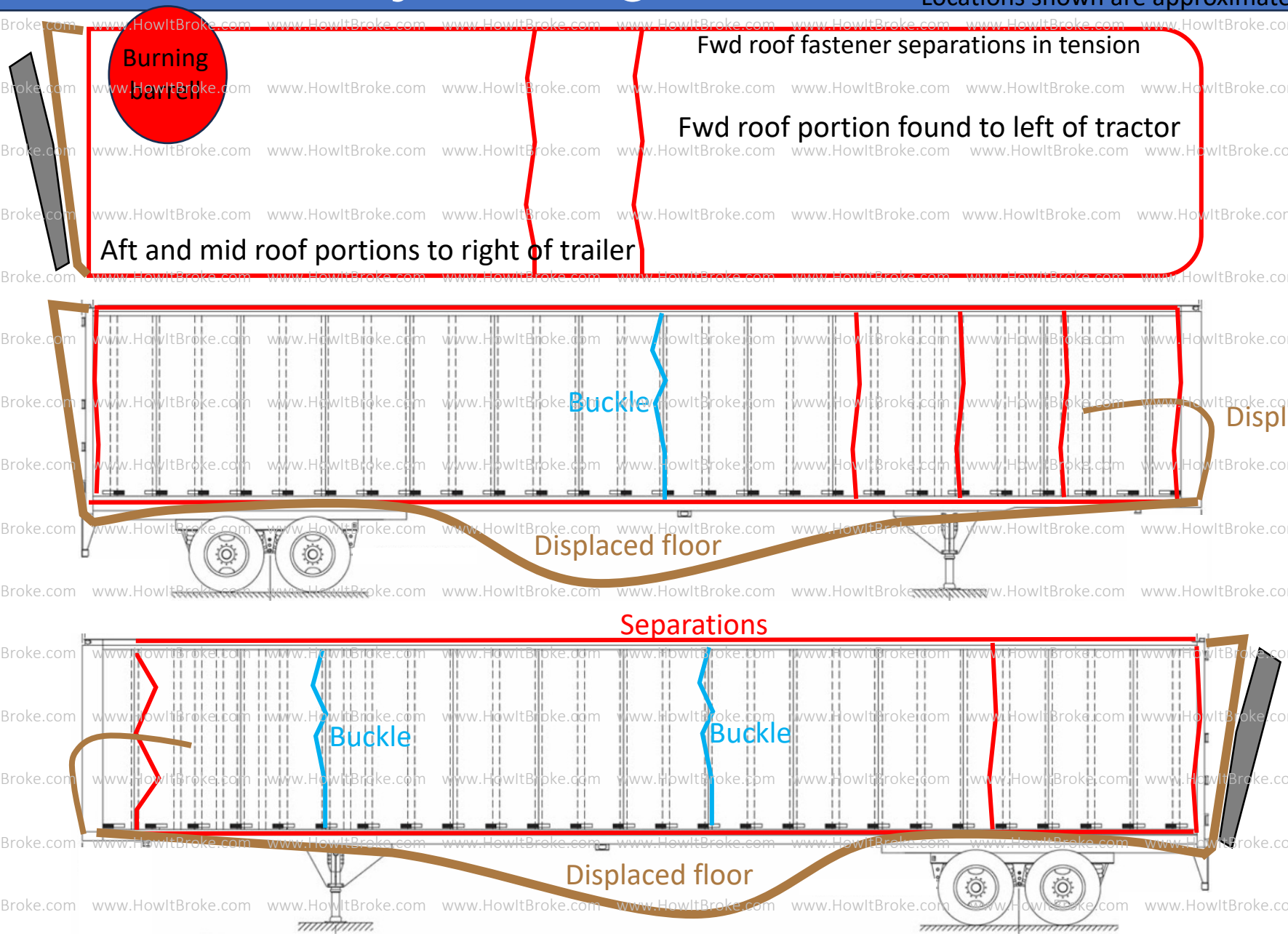


Source: Kuznetsov, M.et.al. (2005). DDT in a smooth tube filled with a hydrogen-oxygen mixture. Shock Waves, 14(3):205-215

HowItBroke.com

Apply to Trailer – Why Damage In These Places?

Locations shown are approximate from photos



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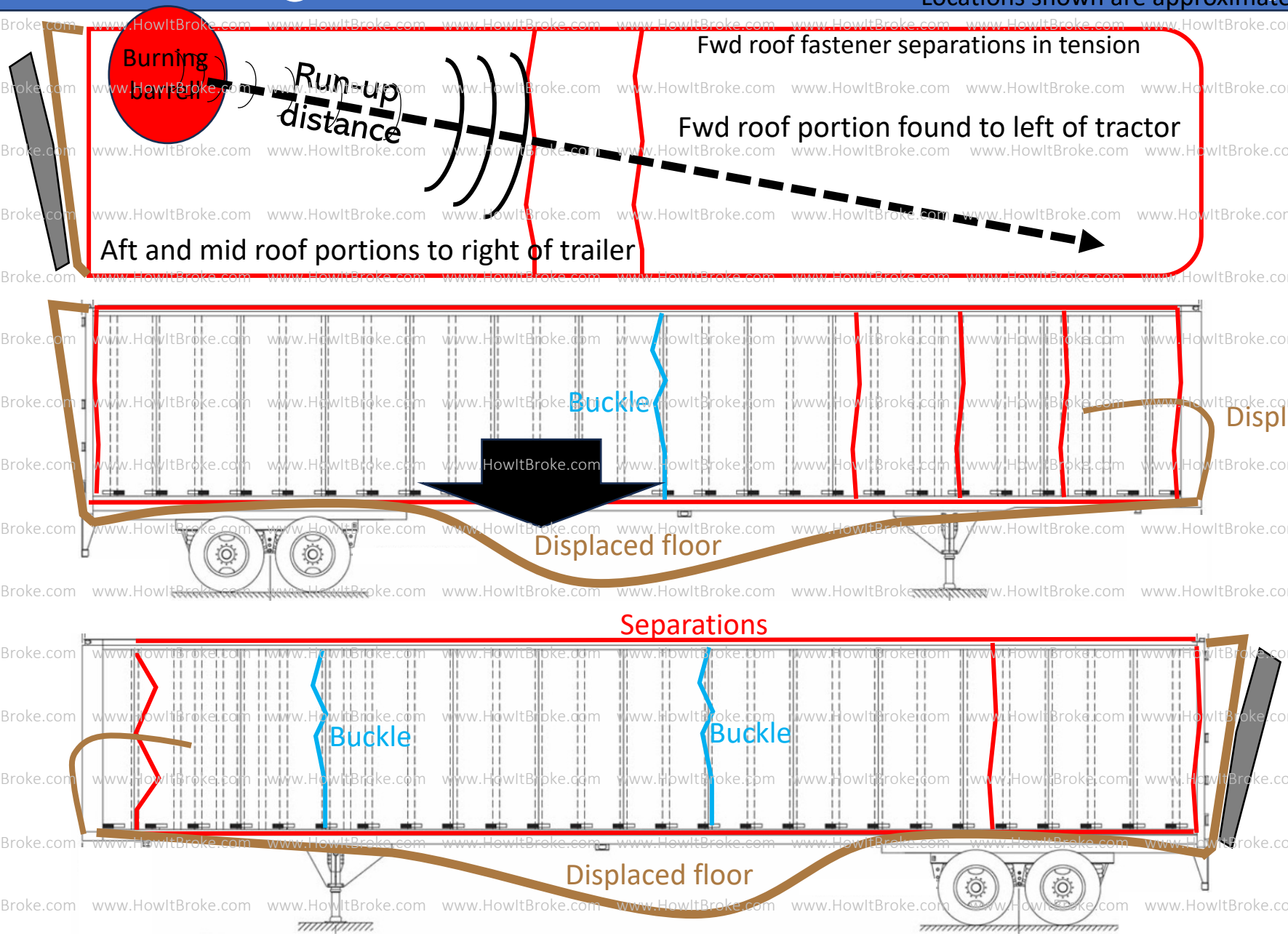
Location of Deflagration to Detonation Transition (DDT)

Locations shown are approximate from photos



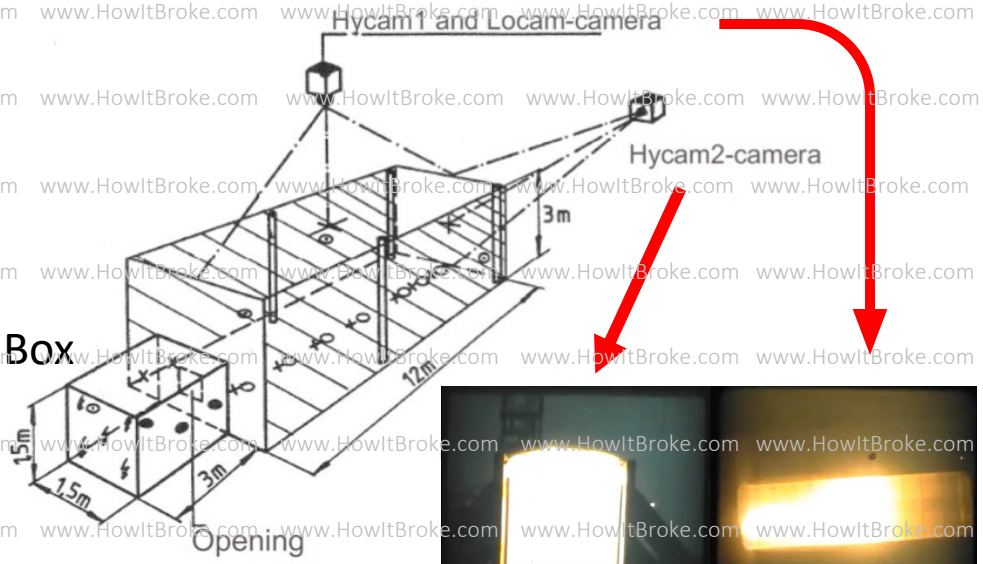
HowItBroke.com

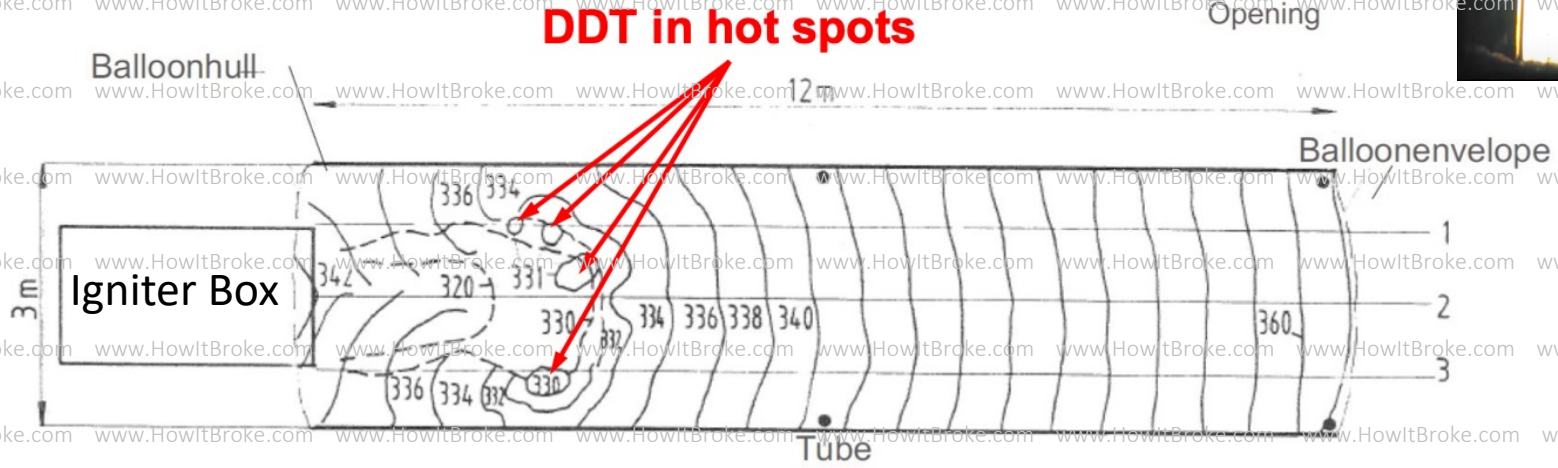
Hydrogen DDT in Volume of Trailer

Dealing with hydrogen explosions

DDT in a "lane"

