SPACEX

Return to Flight

A talk by Bill Carton, EE
(and Space Enthusiast)

At Wavelength Brewing Company
Vista, CA October 9, 2015

Who am I?

- **Bill Carton – Electrical Engineer**
- **STAr-KVD Technologies, Inc.**
- **Mercury-era space enthusiast**

On Social Media

- **Technical Web forum:** `nasaspaceflight.com`
- **SpaceX enthusiast group on Facebook:**
  - `https://www.facebook.com/groups/spacexgroup/`
- **NASA invitation to CRS6 launch in April**

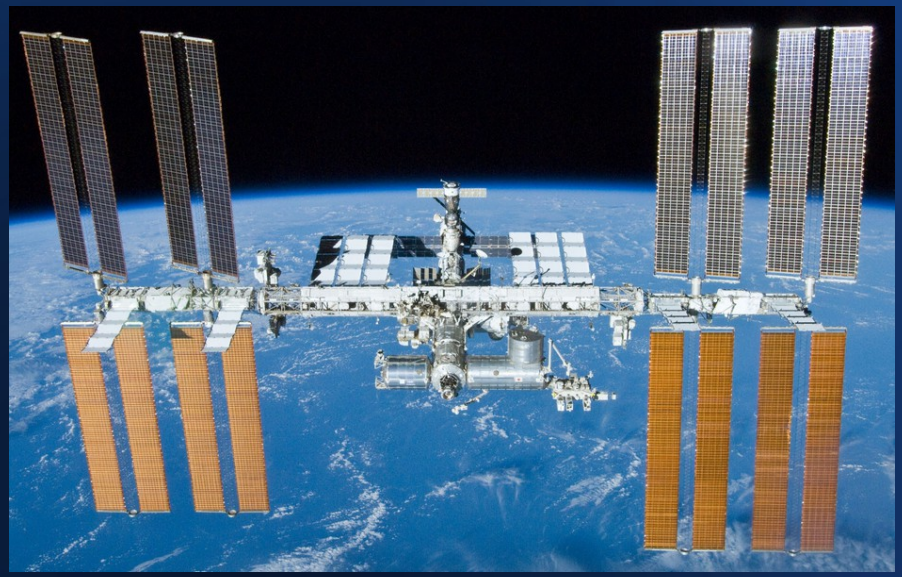
Who is SpaceX?
Space Exploration Technologies

So why do we need a Return to Flight (RTF)?

- Explosion in June
- Investigation
- Corrective Action

What happened on June 28, 2015?

- 18 successes
- Dragon cargo



CRS7 video


LIVE
T- 00:00:02
LAUNCH: CRS-7
SPACE LAUNCH COMPLEX 40, CAPE CANAVERAL, FLORIDA, EARTH
GO/NO-GO POLL
DRAGON INTERNAL
STARTUP
PITCH KICK
MECO
NOSE JETTISON
DRAGON DEPLOY
TERMINAL COUNT
STRONGBACK LOWER
LIFTOFF
MAX-Q
SES-1
SECO-1
SOLAR ARRAY
SPACEX

Trivia Question #1

- **What does CRS stand for?**

  Commercial Resupply Services

SpaceX?

- Started 2002
- Over 4000 employees
- Hawthorne, CA
- Three launch sites soon to be four
- Engine/stage testing facility in Texas
- Elon Musk is CEO and CTO
- Not a public company

Who's Elon Musk?

Seriously.....

- Born June 28, 1971
- Programming at 10
- Degrees in Physics and Economics
- California in 1995
- US citizen in 2002
- Fortunes: Zip2 $22M, PayPal $165M

Cameo in Iron Man 2

Trivia Question #2

- What other connection does Elon have to the Iron Man 2 film?

Part of the film was shot in Hawthorne HQ at 1 Rocket Road

Falcon 1 – Marshall Islands, South Pacific

- First three flights failed
- September 28, 2008 Flight 4 - Success – first private company to place a payload in orbit
- July 2009 – flight 5 a success

Trivia Question #3

- Where did Elon get the name "Falcon"

From Han Solo's Millenium Falcon from Star Wars

Falcon 9

- Rev 1.0 (first 5 launches)
- Rev 1.1 (next 13 launches)
- Rev 1.1 Full Thrust (now)

Trivia Question #4

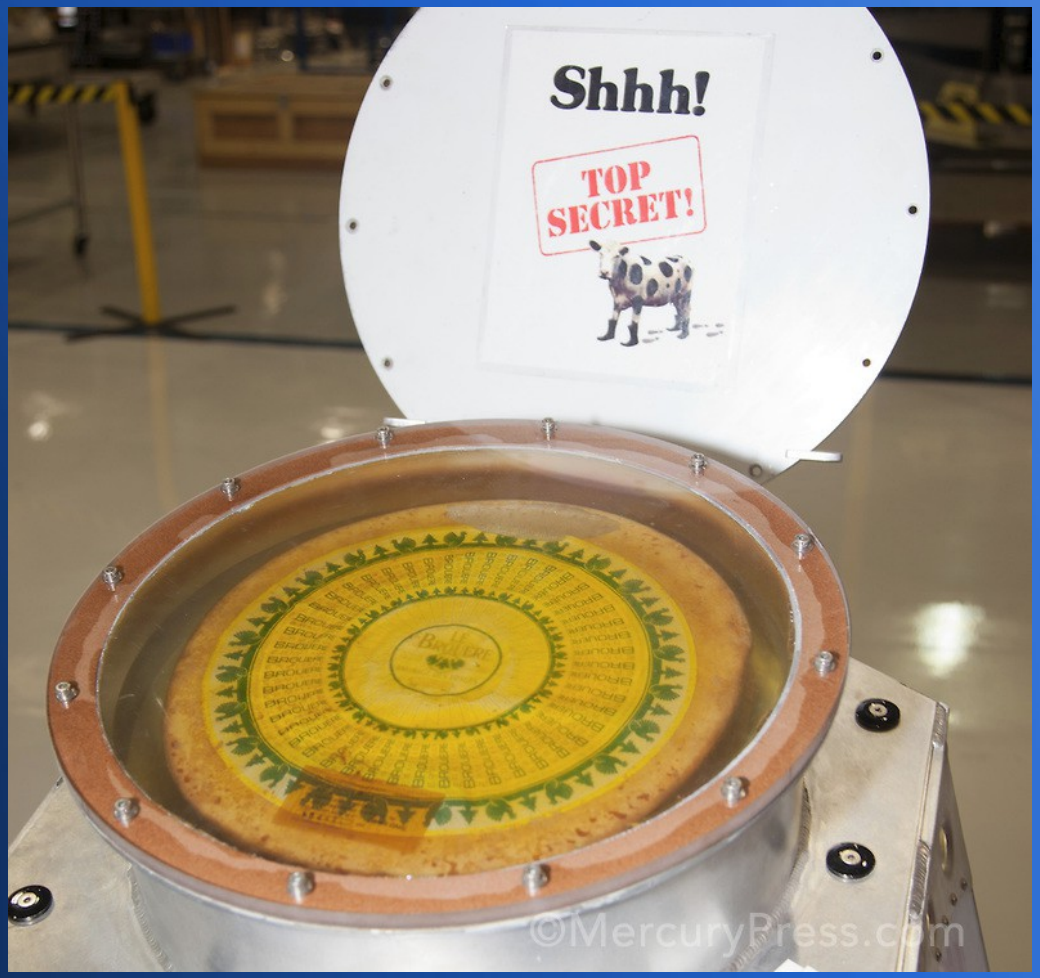
- For true SpaceX trivia fans:

  What distinctive payload was on the first Dragon demo flight in Dec 2010?

The Top Secret! Wheel of Cheese

French Le Brouère cheese

On display in SpaceX HQ, although it's rumored to be starting to stink



Competitors – for another talk

- **Old Space:**

  - United Launch Alliance
    - Atlas 5 & Delta IV
  - Russia
    - Proton & Soyuz
  - Arianespace
    - Ariane 5
  - NASA
    - Space Launch System
  - Japan
    - HII-B

- **New Space:**
  - Virgin Galactic
    - SpaceShip Two
  - Blue Origin
    - New Shepard
  - Orbital/ATK
    - Antares
  - Sierra Nevada
    - Dream Chaser
  - XCOR Aerospace
    - Lynx Rocketplane

Payloads

- **Satellites**
  - Commercial
  - NASA
  - Air Force/DoD (national security)

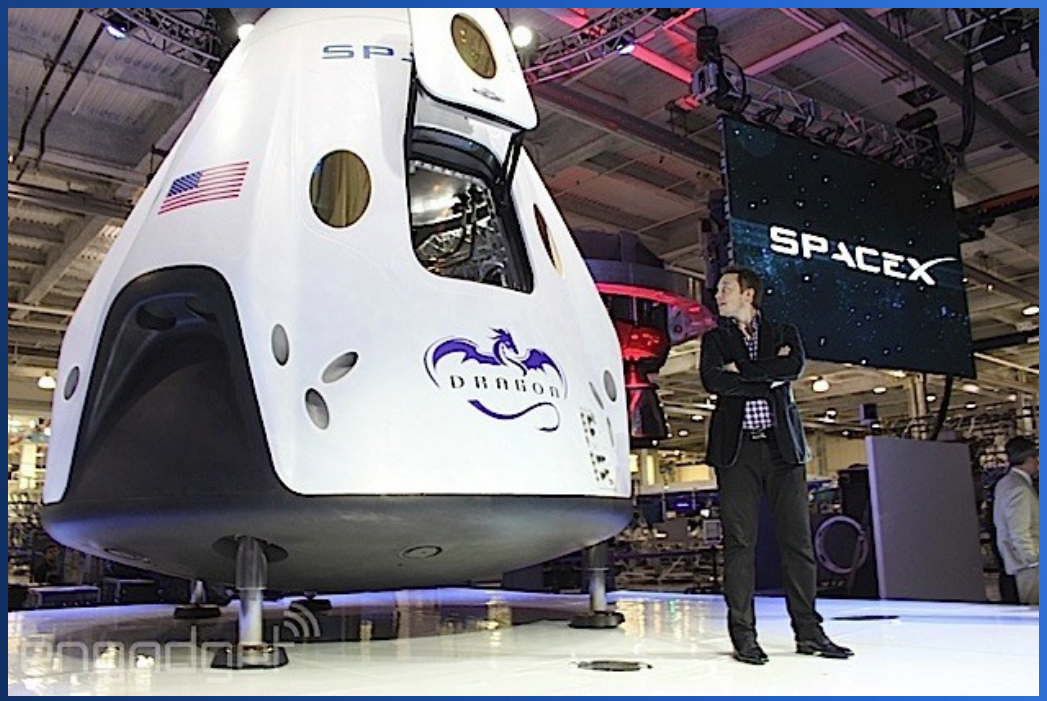
- **Dragon capsules**
  - Cargo to the ISS
  - Crew in 2017
  - Anywhere else

Satellites

- Fairings made of carbon fiber
- Variety of orbits

Dragon Capsules

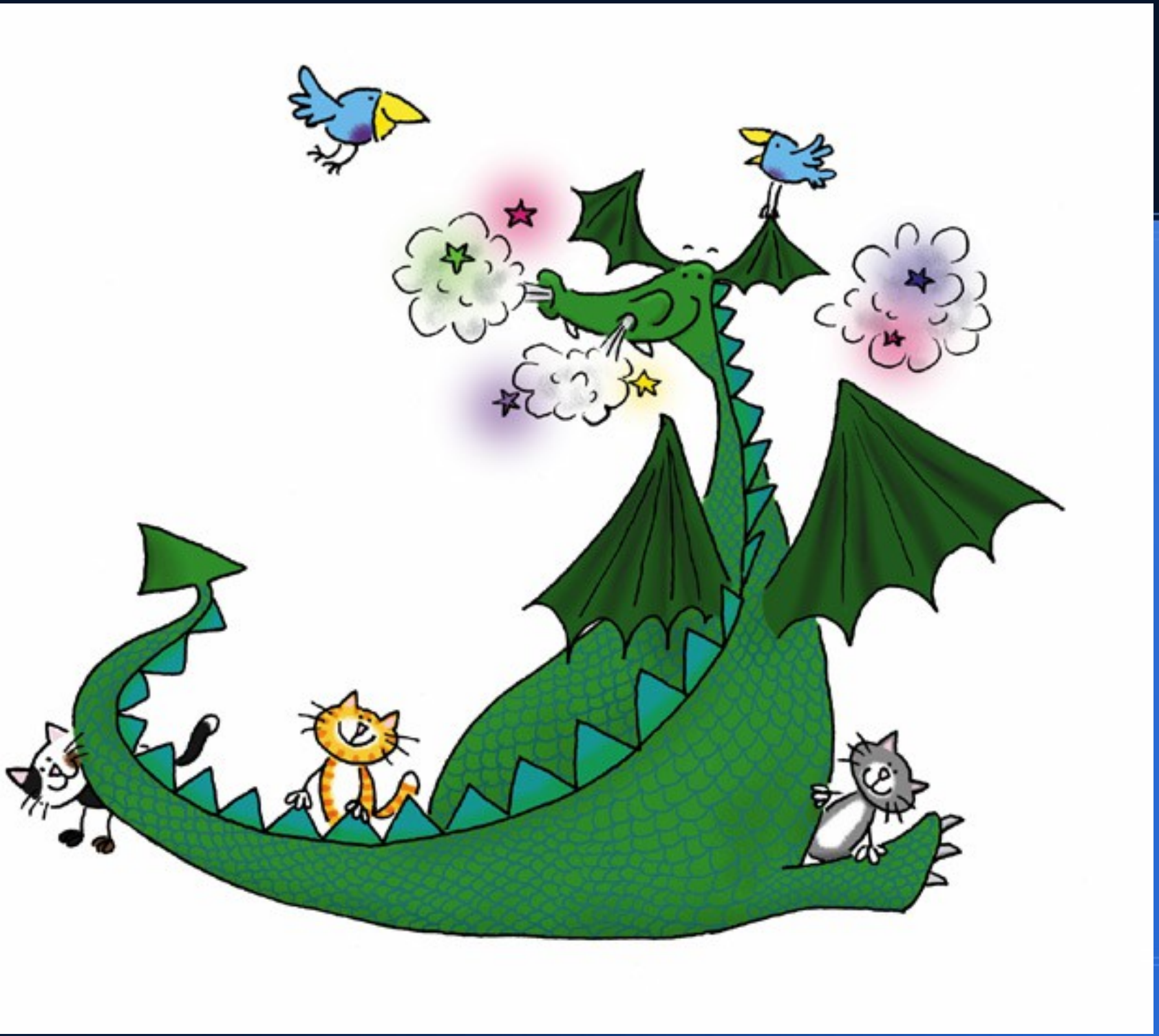
- Cargo deliveries to ISS
- Crew rides to the ISS and other destinations



Trivia Question #5

- **OK, so what inspired "Dragon?"**

after the fictional "Puff the Magic Dragon," from the hit song by music group Peter, Paul and Mary. Musk said he used the name because many critics considered his goals impossible when he founded SpaceX in 2002



SpaceX Production Floor

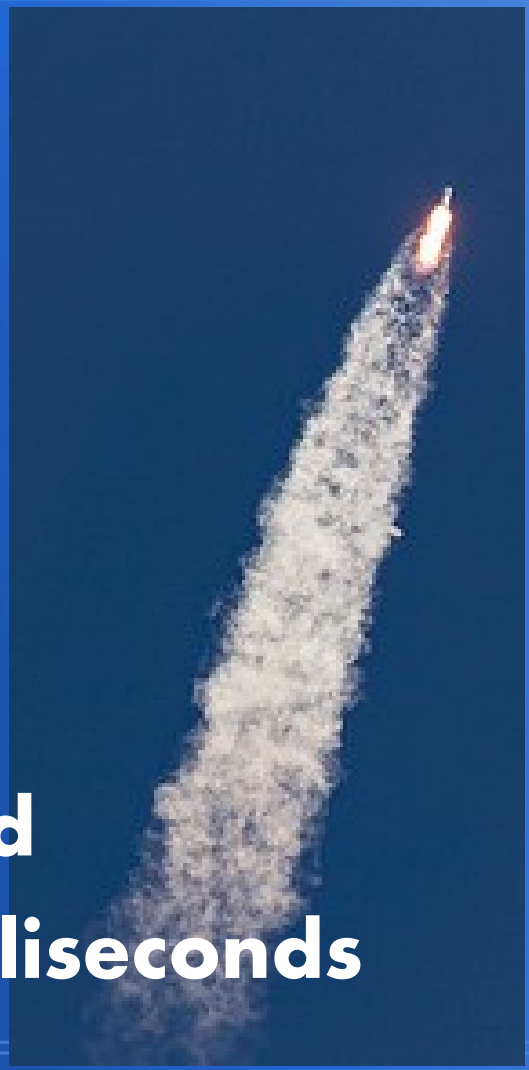
What makes SpaceX disruptive to the launch industry?

- Innovative business practices
- In-house build
- Reusability
- Airline Industry model
- Launch, land, and relaunch

Reusable First Stage and Dragon (CGI)

So what went wrong in June?

- No hint anything was wrong
- Launch was nominal.
- 2:19 after liftoff, event starts
- Dragon capsule pops off
- Second stage disintegrates
- First stage still firing
- Larger propellant and debris cloud
- Telemetry record lasts only 893 milliseconds