- Fh-ICT experiment IA4 (1984)
- 22% hydrogen-air mixture
- 3.0 × 1.5 × 1.5 m "driver" section
- 12.0 × 3.0 × 3.0 m "lane"

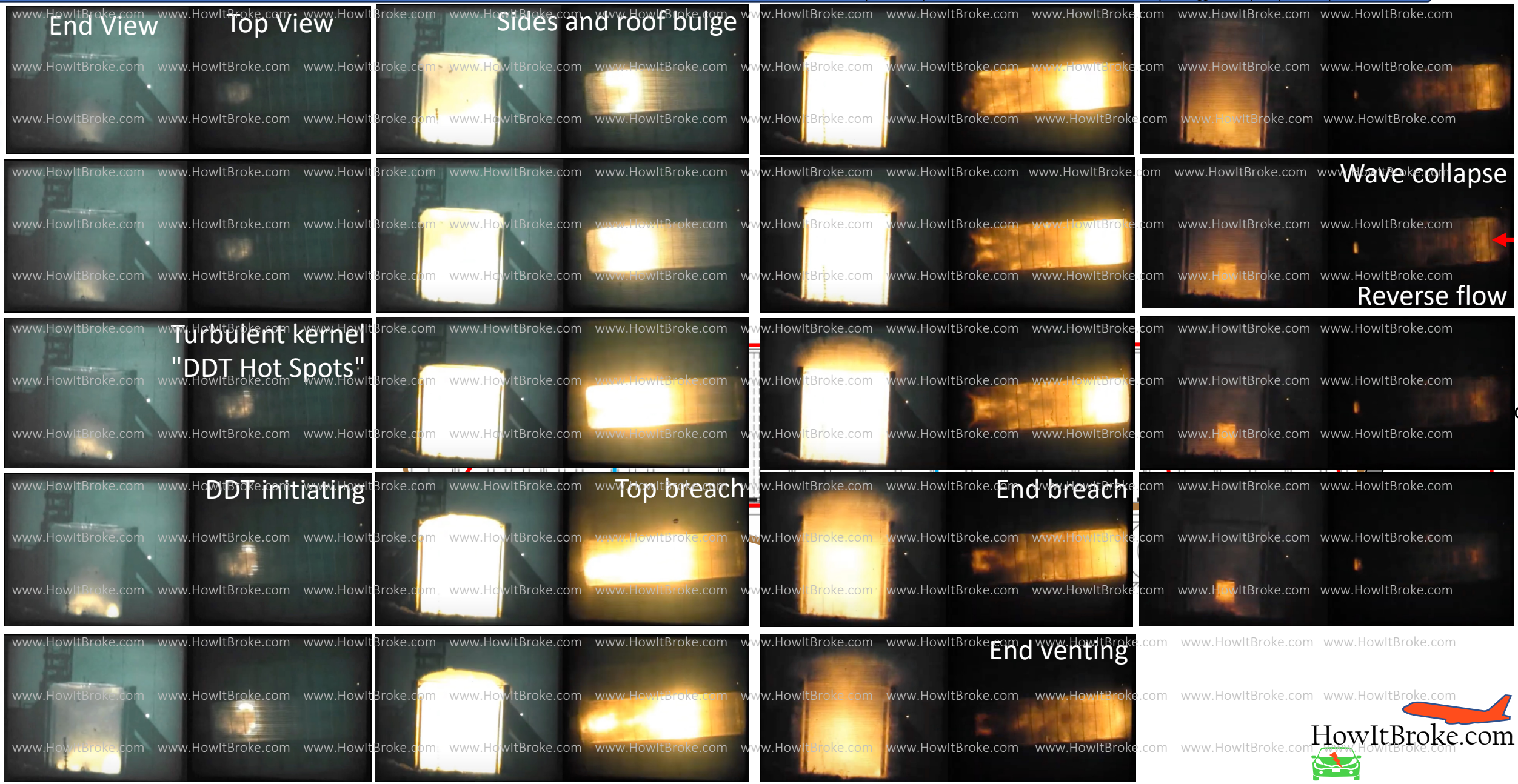




https://hyresponder.eu/wp-content/uploads/2021/06/Lecture-10-slides.pdf

Hydrogen DDT in Volume of Trailer

https://www.youtube.com/watch?v=f54TxnwFlcY&list=PLlphoM9ggM3Rf-Npmdq0S3WrCSpx0U4SL&index=8



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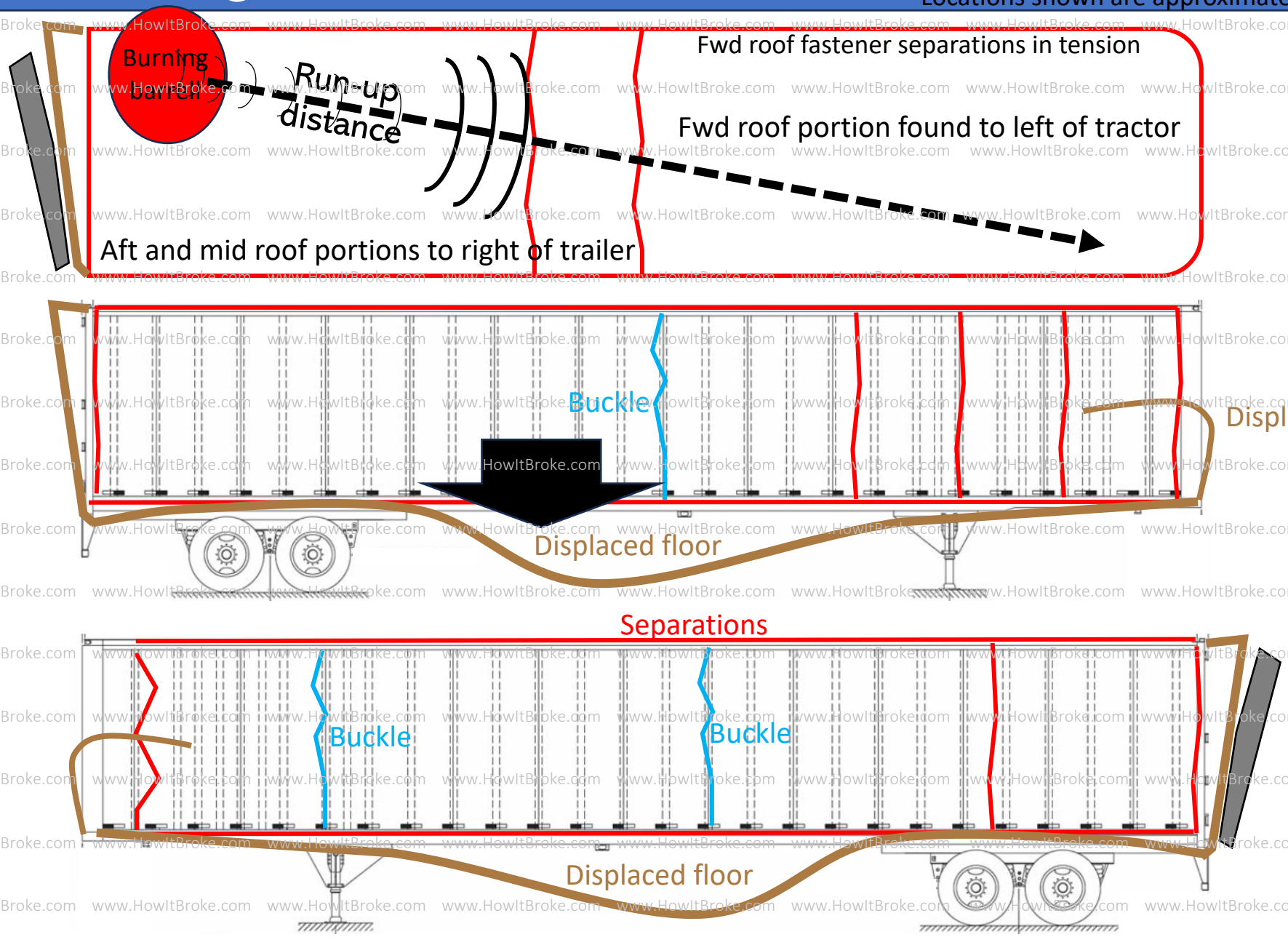
Matches Birmingham DDT Location

Locations shown are approximate from photos



HowItBroke.com

Force And Damage?

Force of Explosions Varies

Rail explosion, Houston, Texas, 4/23/17

Upper of two stacked 53 ft Intermodal steel containers
Lithium-ion batteries being sent to recycler
New Orleans to San Antonio
Exploded in downtown Houston
No Haz Mat markings

Trailer Door, Livermore Pleasanton, CA, 12/23

53 ft Dry van similar to Birmingham
Partial load of batteries at front of box
Exploded when firefighter used circular saw to vent front
No Haz Mat markings

Note lack of hazardous materials markings

HowItBroke.com

Extent of Damage Can Be Crude Indicator of Force

Indicator of fuel load in vapor cloud

Dry van trailers

Structurally similar
Both carrying lithium-ion batteries
Birmingham destroyed, 3/2023
Livermore relatively intact, 12/2023

Garage doors blown off

Erie CO Jeep – blown half way to street, 4/9/2023
Toronto Kona - blown beyond street, 7/26/2019

Can Compare Damaged Containers, 14 Ga Steel (0.75")

20 lb Barbecue propane container has explosive force of about 100 kg (220 lbs) of TNT

Source: WorkSafeBC

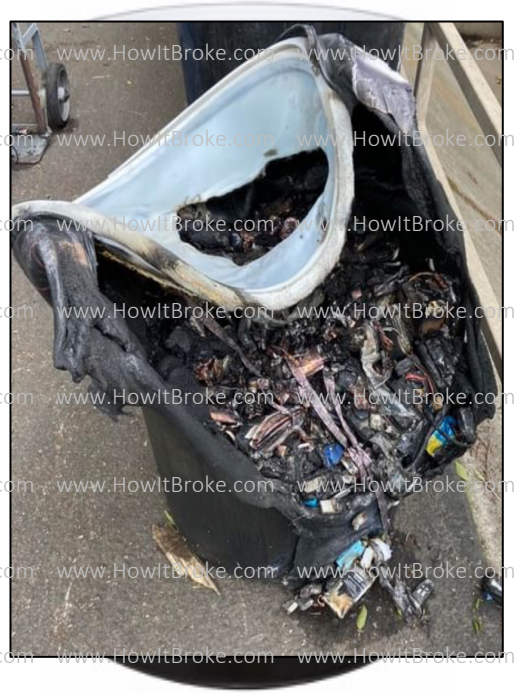
BBQ Propane Tank, Vancouver, BC

Lithium batteries, Houston, TX

Which Can Release More Gas/Smoke ?