Incident Video

Armchair video analysis

Normal up to now

Initial sign of distress at the top of second stage

Expanding plume

Expanding plume

Expanding plume

Expanding plume

Expanding plume

Dragon Capsule separates

Dragon Capsule separates

First stage engines still firing

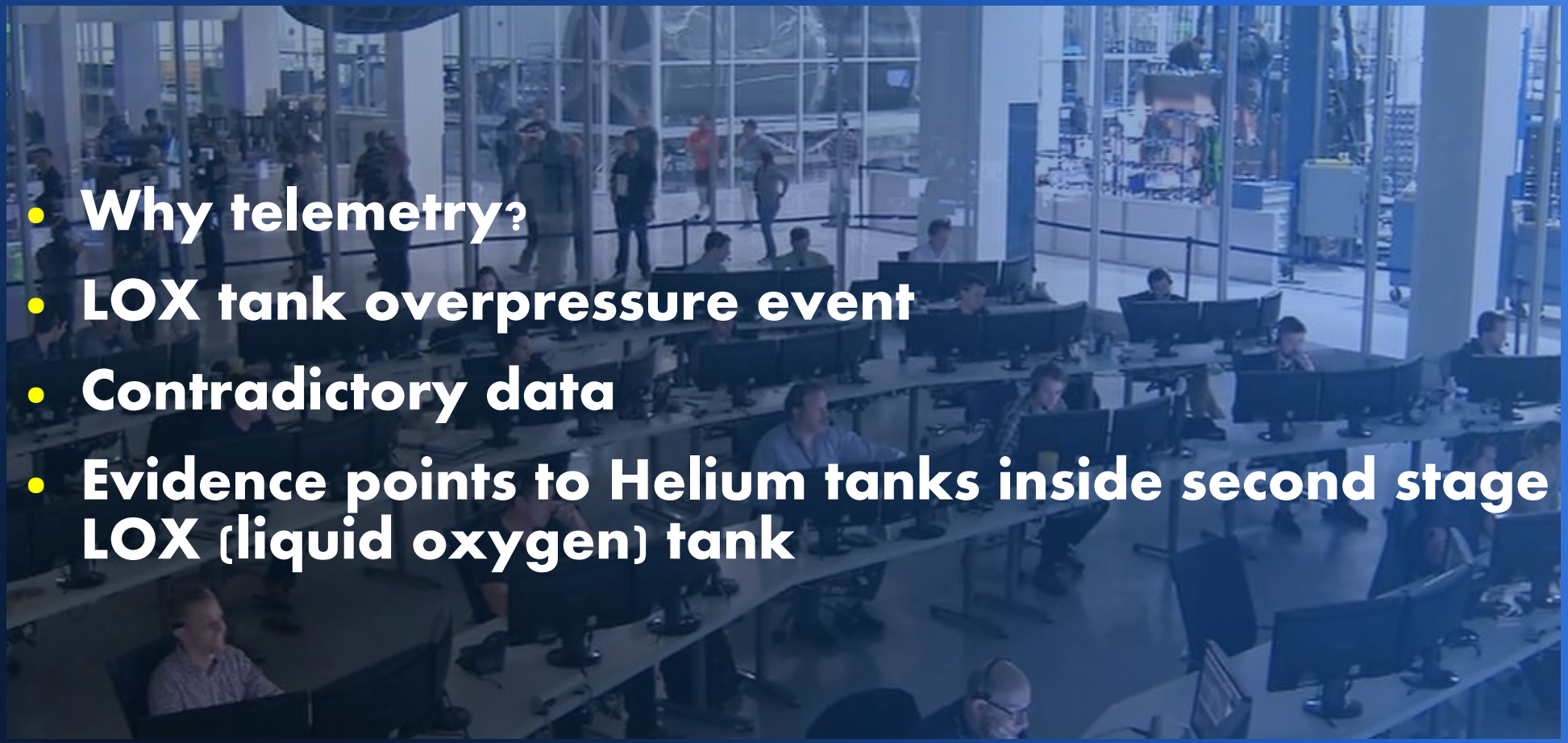
LOX plume smaller for an instant

Then the first stage ruptures

Start of final propellant dispersal

Incident Video SpaceX feed

893 milliseconds of telemetry

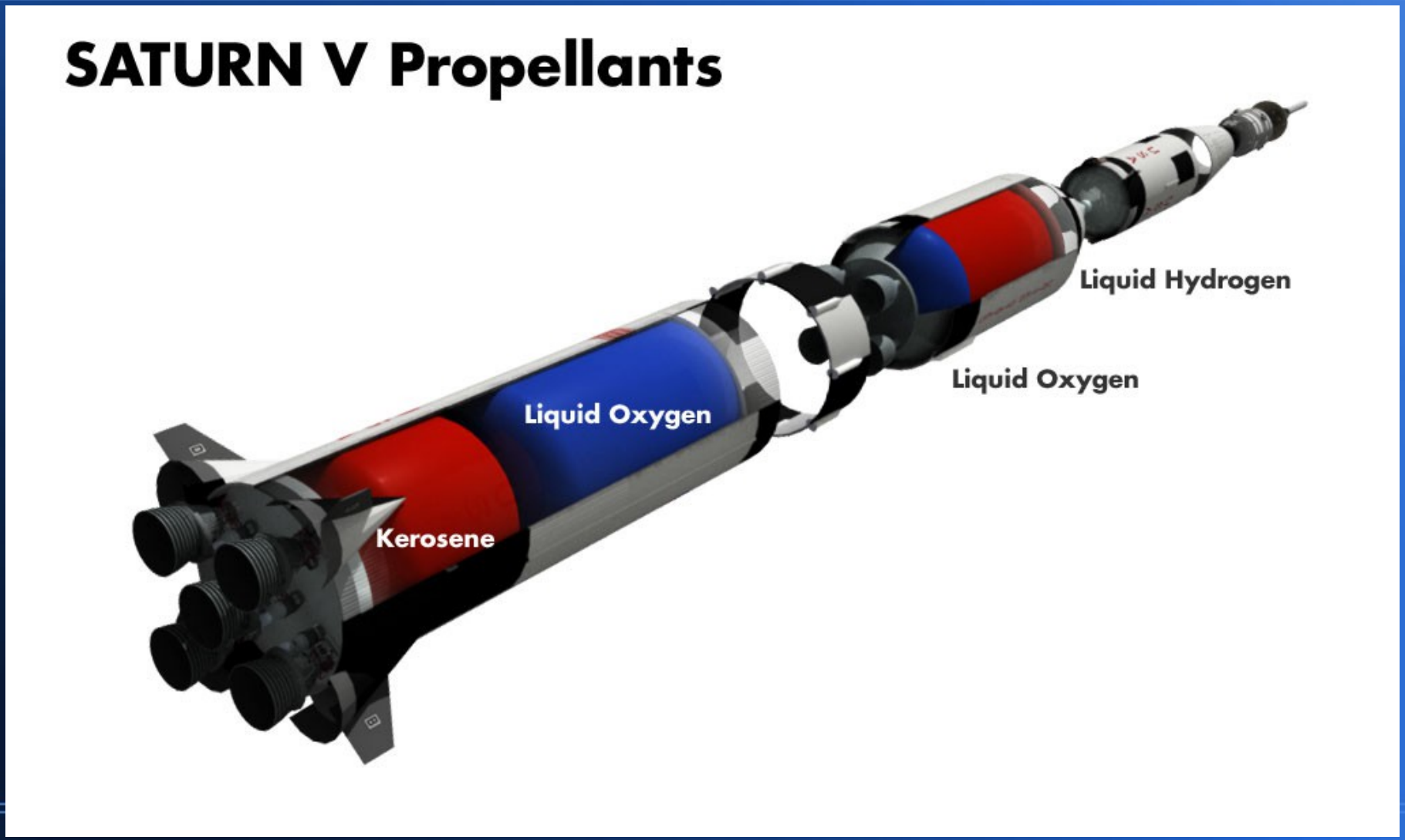


- Why telemetry?
- LOX tank overpressure event
- Contradictory data
- Evidence points to Helium tanks inside second stage LOX (liquid oxygen) tank

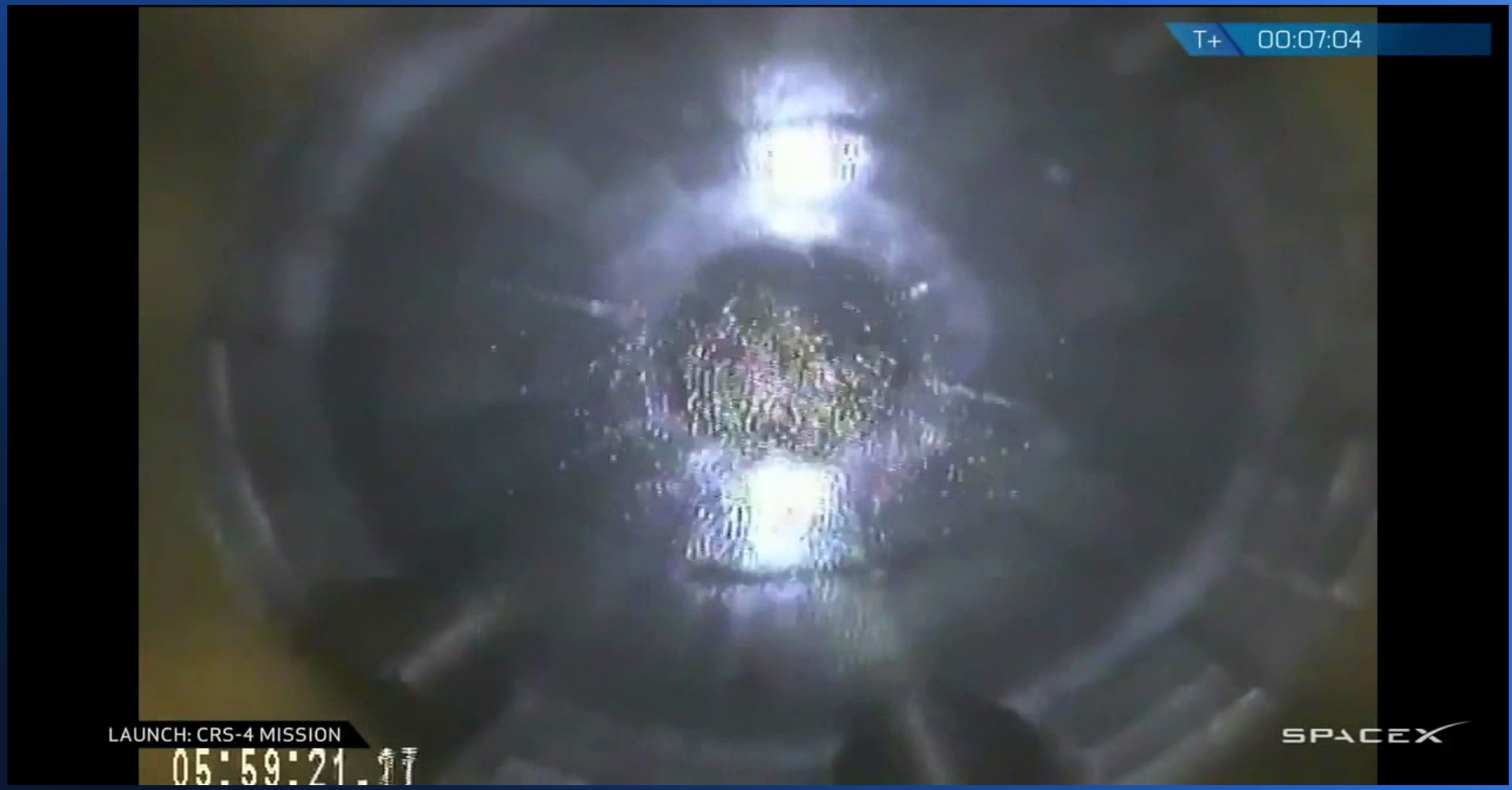
Helium use on rockets

- Light weight
- Won't liquify
- Versatile

Liquid Fuel Propellant tanks



Camera inside a SpaceX LOX tank



Trivia Question #6

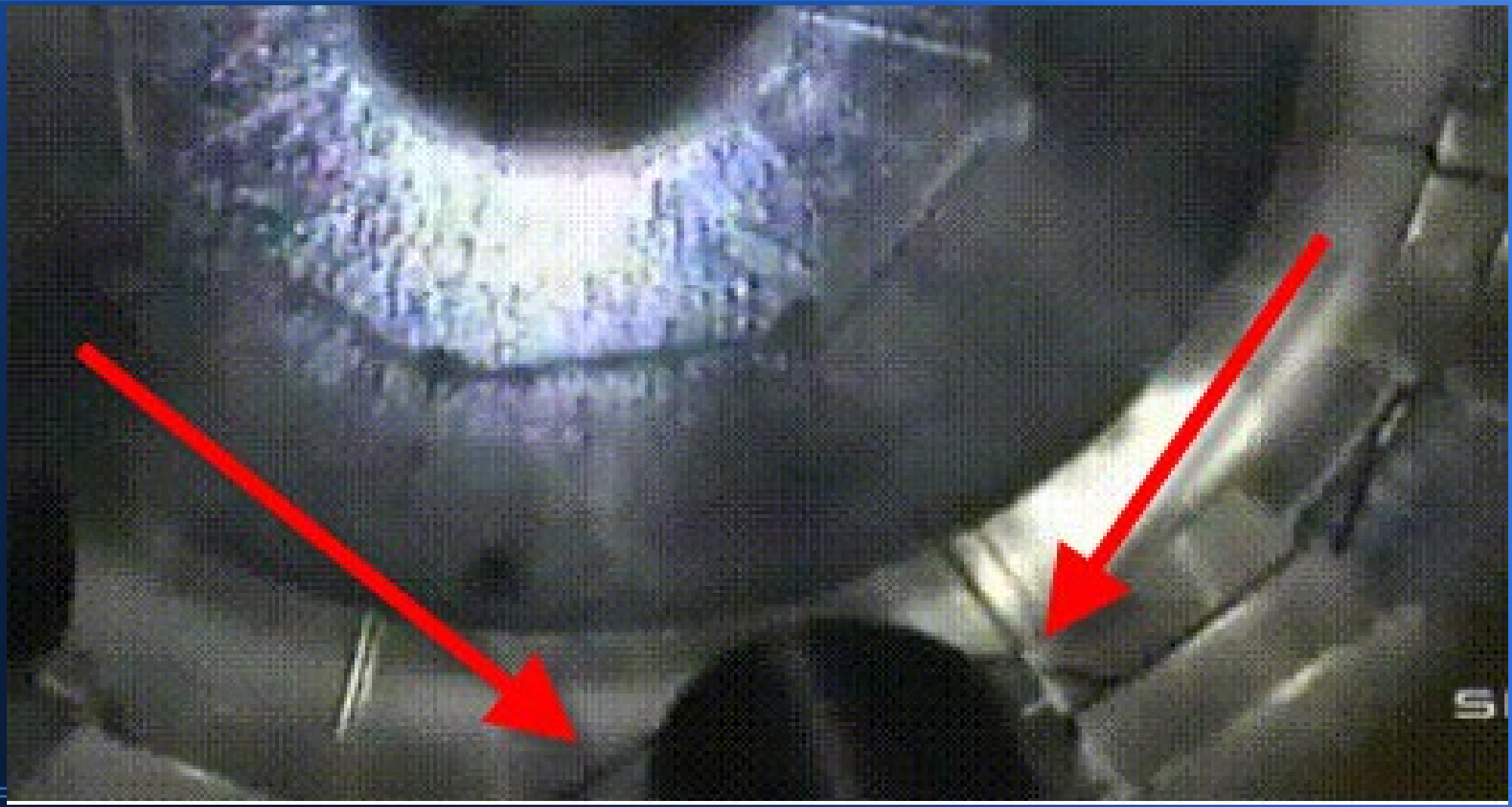
- When the LOX starts floating around when the engine cuts off, what TV show does that remind you of?

The Stargate “Sideways Toilet Flush” effect when the gate opens


STARGÅTE
SG·1

Three Helium storage tanks inside the second stage LOX tank

Mounting struts pointed out in red

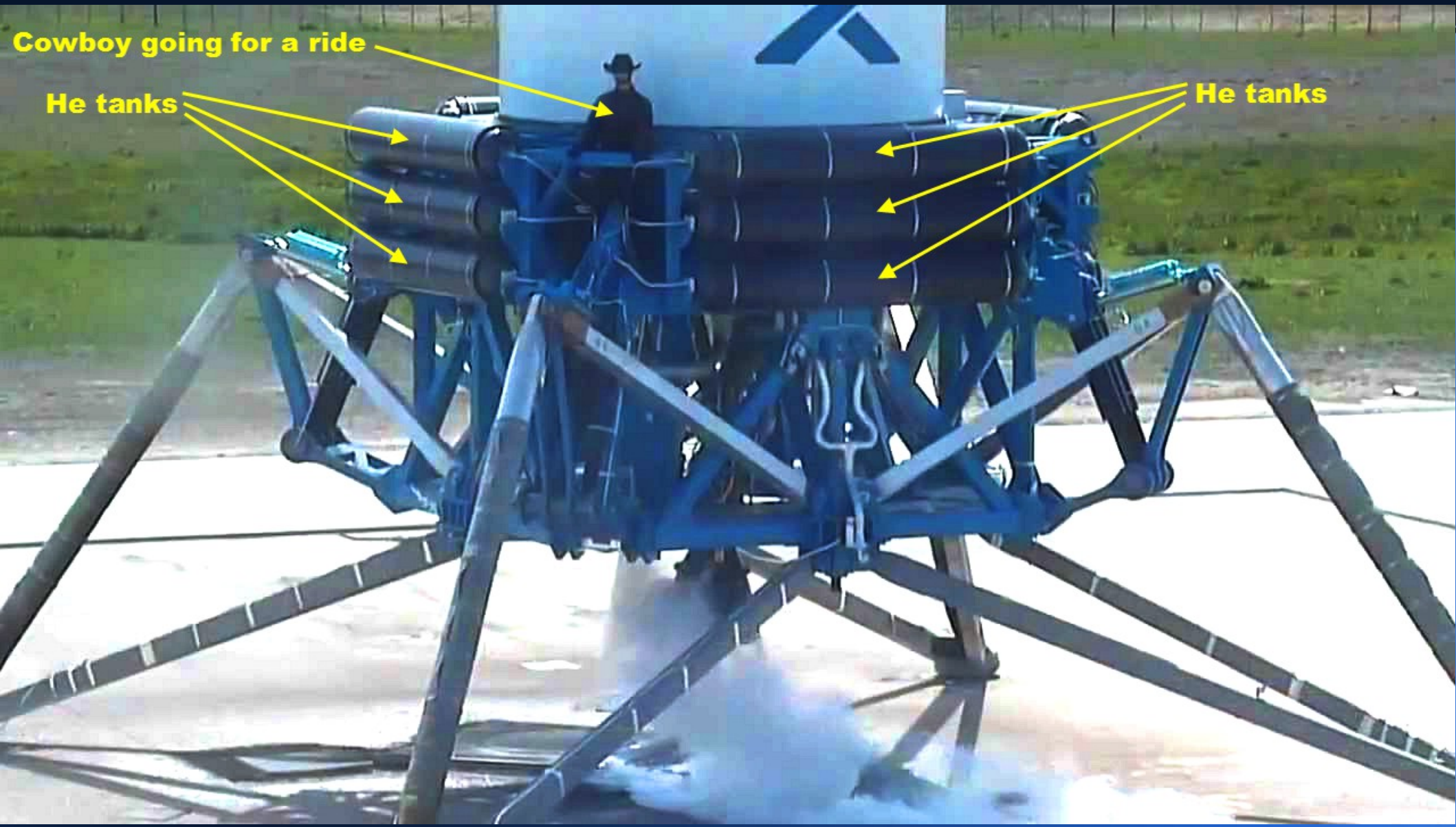


Struts also seen behind Elon in a tank under construction

Carbon (fiber) Overwrapped (titanium) Pressure Vessel

- COPV tank recovered after a second stage re-entry
- Other commercial tanks

COPV Helium tanks used on Grasshopper test vehicle

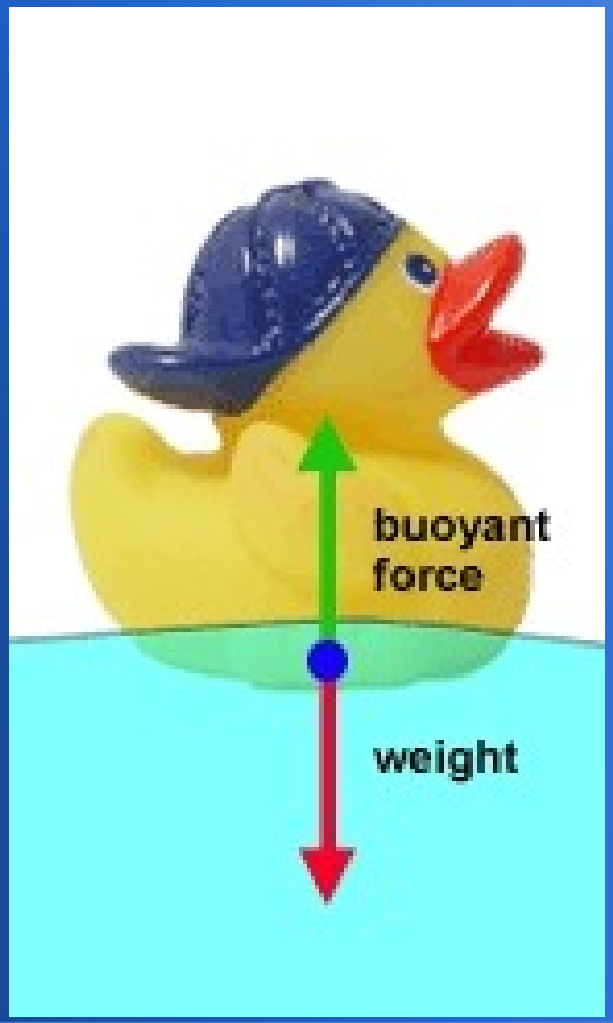


Helium tanks inside the LOX tank?

- **SHRINKAGE** at cryogenic temps
- Up to FOUR to ONE
- ~5000 PSI like a SCUBA tank

So what happens during a launch?

- Helium tanks submerged
- Held down by struts
- Weight higher during launch acceleration
- But the buoyancy force is even higher!
- Funny behavior of helium balloon in a car

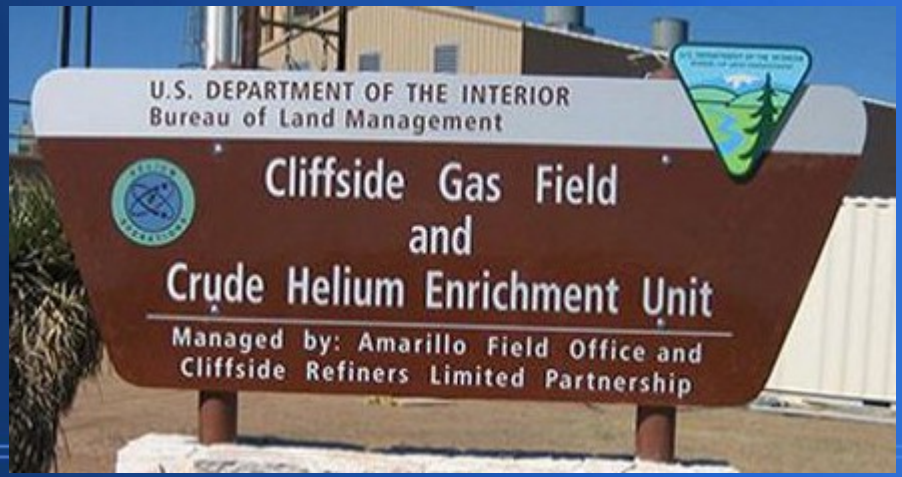


Balloon in a car goes opposite direction to what you expect

Trivia Question #7

- **Why should we forbid the use of Helium in party balloons?**

Worldwide shortage caused by politics, and reduced production of natural gas

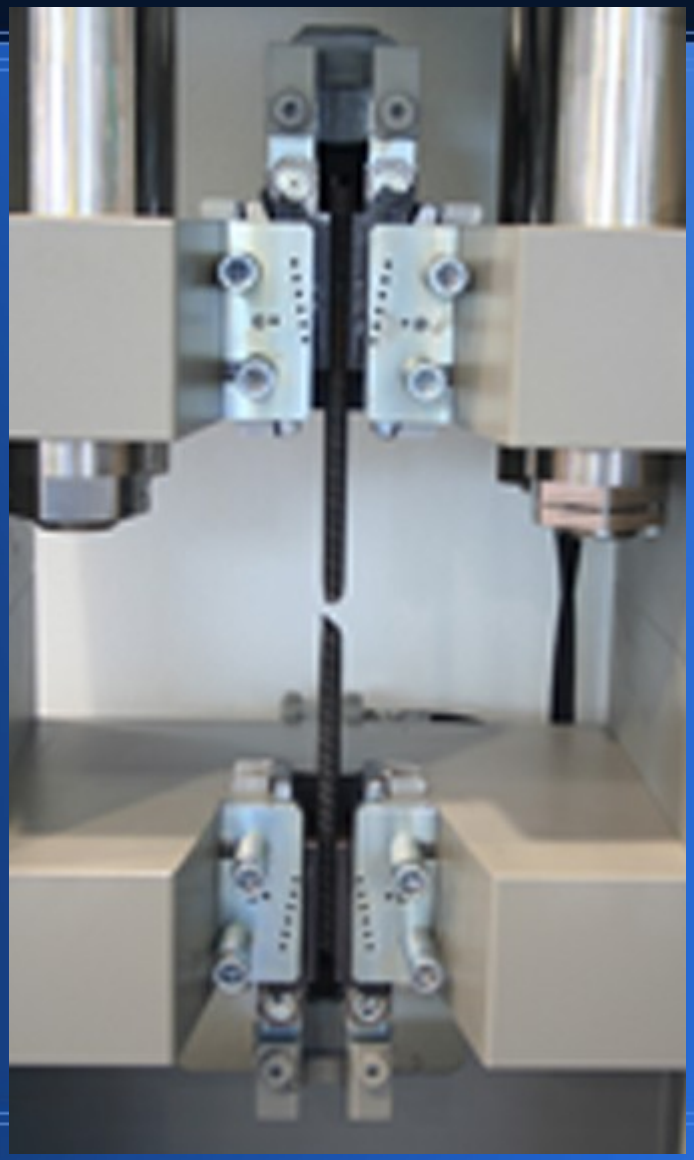


Got any math?