	Size	Gas
Propane Tank	20 Gallon = 167 ft^3	167 ft^3
55 Gallon Drum	7.35 ft^3 holds up to 8,589 cells (2170)	864 (50% SOC) to 2,729 ft^3
53 Ft Trailer	4,035 ft^3 - 800 ft^3 Drums & pallets	3,255 ft^3

27-84%



=

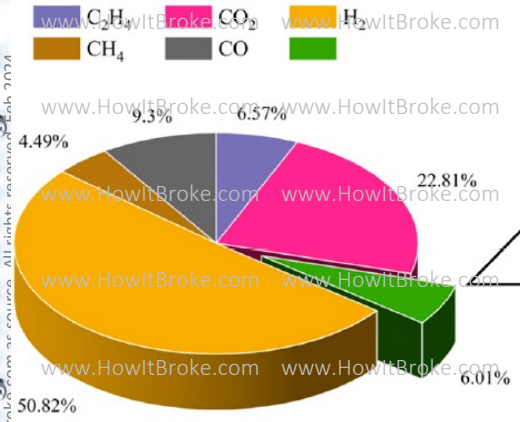
Up to 9 Liters (100% SOC)
2.85 L @ 50%

Note: NCM = 3.3 L/ Ah
NMC = 1.2–2.5 L/Ah
https://www.mdpi.com/2313-0105/9/6/300

HowItBroke.com

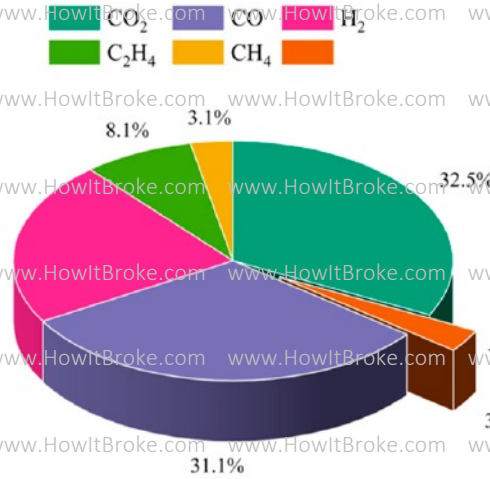
Gas/Smoke Constituents

LFP (100%SOC)



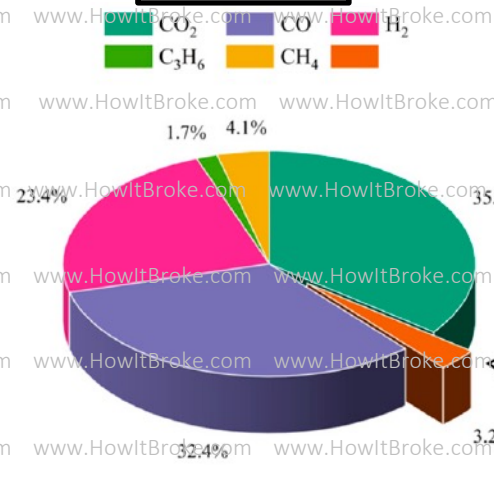
C_4H_6	2.57%
C_2H_6	2.40%
C_3H_4	0.51%
C_4H_8	0.55%
C_3H_8	0.39%
C_4H_6	0.16%
C_2H_2	0.05%

NCM523



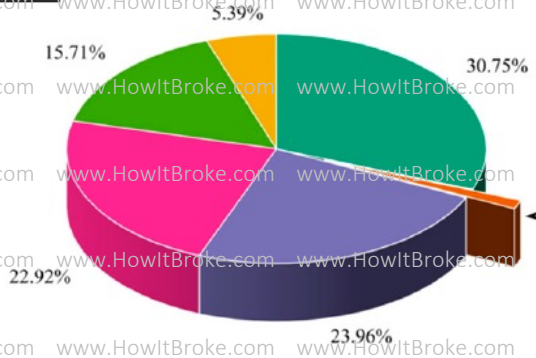
C_2H_6	0.39%
C_3H_8	0.09%
C_3H_6	1.21%
C_2H_2	0.05%
C_4H_6	0.49%
C_3H_4	0.75%
C_4H_8	0.09%

NCM622



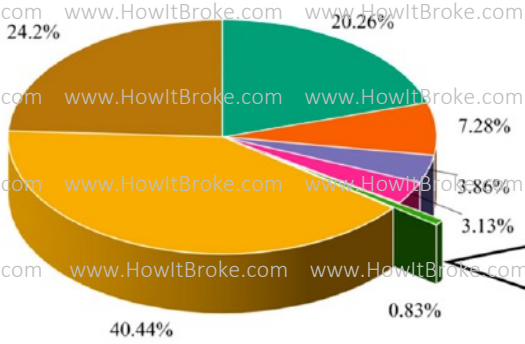
C_3H_8	1.54%
C_4H_6	0.96%
C_3H_4	0.65%
C_2H_6	0.46%
C_4H_6	0.44%
C_4H_8	0.17%
C_4H_{10}	0.11%
C_3H_8	0.09%
C_2H_4	0.08%
C_2H_2	0.01%

NCM811



C_2H_6	0.57%
C_3H_4	0.40%
C_4H_8	0.20%
C_3H_8	0.08%
C_2H_2	0.01%

NCM9 0.5 0.5



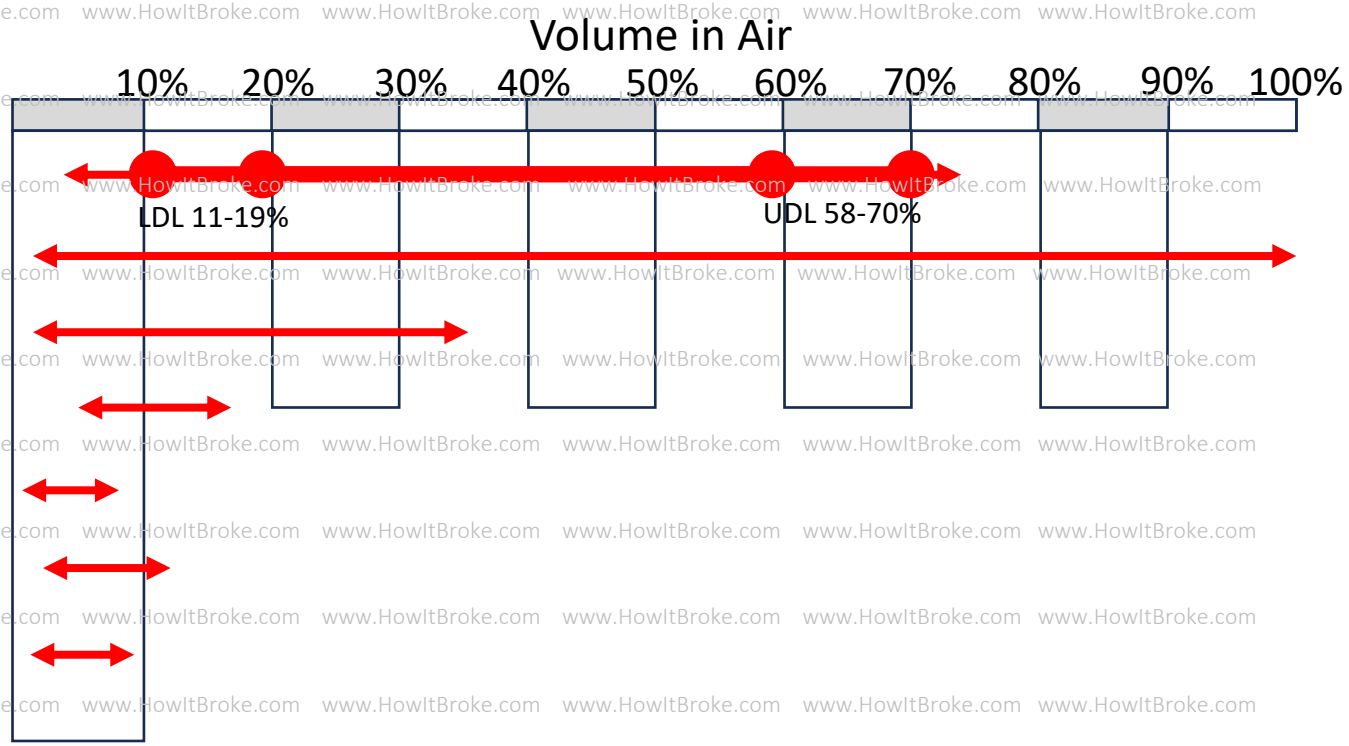
C_2H_6	0.11%
C_3H_8	0.02%
C_2H_2	0.01%
C_4H_8	0.05%
C_3H_4	0.15%
C_4H_6	0.12%
C_4H_{10}	0.37%

Source: *Thermal Runaway Characteristics and Gas Composition Analysis of Lithium-Ion Batteries with Different LFP and NCM Cathode Materials under Inert Atmosphere*
https://www.mdpi.com/2079-9292/12/7/1603