- Details are proprietary
- Buoyancy force estimated to be 4000 pounds
- Design margin estimate agrees with Elon's tweet – 10,000 pounds.

How did one break?

- "New Space" culture
- Trusting the vendors
- Strut violated spec
- There were others
- Elon tweeted: metallurgical flaw



Detailed sequence (professionally-informed speculation)

- Weak strut failed
- Helium tank tore loose and shot upwards
- High pressure leak into the LOX tank
- Contradictory telemetry data
- Helium tank punched through LOX tank dome
- Dragon capsule popped off
- Telemetry radios taken out

Quickie video simulation by Youtube user “SpaceFX”

The post-failure process

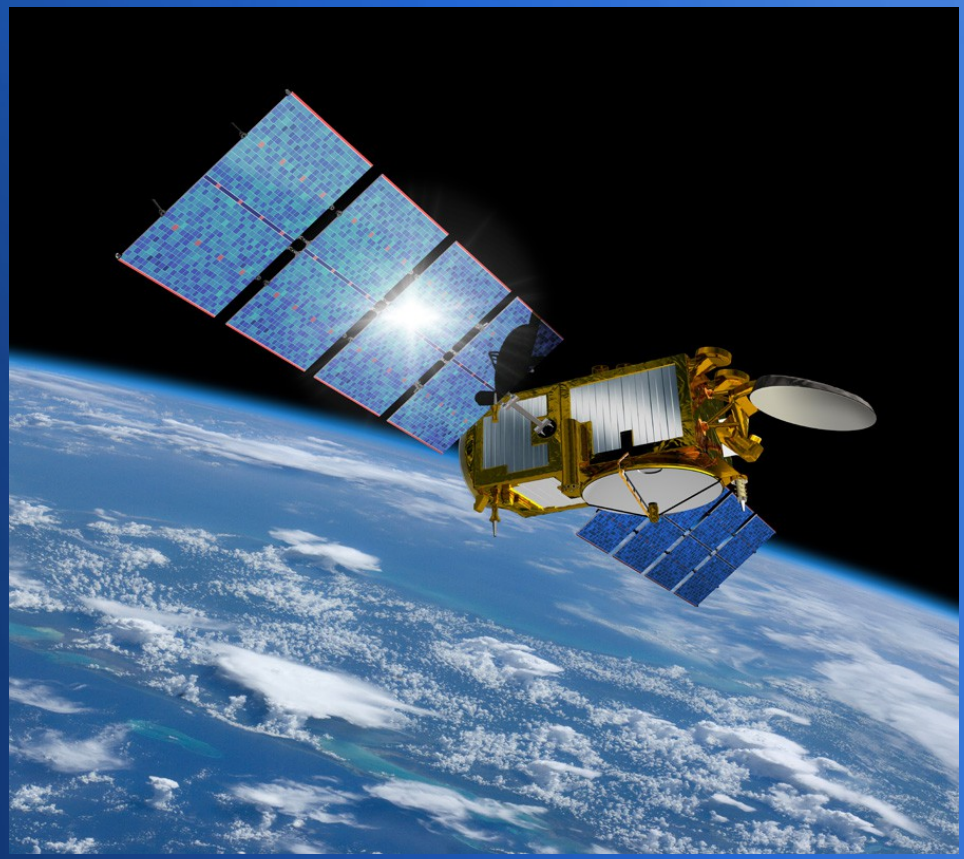
- Initial response
- Accident Investigation Process
- Fault Tree Analysis
- Corrective Actions

What SpaceX is doing to Return to Flight

- "Deep design scan"
- Fix other issues
- Introduce planned improvements
- Write and defend report
- Modify culture

Upcoming payloads

- **SES9**, Société Européenne des Satellites, Luxembourg
  - Communications/TV satellite
- **CRS8**, NASA - ISS resupply mission
  - Cargo Dragon
- **Jason3**, NOAA
  - Ocean Height Sensing mission



SpaceX goes BOLD!
How many in jokes do you count?

Trivia Question #8

- **In the video, there's a headstone for Elon on Mars. What's the funny saying about his own old-age plan?**

  " I think it would be great to be born on Earth and to die on Mars. Just hopefully not at the point of impact."

- **http://shitelonsays.com/**

Thanks for coming: Hope you're as excited about SpaceX as I am!

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Vista, CA October 9, 2015

Who am I?

- **Bill Carton – Electrical Engineer**
- **STAr-KVD Technologies, Inc.**
- **Mercury-era space enthusiast**

- Bill Carton – Electrical Engineer for Semiconductor Test Equipment
- Working for STAr-KVD Technologies, Inc., Carlsbad, CA
- Space enthusiast since the Mercury program in the early 60's
- Lead administrator for the Facebook unofficial SpaceX Enthusiast Group (14,000 members)
- NASA Social Media participant for the CRS6 launch, April 2015

On Social Media

- Technical Web forum: nasaspaceflight.com
- SpaceX enthusiast group on Facebook:
  - https://www.facebook.com/groups/spacexgroup/
- NASA invitation to CRS6 launch in April

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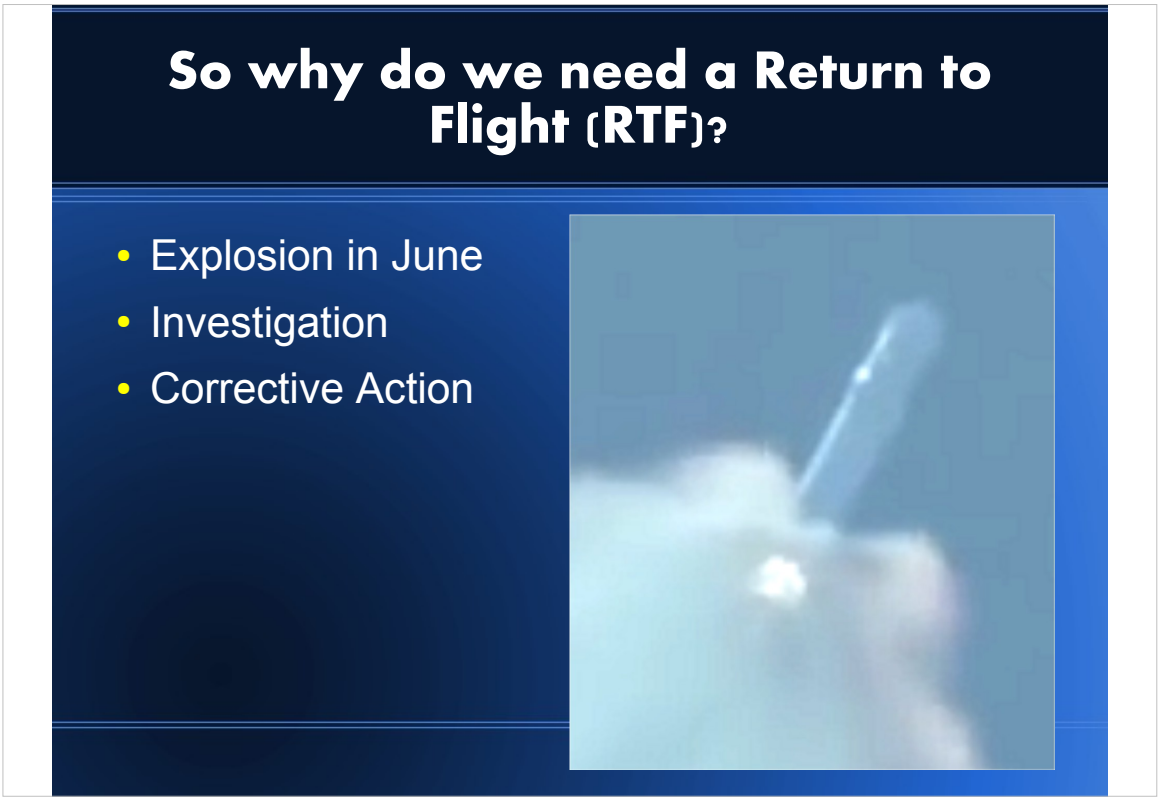
- NASA invitation to CRS6 launch in April
- Thanks to my wife Kae for putting up with this hobby since our honeymoon, 25th anniversary, and now.

Third launch is from Vandenberg
Fourth vehicle is the Grasshopper hover/landing test unit in McGregor Texas



- Explosion on June 28, 2015
- Investigation
- Corrective Action

- 19th Falcon 9 launch
- 18 preceeding mission successes
- Payload was a Dragon Cargo capsule carrying International Space Station (ISS) supplies, plus unpressurized cargo in the trunk such as the new standard International Docking Adapter

CRS7 video


LIVE
T- 00:00:02
LAUNCH: CRS-7
SPACE LAUNCH COMPLEX 40, CAPE CANAVERAL, FLORIDA, EARTH
GO/NO-GO POLL
DRAGON INTERNAL
STARTUP
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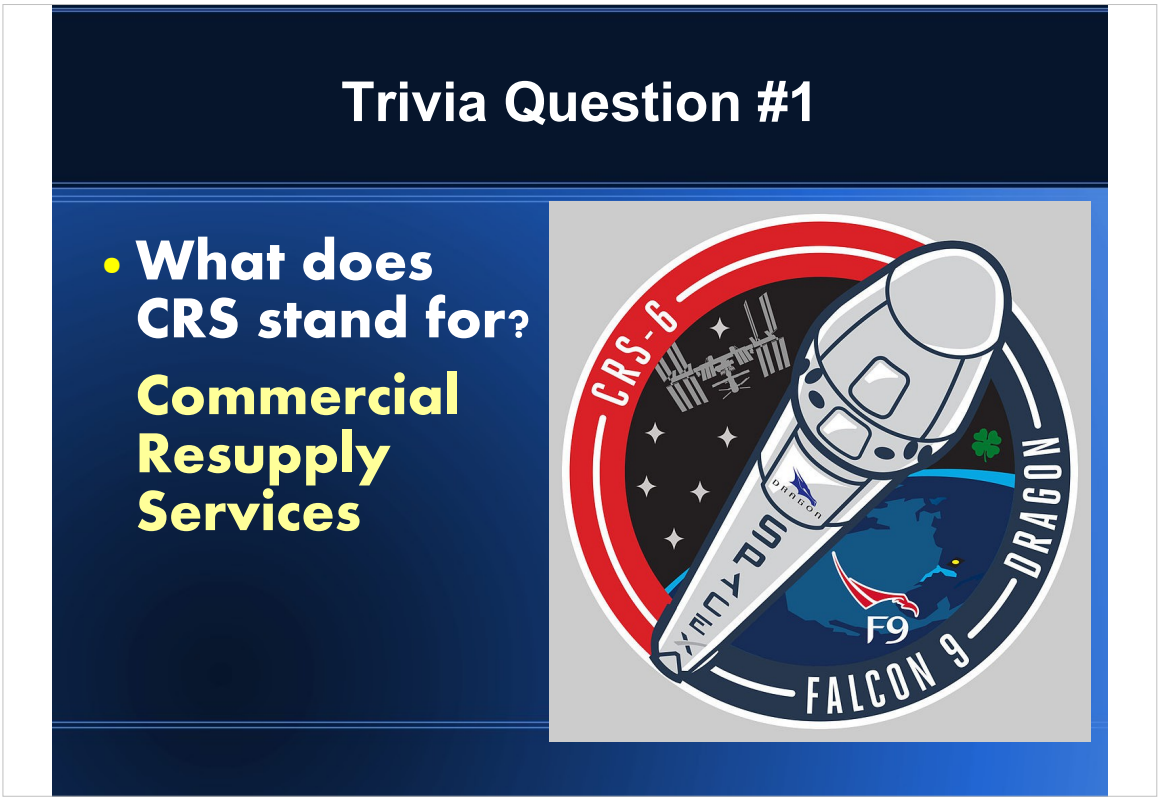


Commercial Resupply Services

Also discuss mission patch details

- Founded in 2002 by Elon Musk, using proceeds from the sale of his stock in PayPal.
- Currently over 4000 employees
- HQ in Hawthorne, CA
- Launch sites at Vandenberg AFB, CA and two sites in Florida (former Apollo and Shuttle LC39A and nearby LC40). Planned site near Brownsville, TX
- Engine/stage testing facility in McGregor, TX, near Waco
- Elon is CEO and CTO, Tom Mueller is VP of Propulsion, Gwynne Shotwell is President and COO.
- Notably, not a public company. Elon said would interfere with his ultimate Mars mission

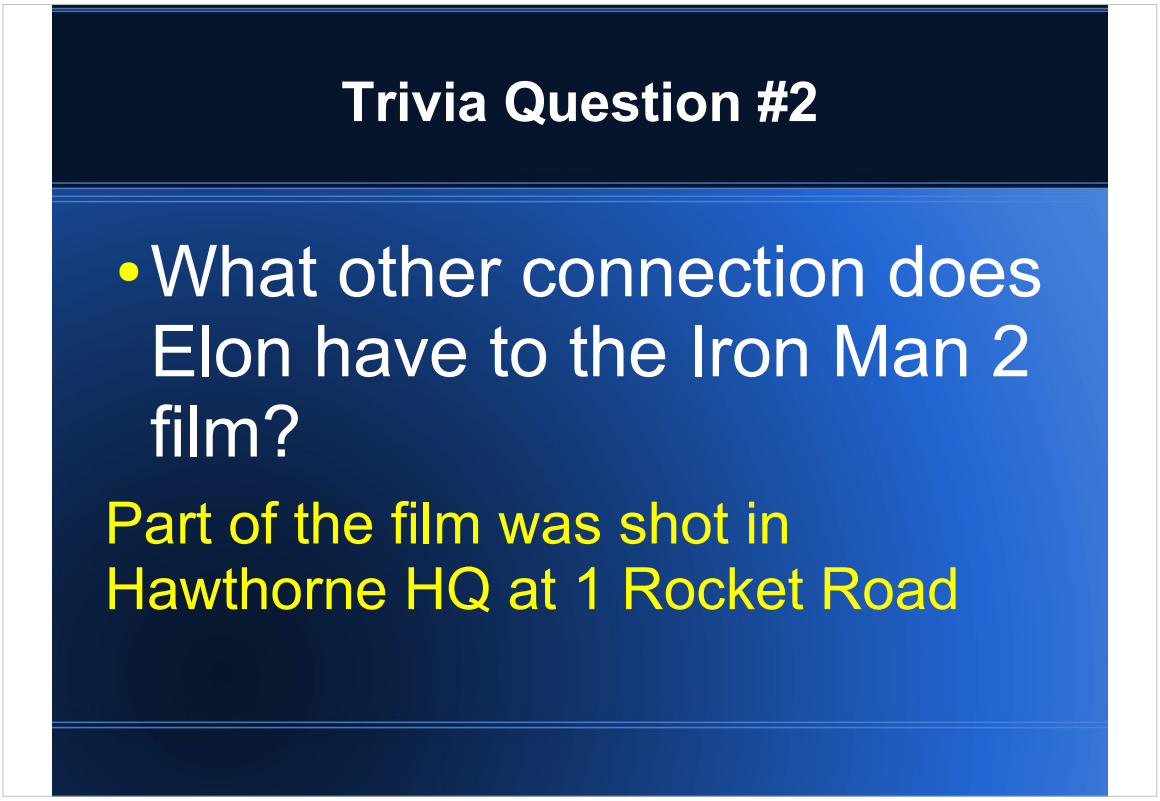
Who's Elon Musk?

Been compared to Tony Stark

Robert Downey, Jr. has modeled some of his character on Elon

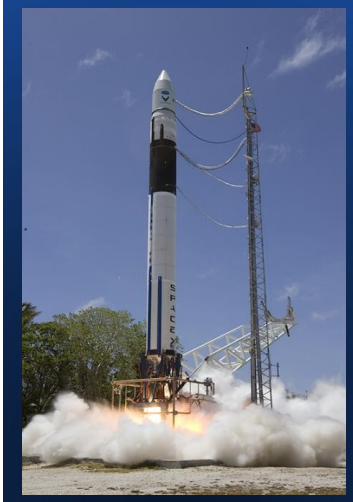
- Born June 28, 1971 in South Africa to South African and Canadian parents. Dual citizenship.
- Taught himself programming at age 10, sold first video game at 12 for $500.
- Went to college in Canada, then University of Pennsylvania. Dual Bachelor degrees in Physics and Economics
- Moved to California in 1995 to begin a PhD program at Stanford in applied physics. Left after two days to pursue entrepreneurship
- Became a US citizen in 2002
- Sold his shares in Zip2 in 1999 for $22M, PayPal in 2002 for $165M
- Science Fiction enthusiast, very worried about the emergence of evil AI, a view shared by Stephen Hawking and Bill Gates

Cameo in Iron Man 2



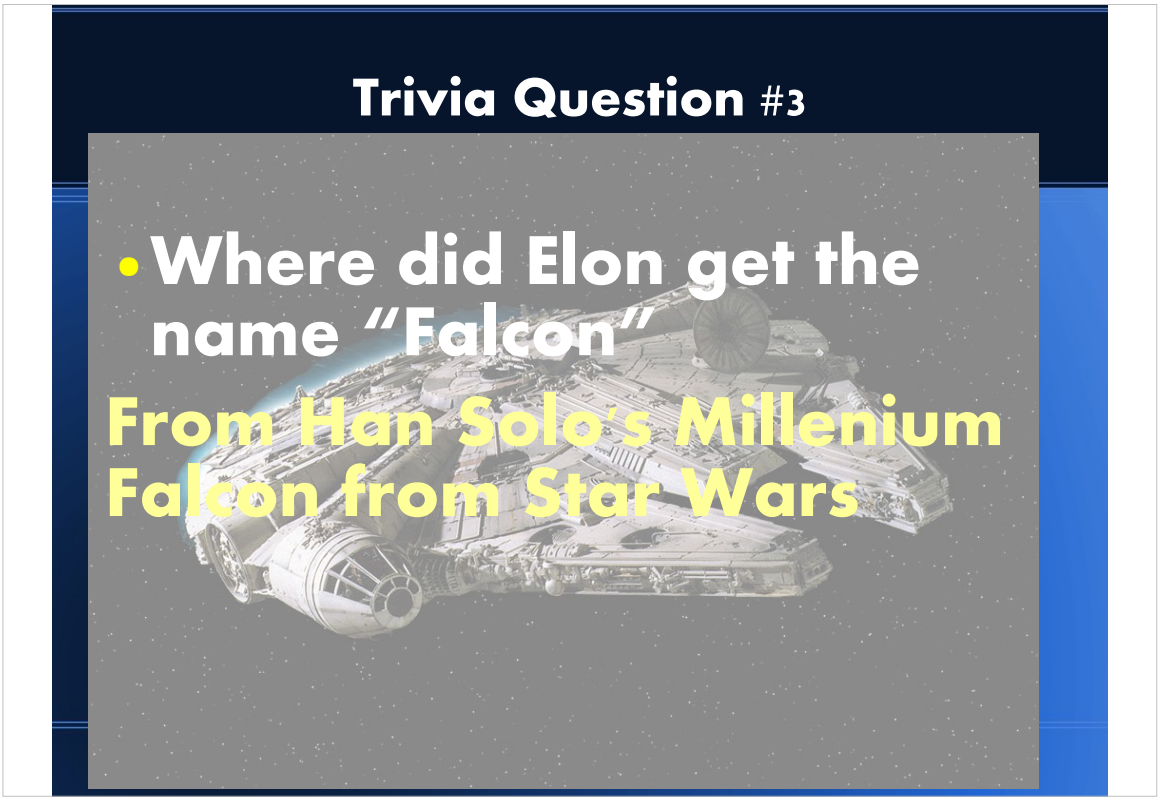
Part of the film was shot in Hawthorne HQ

Falcon 1 – Marshall Islands, South Pacific



- First three flights failed
- September 28, 2008 Flight 4 - Success – first private company to place a payload in orbit
- July 2009 – flight 5 a success

- March 24 2006 – fuel line leak, fire right after launch
- March 2007 – bump at staging, second stage oscillated and failed
- August 2008 – another bump at staging, failure
- September 28, 2008 Flight 4 - Success – first private company to place a payload in orbit
- July 2009 – flight 5 also successful