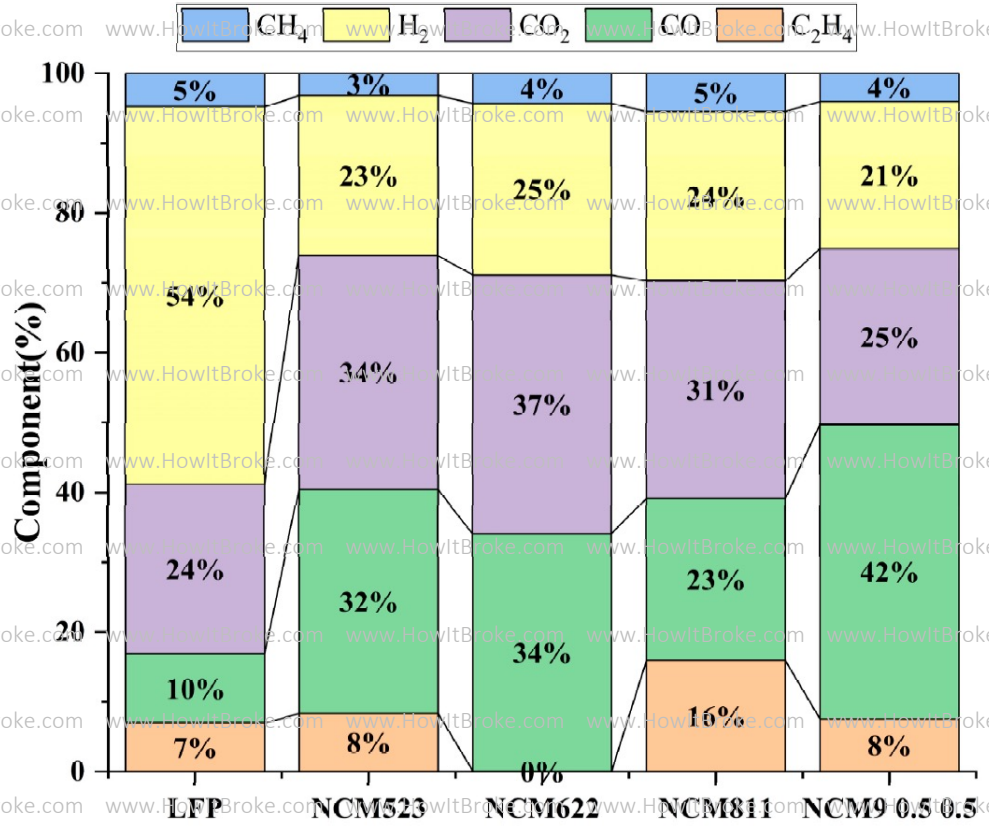
HowItBroke.com

Gas Flammability Limits Versus Detonation Limits

		Burn temp in air	LEL by Volume	UEL by Volume
Hydrogen	H_2	2483K = 4010F	4	75
Acetylene	C_2H_2	2604K = 4233F	2.5	100
Ethylene	C_2H_4	2375K = 3815F	2.7	36
Methane	CH_4	2236K = 3565F	5	17
Benzine	C_6H_6	2363K = 3794F	1.3	7.9
Ethane	C_2H_6	2222K = 3539F	3	12.4
Propane (ref)	C_3H_8	2250K = 3590F	2.1	9.5



Gas/Smoke Constituents

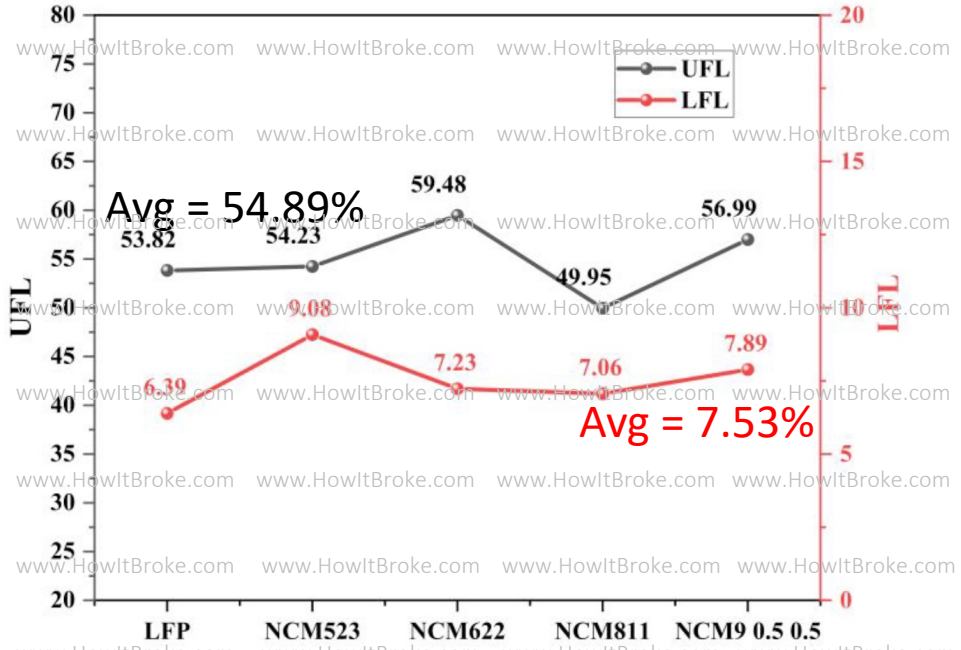


LFP	NCM523	NCM622	NCM811	NCM9 0.5 0.5
67.89%	36.5%	32.4%	46.32%	32.23%

Flammable gasses

Source: *Thermal Runaway Characteristics and Gas Composition Analysis of Lithium-Ion Batteries with Different LFP and NCM Cathode Materials under Inert Atmosphere*
https://www.mdpi.com/2079-9292/12/7/1603

Flammable Limits For Five Chemistries



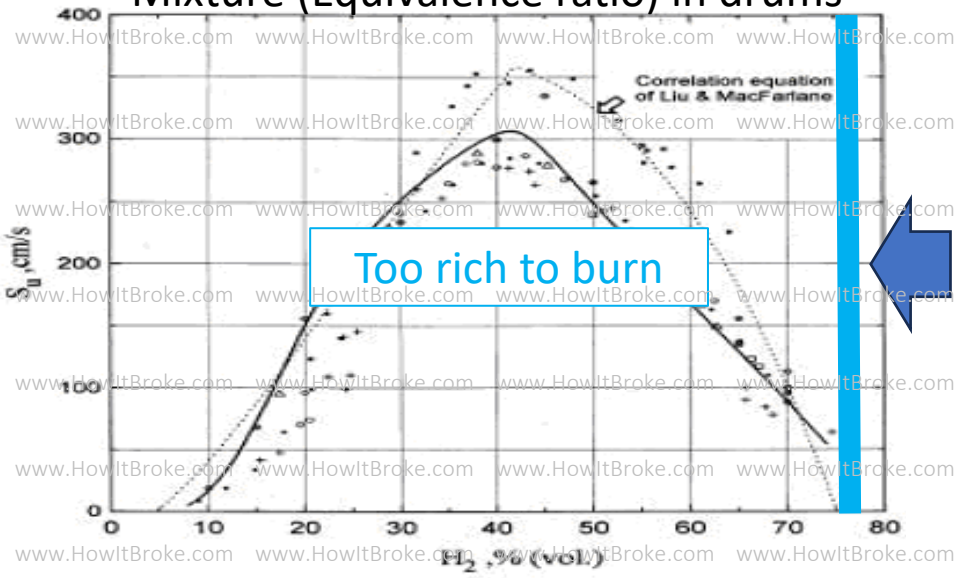
HowItBroke.com

Drum Flammability And Duration of Leakage

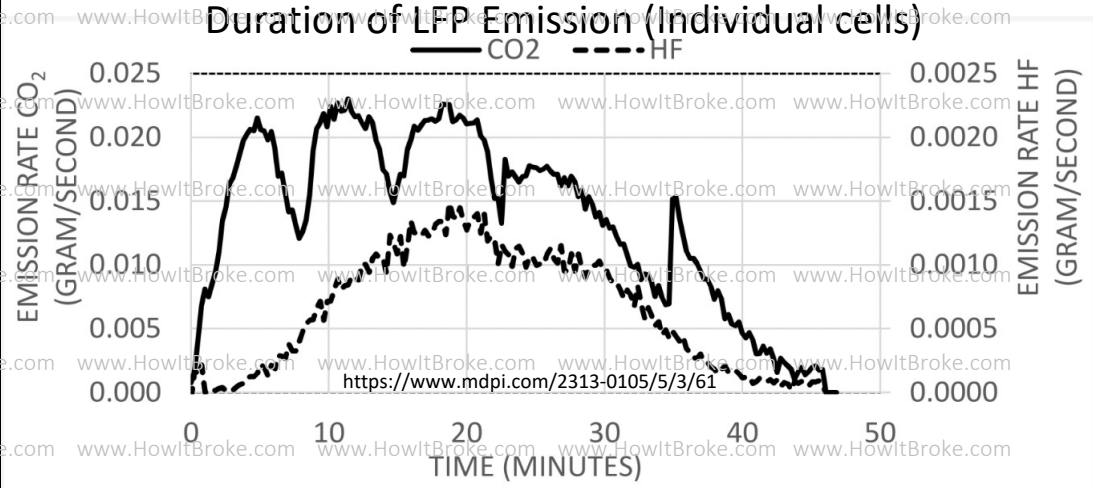
Sealed drums would pass UFL quick since volume was filled with batteries

Drums could leak hydrogen into trailer at 4-14 psi for long period of time

Mixture (Equivalence ratio) in drums



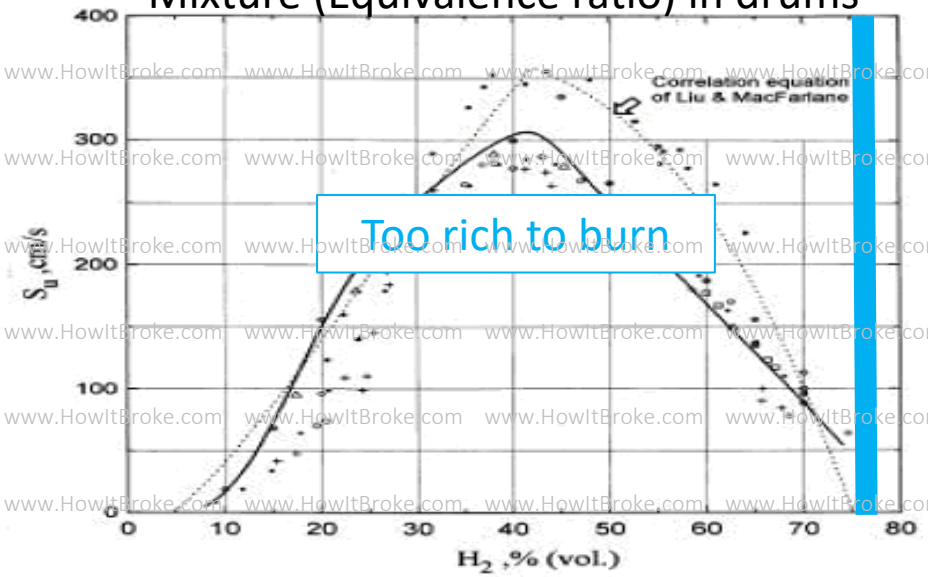
Duration of LFP Emission (Individual cells)