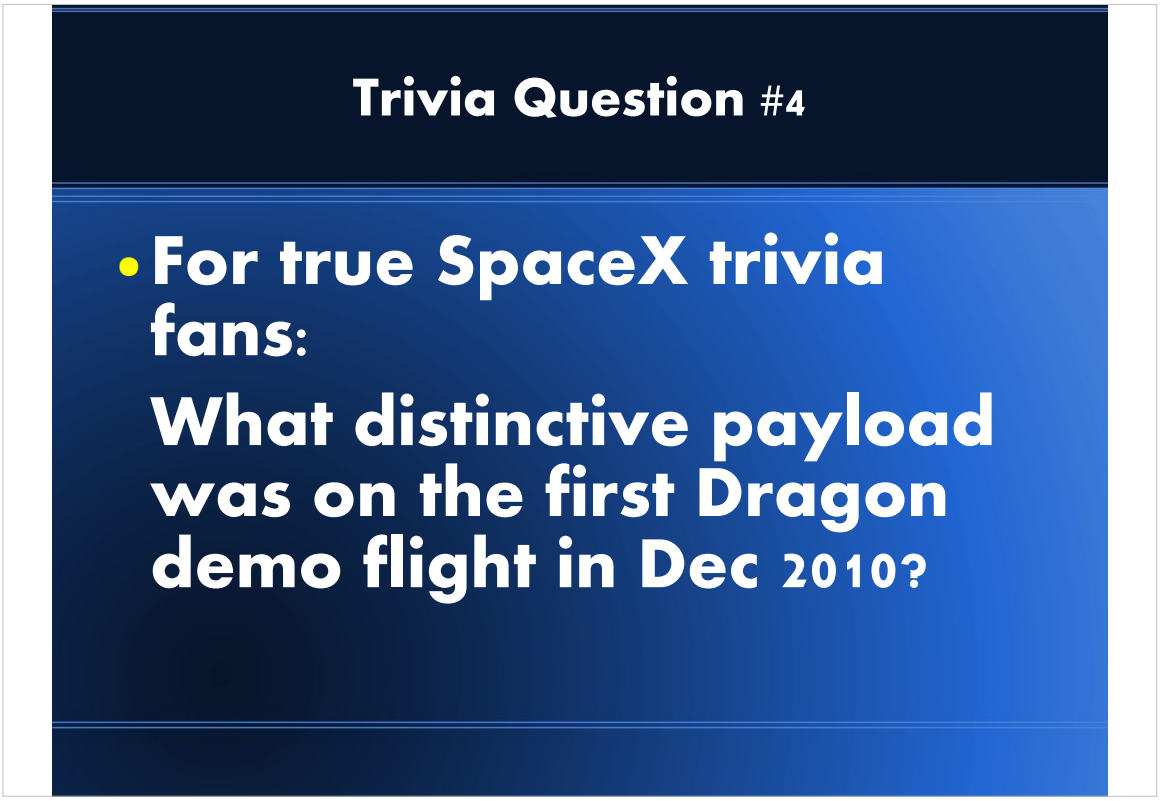


From Han Solo's Millenium Falcon from Star Wars

Falcon 9

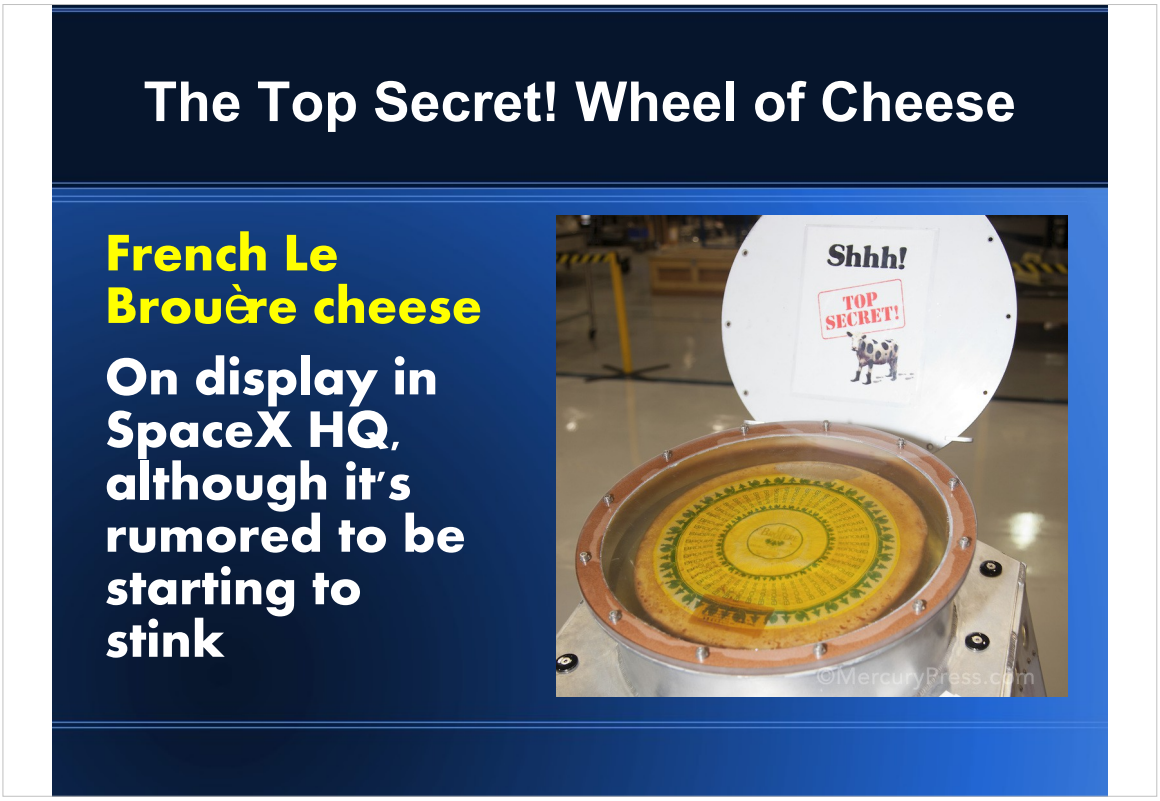
- Rev 1.0 (first 5 launches)
- Rev 1.1 (next 13 launches)
- Rev 1.1 Full Thrust (now)

Rev 1.0 – Tic tac toe engines, Merlin 1C
Rev 1.1 – Octaweb, Merlin 1D
Rev 1.1 Full Thrust – 30% more performance, supercooled propellants, stretched 2nd stage



The wheel of cheese was launched in honor of a classic skit from actor John Cleese in the British comedy show Monty Python's Flying Circus.

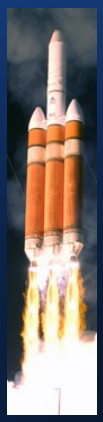
"It's kind of funny," Musk told reporters after the successful launch in 2010. "If you like Monty Python, you'll love the secret."



French Le Brouère cheese. This cheese is produced in Bulgnéville, Vosges. It was packed as a joke, and references the Cheese Shop sketch from Monty Python's Flying Circus. The barrel's lid was pasted with an image from the poster for the 1984 spoof film Top Secret!

Competitors – for another talk

- **Old Space:**



  - United Launch Alliance
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- **New Space:**
  - Virgin Galactic
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  - XCOR Aerospace
    - Lynx Rocketplane

Payloads

- **Satellites**
  - Commercial
  - NASA
  - Air Force/DoD (national security)

- **Dragon capsules**
  - Cargo to the ISS
  - Crew in 2017
  - Anywhere else

- Cargo to the ISS
- Crew in 2017 to the ISS and to future Low Earth Orbit (LEO) habitats such as from Bigelow Aerospace
- Anywhere else he has a paying customer (lunar or asteroid mining, lunar lander Xprize, Mars lander, planetary moon missions)

Satellites

- Fairings made of carbon fiber
- Variety of orbits

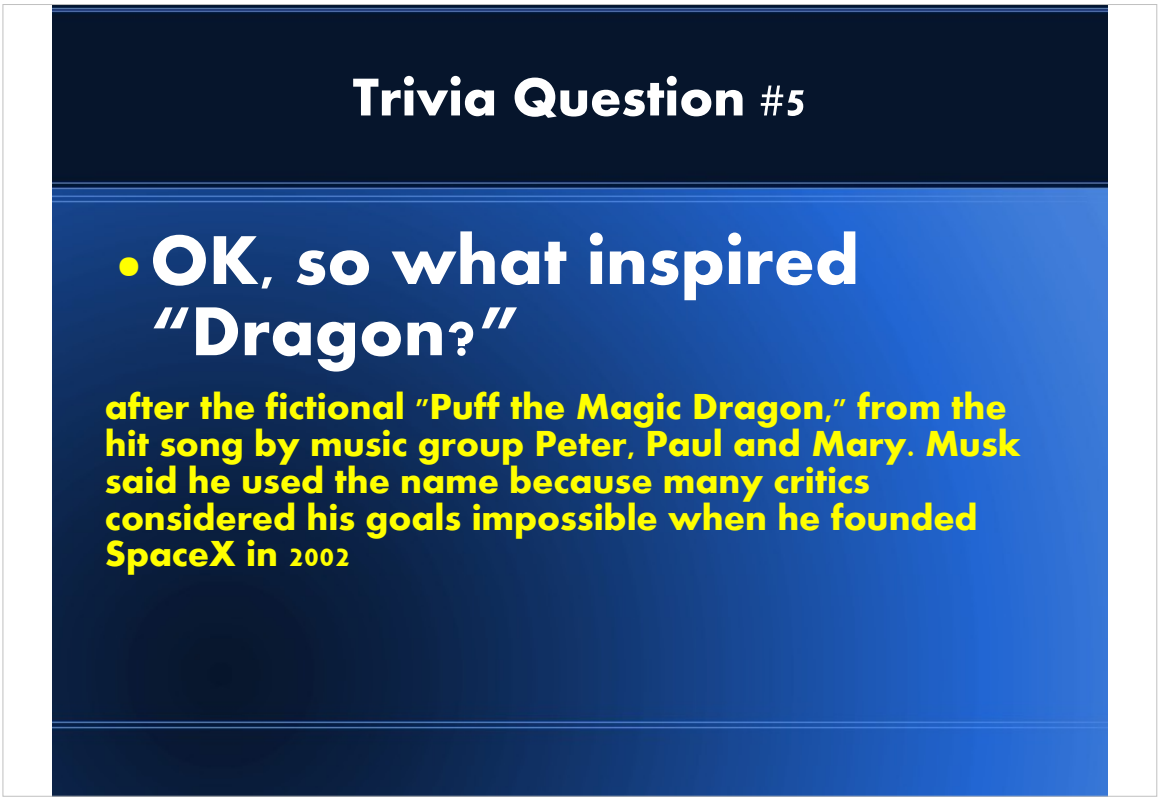
- Enclosed in a fairing that separates and is discarded above the atmosphere
- Can be lofted to Low Earth Orbit, or to Geosynchronous Transfer Orbits where communication satellites are useful

Commercial Resupply Services contracts started in 2008 with SpaceX and Orbital Sciences

Public laws back to 1984 and 1990 directed NASA to use commercial providers if available

Commercial Crew development contracts started in 2009 with five companies, ending with Boeing and SpaceX awarded final capability contracts in 2014

Will save us paying Russia $70M per Soyuz seat now Shuttle's been retired



after the fictional "Puff the Magic Dragon," from the hit song by music group Peter, Paul and Mary. Musk said he used the name because many critics considered his goals impossible when he founded SpaceX in 2002.

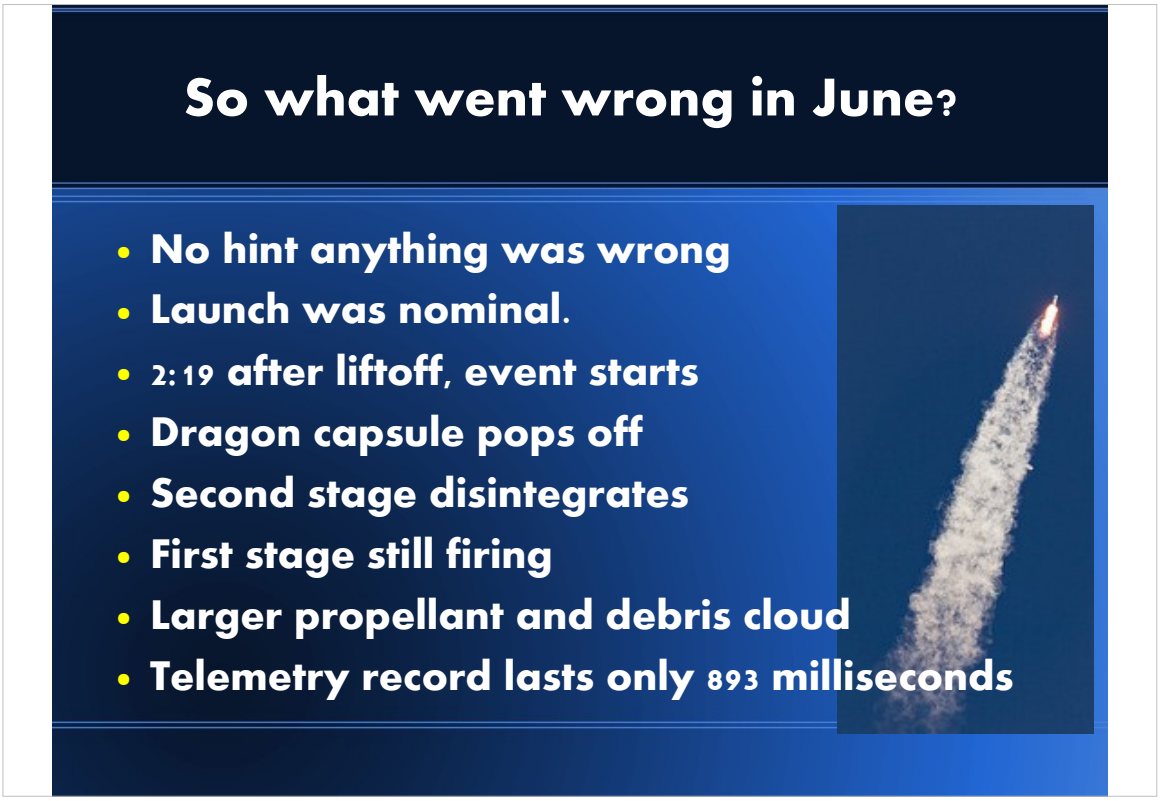
SpaceX Production Floor

What makes SpaceX disruptive to the launch industry?