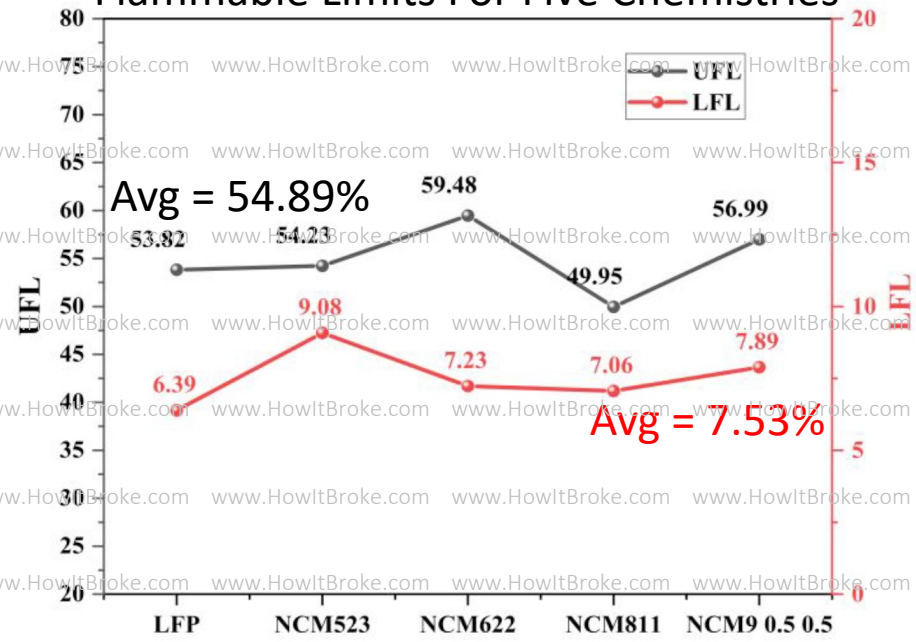
HowItBroke.com

Flammability of Birmingham Drums Versus Trailer

Mixture (Equivalence ratio) in drums



Flammable Limits For Five Chemistries



Vent gas volume in trailer =

27-84%

Drum x 7.35 ft³ with 8,589 cells (max) = 864 ft³ (50% soc) to 2,729 ft³

53 Ft Trailer, 4,035 ft³- 800 ft³ Drums & pallets = 3,255 ft³

Volume of flammable gas in trailer

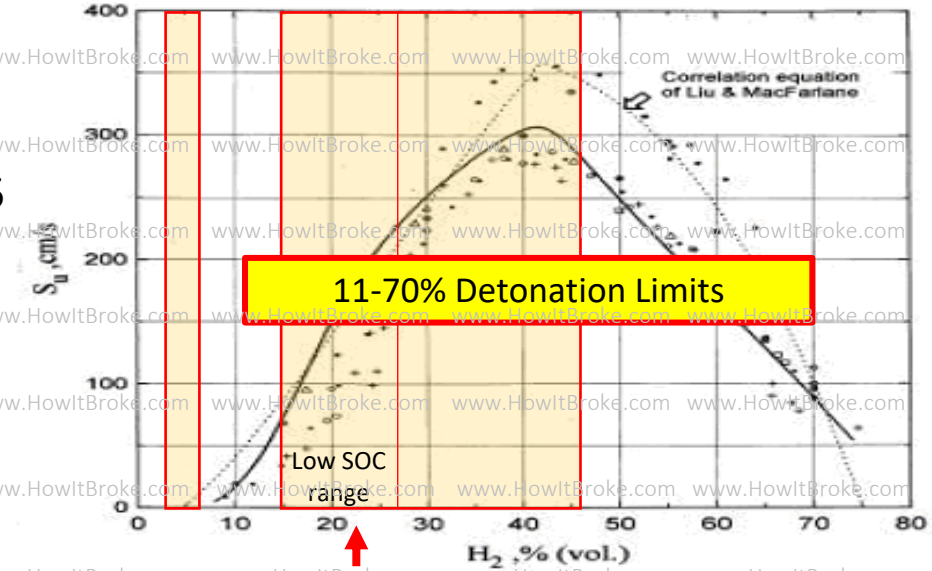
27% x 54.89% avg UFL = 14.8%

84% x 54.89% avg UFL = 46.1%

27% x 7.53% avg LFL = 2.0%

84% x 7.53% avg LFL = 6.3%

Mixture Ratio In Trailer



HowItBroke.com

Calculating DDT Force In The Birmingham Trailer

Equal pressure distribution to all surfaces inside trailer

4,035 ft^3 interior volume

Floor dimensions 632” X 100.5” = **63,516 in^2** (441 sq.ft.)

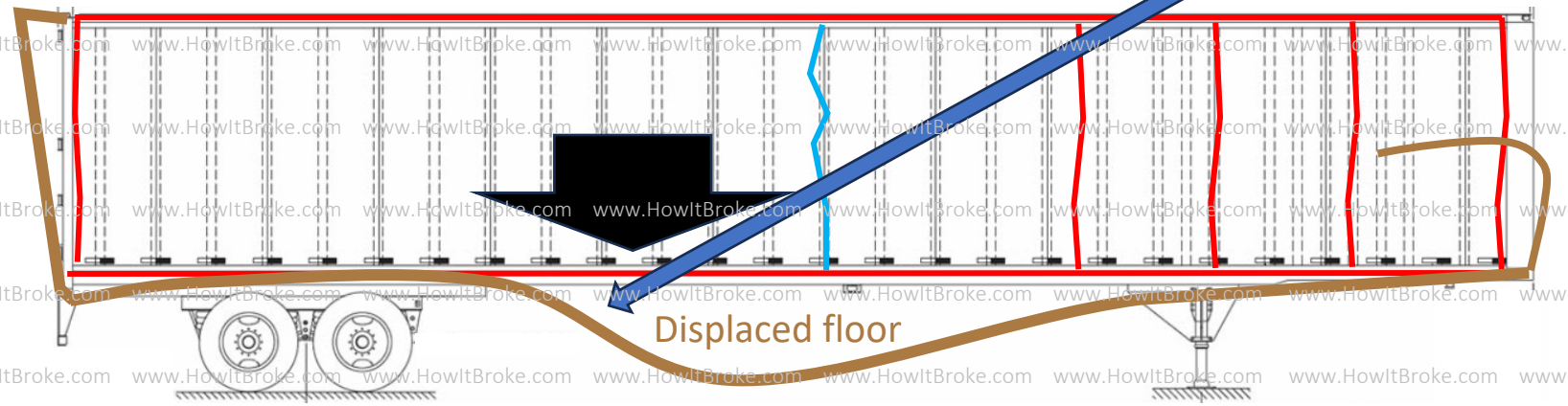
From TWA 800 investigation with aluminum box fuel tank

3,447 ft^3 interior volume

Pressure: 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



Flammability For Livermore Pleasanton Trailer

Trailer Door, Livermore Pleasanton, CA, 12/23

Equal pressure distribution to all surfaces inside trailer

4,035 ft^3 interior volume nearly empty

Floor dimensions 632” X 100.5” = 63,516 sq.in. (441 sq.ft.)

Limited box(es) of batteries, not sealed drums at front

Assume equal to 1/4 of one drum total = 1.84 ft^3

Gas volume = 216 (50% SOC) to 682 ft^3

Trailer Volume: 216/4,035= 5% to 682/4,035= 17%

Volume of flammable gas in trailer

5% x 54.9% avg UFL = 2.7%

17% x 54.9% avg UFL = 9.3%

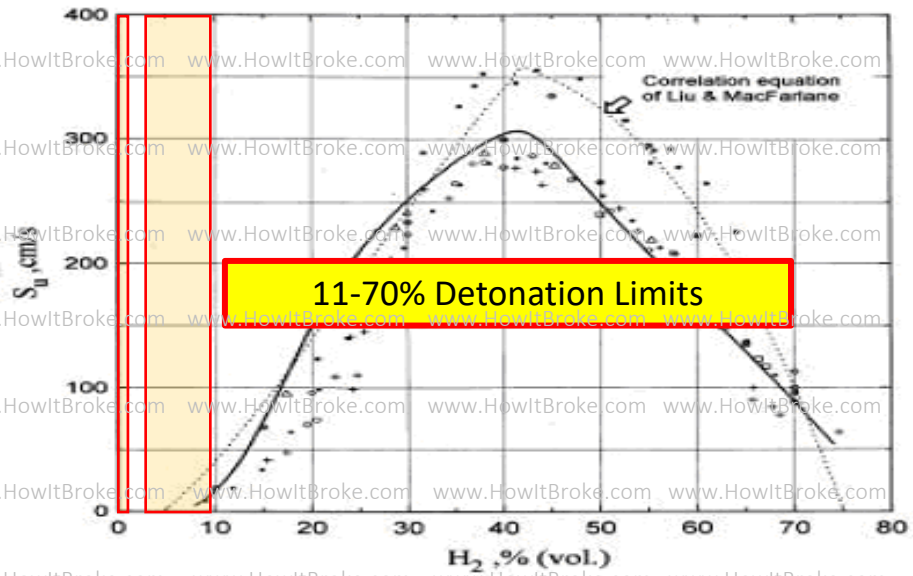
5% x 7.5% avg LFL = .38%

17% x 7.5% avg LFL = 1.3%

https://www.youtube.com/watch?v=oU7nr3WqcEM

Source: Livermore Pleasanton FD

Mixture Ratio In Trailer



HowItBroke.com

Jeep Wrangler 4xe Explosions

Belgium, October 30, 2023

Samsung SDI cell lot found defective
96 prismatic cells, Samsung SDI 2700,
94 Ah nickel manganese cobalt NMC cells, 3.7v cell,

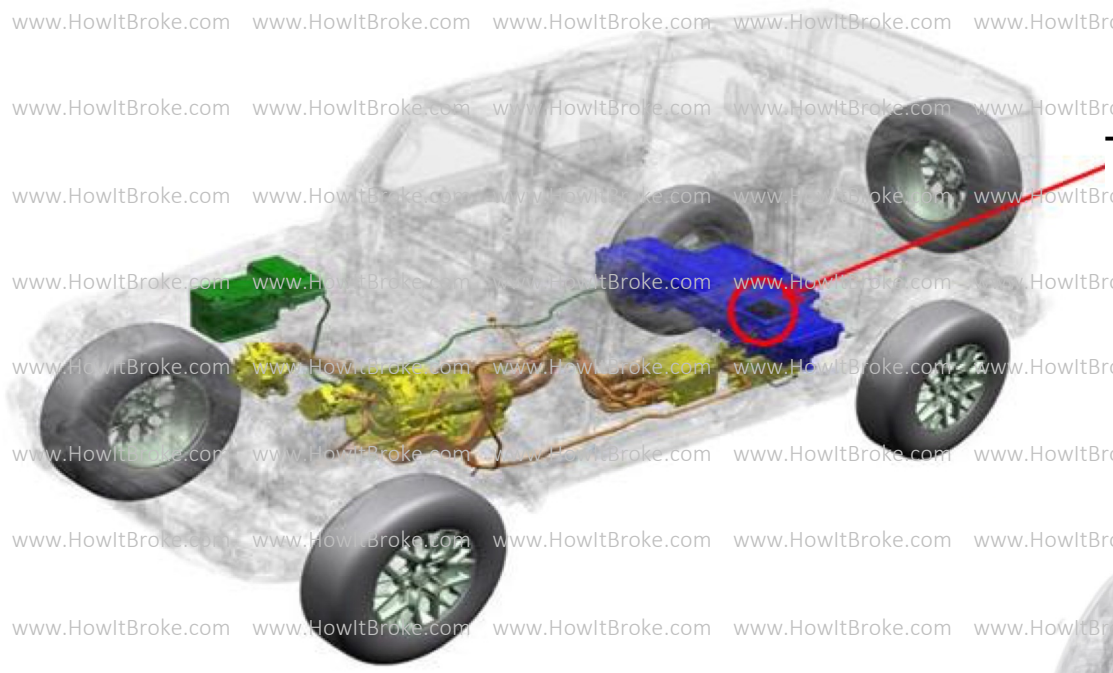
Cabin Flled With Smoke
Detonated After Breaking Window

Nine 2021-2023 destroyed
32,125 Vehicles (1%)

NHTSA Recall: 23V-787
Mfg Recall: B9A

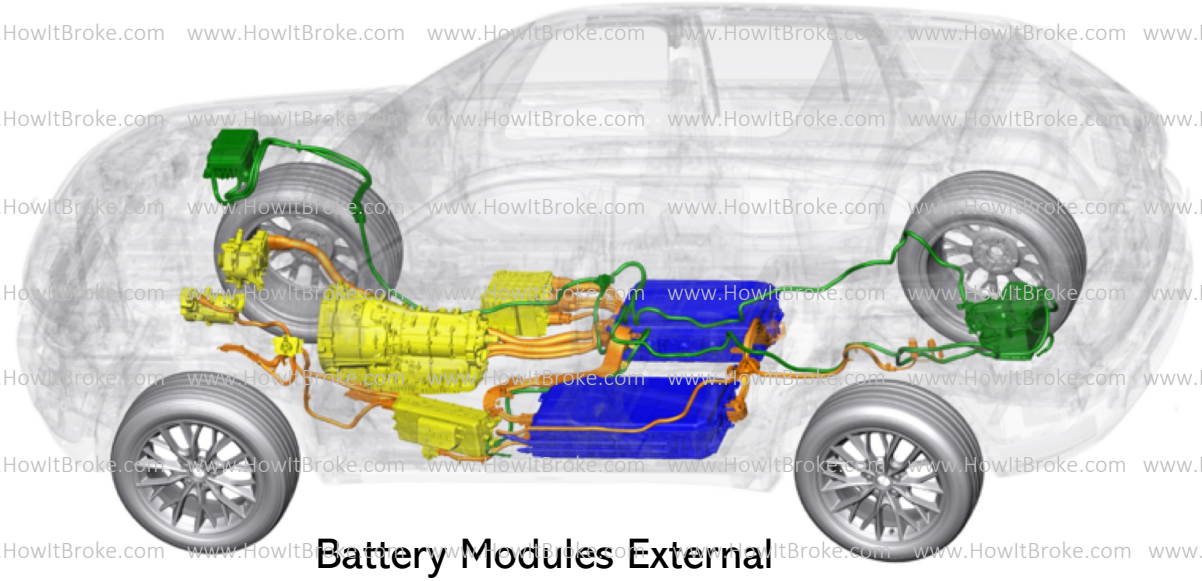
Jeep Wrangler 4xe Versus Grand Cherokee 4xe

Battery Module Installed in Interior



Interior Access High Voltage
Test and Service Module Access

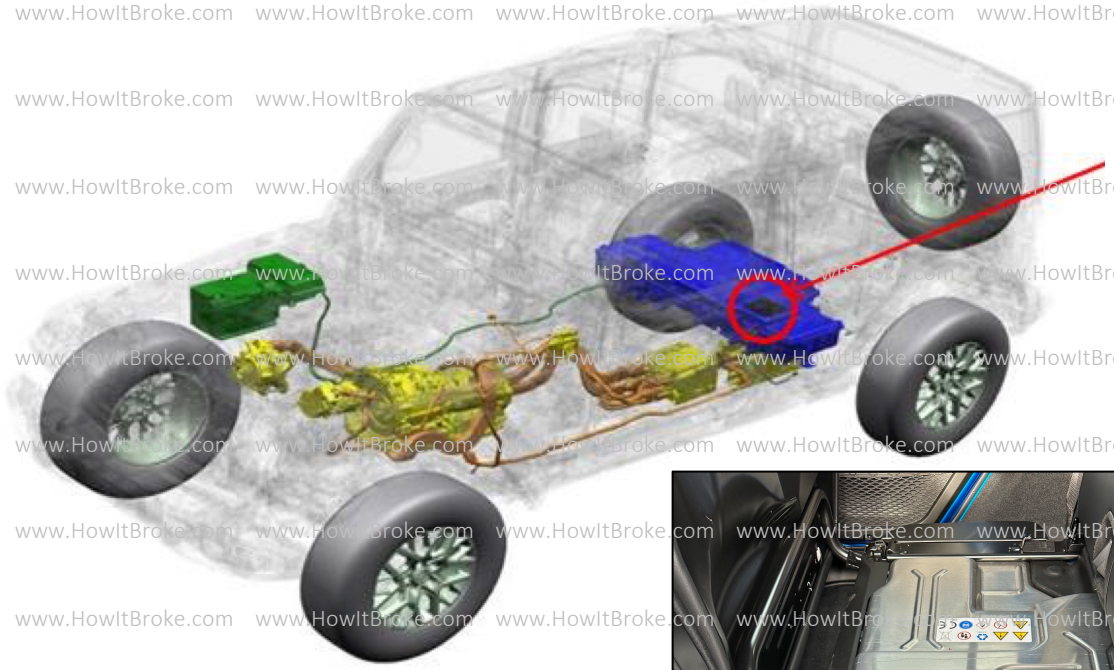
No fires or explosions
Not affected by recall



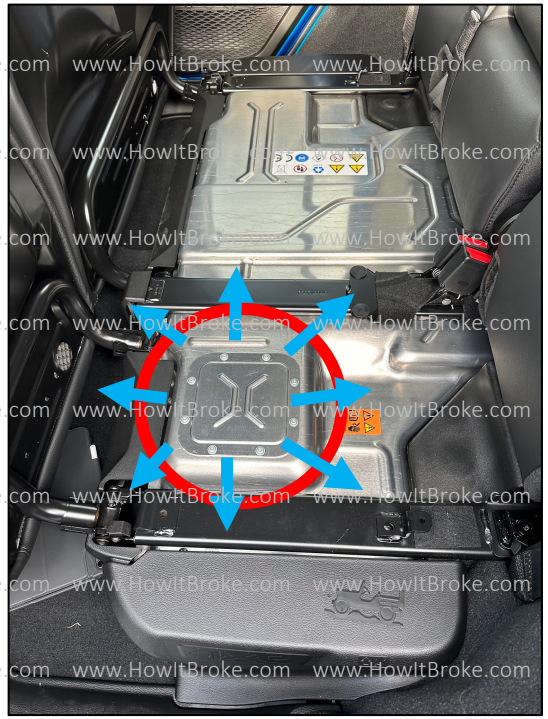
Battery Modules External
Beneath Floor Pan

Jeep Wrangler 4xe

Battery Access Beneath Rear Seat



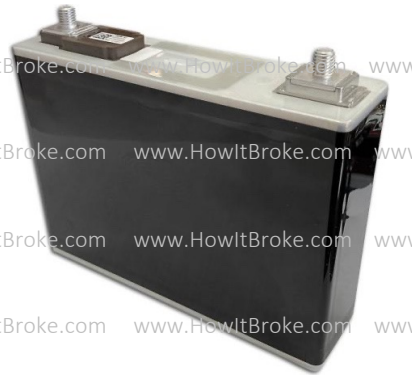
High Voltage Test and Service Module Access



Battery volume = about 255 Liters (9 ft^3).
Estimate 90% filled, leaving 25 liters empty volume.

Each **cell** can produce **up to 110 liters (29 gal)** of smoke/gas.

Battery case would go beyond UFL almost immediately.
Pressure of gas defeats seal of access plate.
Smoke/gas vents into passenger cabin.

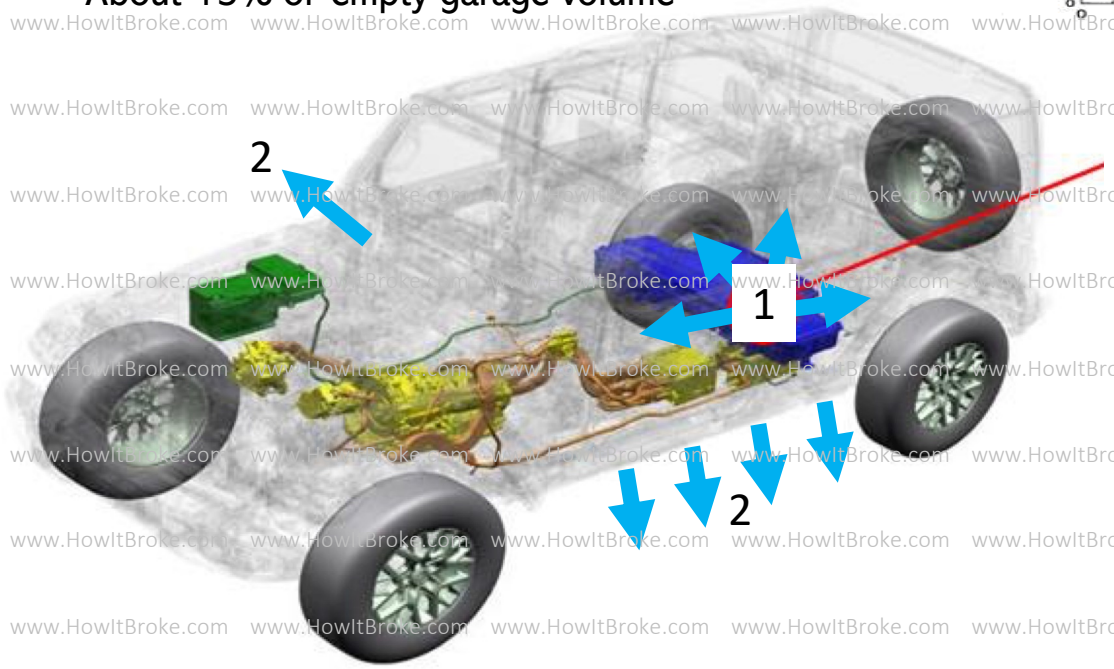


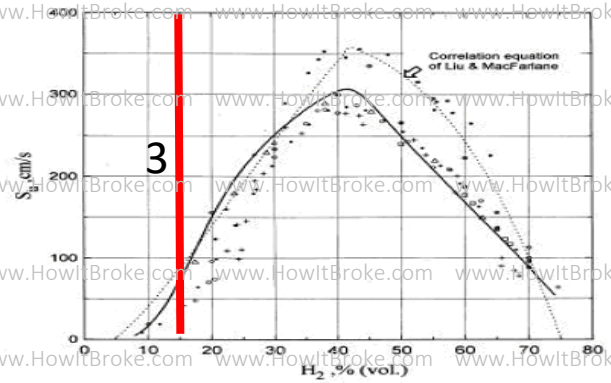
Vapor Cloud In Garage Explosions

Migration

1. From battery case (above UFL)
2. Through vehicle
3. To fill garage

96 cells X 110 liters = up to 373 ft³
About 15% of empty garage volume





Interior High Voltage Test and Service Module Access

Erie CO, Jeep Wrangler, Door blown half way to street, 4/9/2023

Toronto, Hyundai Kona, Door blown beyond street, 7/26/2019

If venting, **retreat until sure** smoke/gas is not over UFL and/or coming down into flammable/explosive range

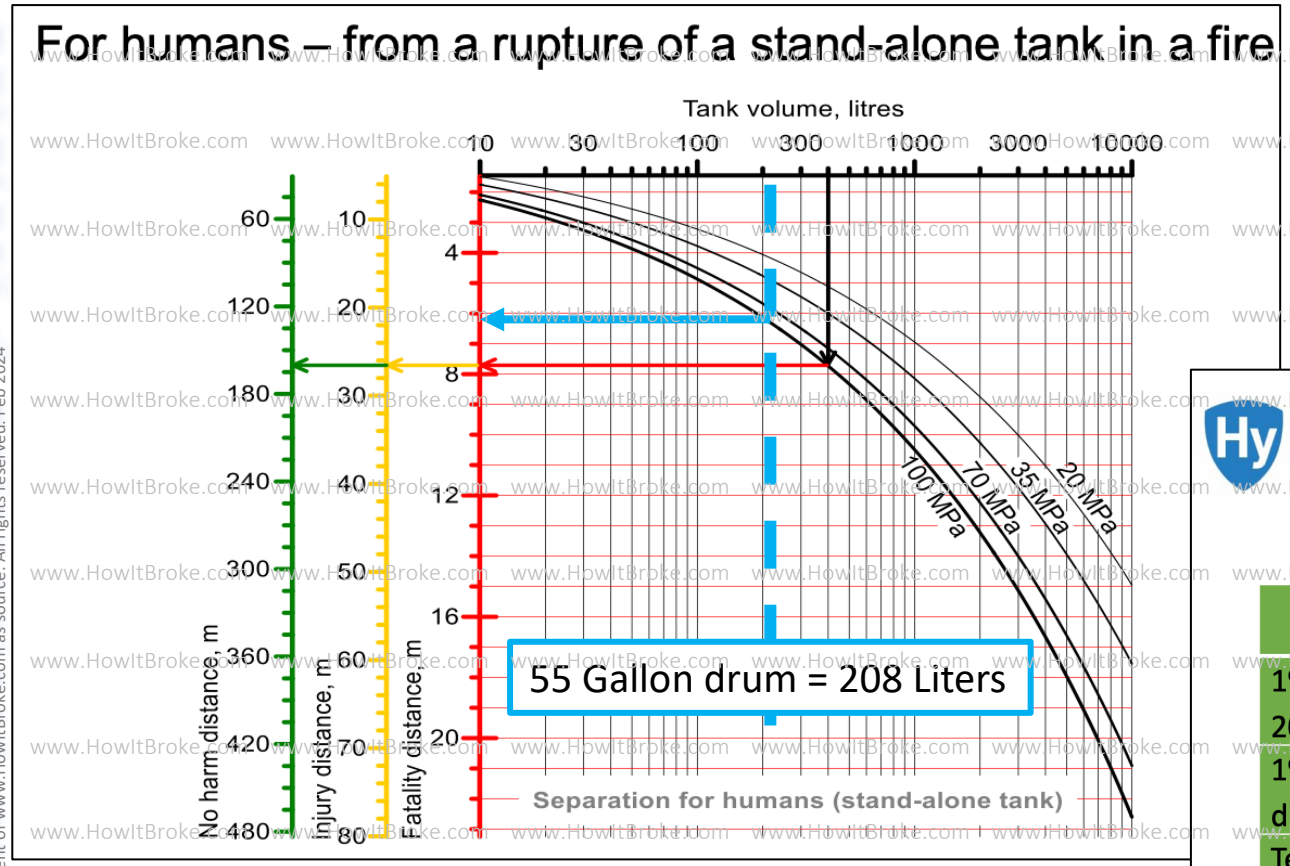
HowItBroke.com

SAE 3108 Alternate Fuel Identification

Difficulty in identifying alternative fuel vehicles led to SAE development of license plate stickers

HowItBroke.com

Overpressure Blast Injuries



Dealing with hydrogen explosions

Threshold of overpressure: harm to humans

Harm criteria (selected thresholds)	Overpressure, kPa	
1% fatality probability due to lung haemorrhage (Mannan, 2005): "fatality" hazard distance	100	14.5 psi
1% eardrum rupture probability (Mannan, 2005): "injury" distance	16.5	2.4 psi
Temporary threshold shift (Baker, 1983): "no harm" hazard distance (evacuation perimeter)	1.35	0.2 psi

60

European Hydrogen Train the Trainer Programme for Responders

Prevention and Mitigation

PREVENTION:

Passive:

Packaging cargo properly (Look for markings)

Eliminate ignition sources (impossible)

Cooling (some fuels, not Li-ion venting)

Allow drums to vent (unsealed) if not enclosed

Natural venting, open top, or flatbed trailer

Active:

Forced ventilation

- Vented trailers or removed doors

Detection leading to response

- Requires new system

Nitrogen inerting (expensive)

MITIGATION:

Passive:

Deflagration venting (fabric sides or top)

- Results in fire without explosion

Active:

Emergency response

- Determine whether smoke is flammable
- If venting, retreat until sure not over UFL

Prevention and Mitigation

PREVENTION:

Passive:

Packaging cargo properly requires interaction with shippers

Eliminate ignition sources (impossible)

Cooling (some fuels, not Li-ion venting)

Allow drums to vent (unsealed) if not enclosed

Natural venting, open top, or flatbed trailer

Individual packaging

Prevention and Mitigation

PREVENTION:

Passive:

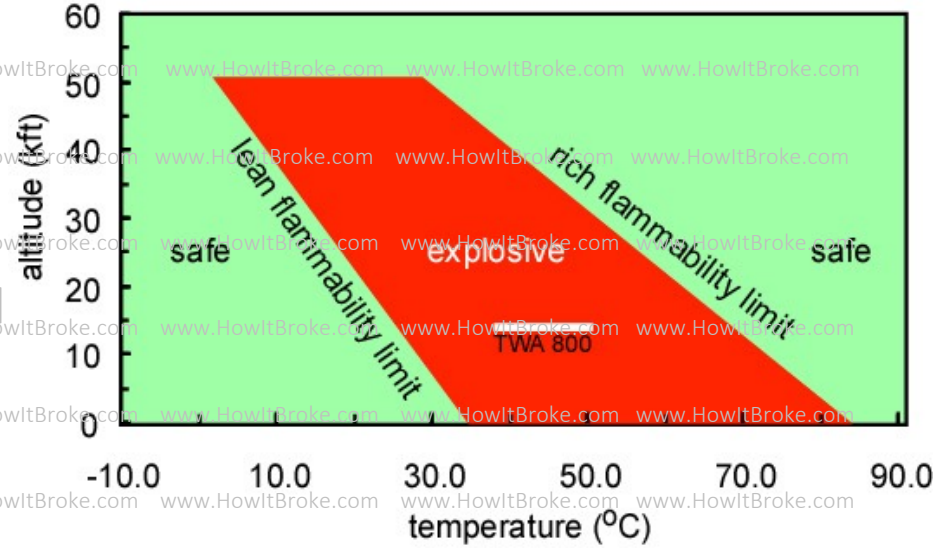
Packaging cargo properly (Look for markings)

Eliminate ignition sources (impossible)

Cooling (some fuels, not Li-ion venting)

Allow drums to vent (unsealed) if not enclosed

Natural venting, open top, or flatbed trailer



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Prevention and Mitigation

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Prevention and Mitigation

Active:

Forced ventilation

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Prevention and Mitigation

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Prevention and Mitigation

Active:

Forced ventilation

Vented trailers or removed doors

Detection leading to response

Requires new system

Nitrogen inerting (expensive)

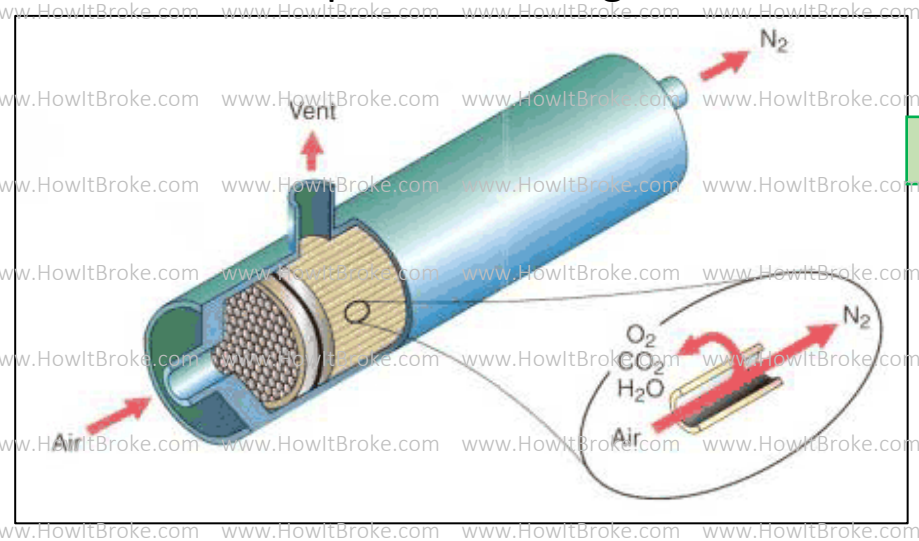
1996 NTSB Called For Nitrogen Inerting Fuel Tanks

NTSB Recommended in 1996 fuel tanks which can be flammable must be inerted.

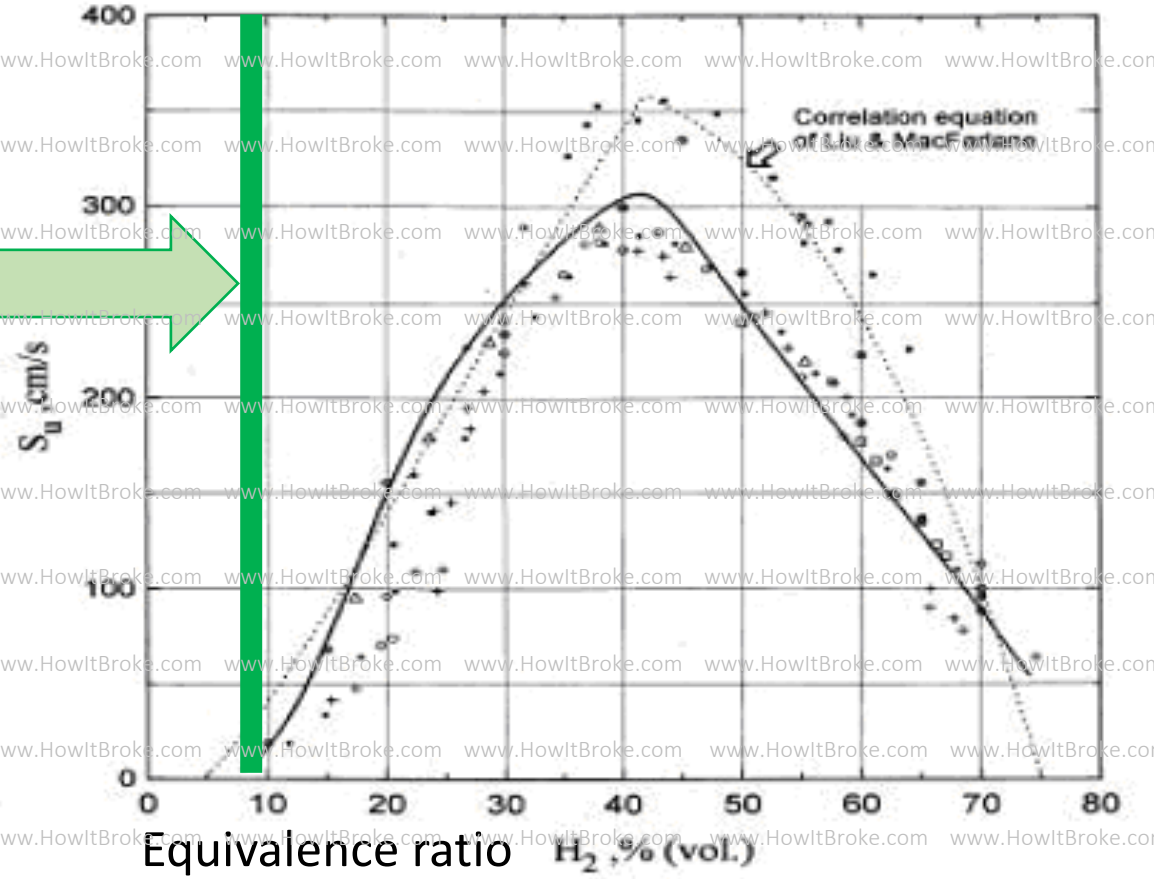
FAA Research led to requirement in 2004

On Board Inert Gas Generating System (OBIGGS)

Membrane separation of engine bleed air

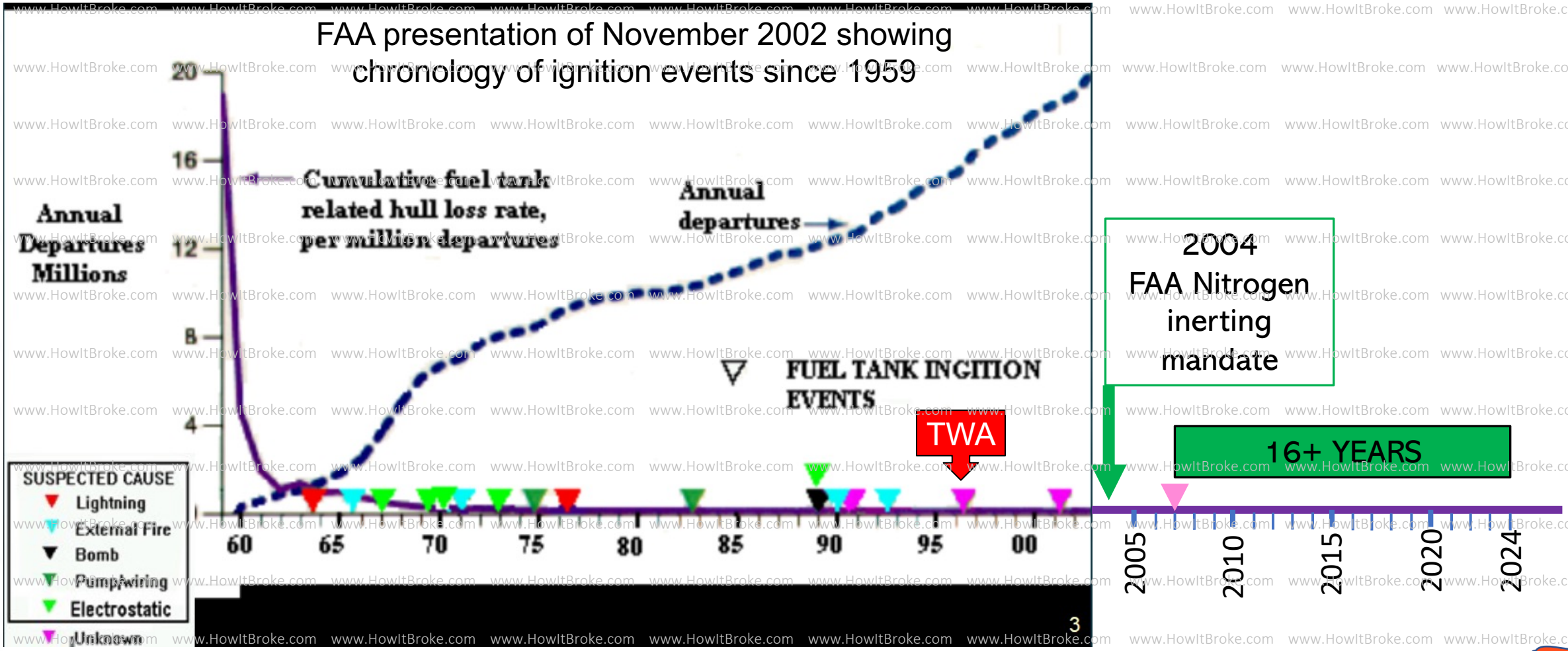


Mixture directly affects H_2 burning velocity (and detonation distance)



2004 Nitrogen Inerting Requirement Result

Not until TWA800 was it realized that commercial aviation fuel tank explosion rate averaged about 52 months. Congress funded a major test program.



HowItBroke.com

Prevention and Mitigation

MITIGATION:

Passive:

Deflagration venting (fabric sides or top)

Results in fire without explosion

Germany, June 2023

Blow Out (Gore) Panels – Present New Issues

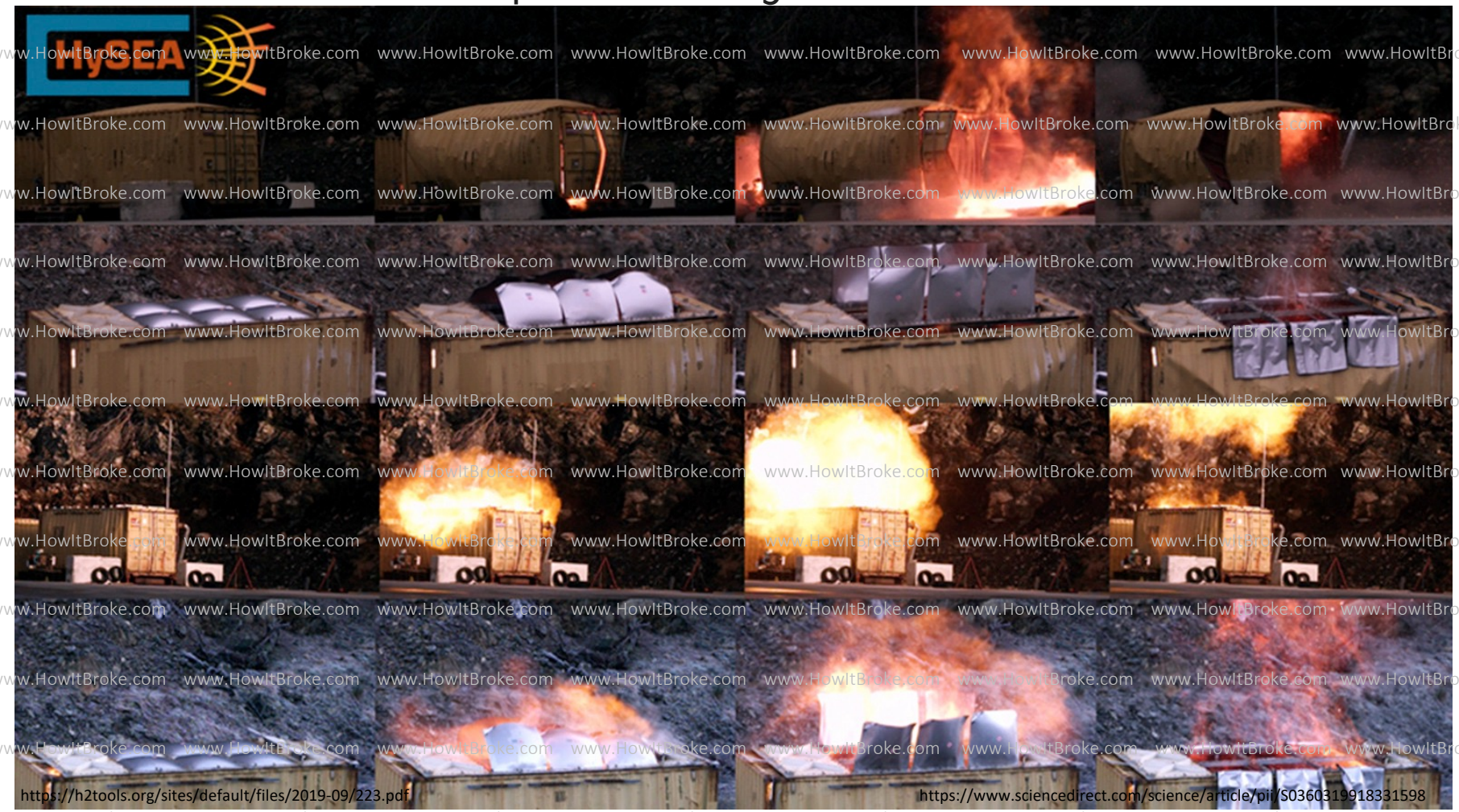
Hydrogen DDT Propagates Too Fast

66 European tests using 20 ft containers

End venting area is insufficient

Venting must be extensive and direct the explosion

Potential shrapnel becomes an issue



https://h2tools.org/sites/default/files/2019-09/223.pdf

https://www.sciencedirect.com/science/article/pii/S0360319918331598

Prevention and Mitigation

If venting, **<u>retreat</u> until sure** smoke/gas is not flammable.

AND

Smoke/gas is not over UFL yet to come down into flammable/explosive range

Prevention and Mitigation

PREVENTION:

Passive:

Packaging cargo properly (Look for markings)

Eliminate ignition sources (impossible)

Cooling (some fuels, not Li-ion venting)

Allow drums to vent (unsealed) if not enclosed

Natural venting, open top, or flatbed trailer

Active:

Forced ventilation

- Vented trailers or removed doors

Detection leading to response

- Requires new system

Nitrogen inerting (expensive)

MITIGATION:

Passive:

Deflagration venting (fabric sides or top)

- Results in fire without explosion

Active:

Emergency response

- Determine whether smoke is flammable
- If venting, retreat until sure not over UFL

Questions?

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