- Innovative business practices
- In-house build
- Reusability
- Airline Industry model
- Launch, land, and relaunch

- Low cost production using Silicon Valley thinking, not “old space” gold plated hammers
- In-house build of as many items as possible such as engine actuators and electronics
- Innovative and disruptive reusability
- We would never have an airline industry for the masses if you threw the jet away after only one trip!
- Launch, land, and relaunch

Reusable First Stage and Dragon (CGI)



- All testing and preparation went nominally
- Launch was nominal. Second stage engine was in chill-down mode just before staging and getting rid of the first stage
- 2:19 after liftoff, massive LOX (liquid oxygen) cloud appears
- Dragon capsule pops off and can be seen tumbling away through the cloud
- Aerodynamic pressure damages the front structure of the second stage
- First stage, amazingly, is still firing through all this going on up front
- Larger propellant and debris cloud as aerodynamic forces tear it apart
- Telemetry record of as many as 3000 channels of data lasts only 893 milliseconds from first sign of trouble to total loss of signal.

Incident Video

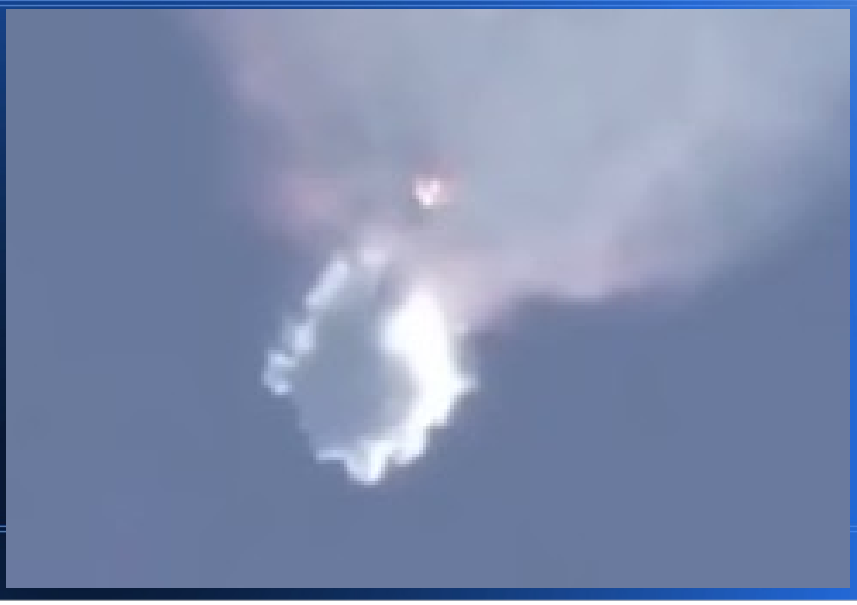
Armchair video analysis

Normal up to now

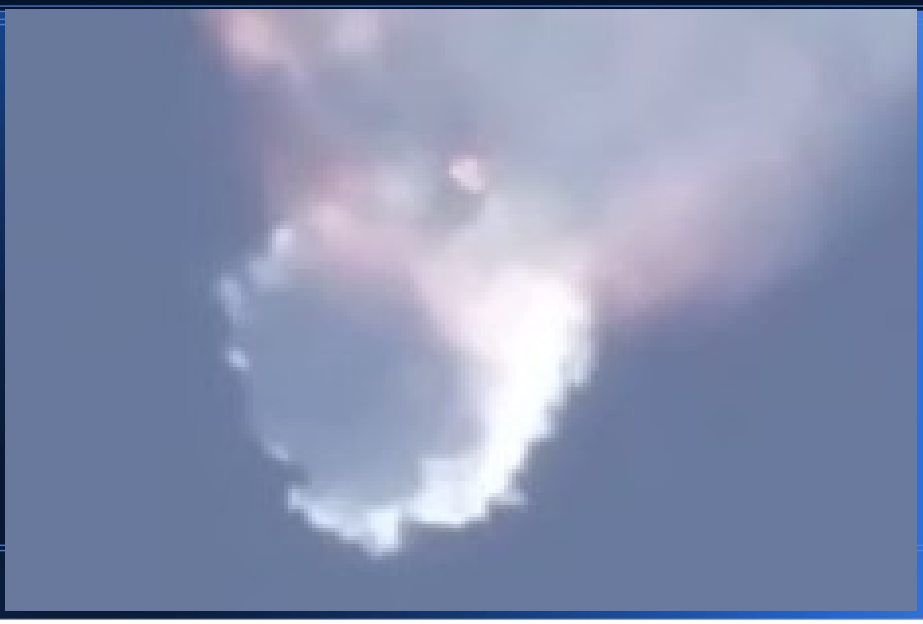
Initial sign of distress at the top of second stage

Expanding plume

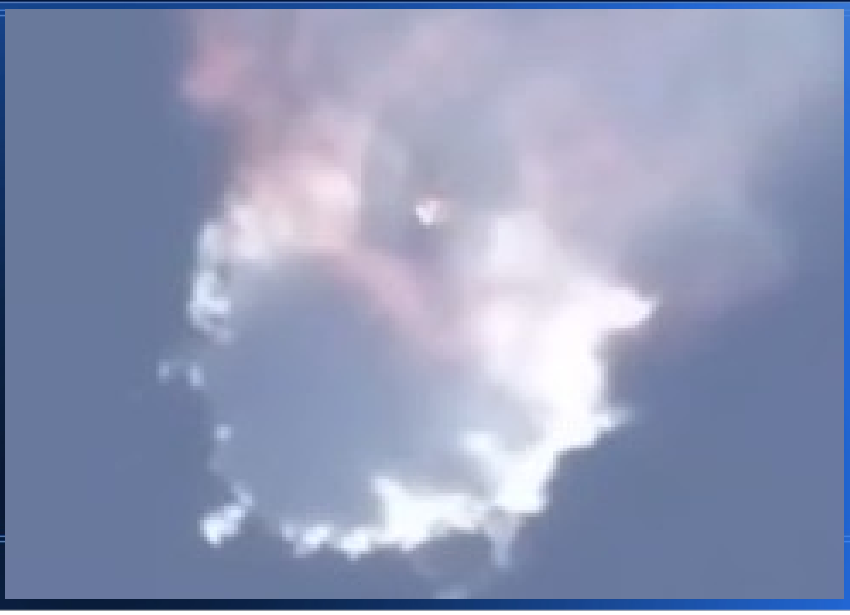
Expanding plume



Expanding plume



Expanding plume



Expanding plume

Dragon Capsule separates

Dragon Capsule separates

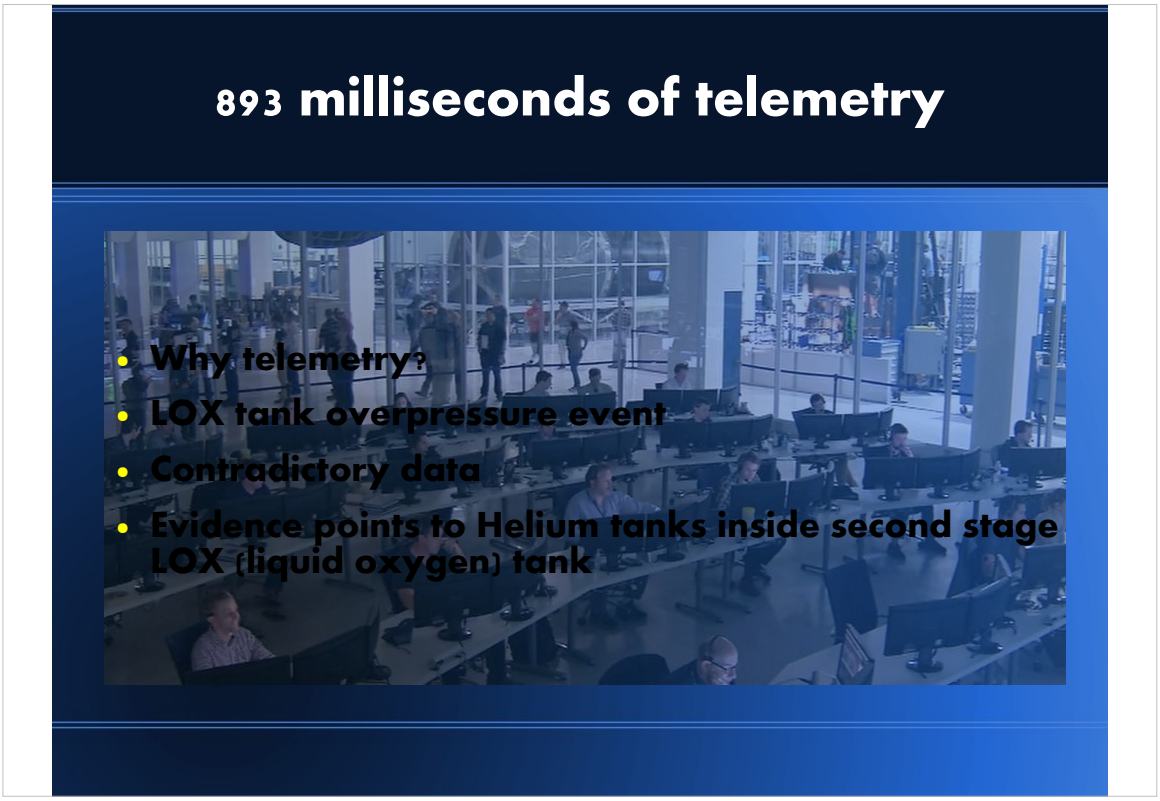
First stage engines still firing

LOX plume smaller for an instant

Then the first stage ruptures

Start of final propellant dispersal

Incident Video SpaceX feed



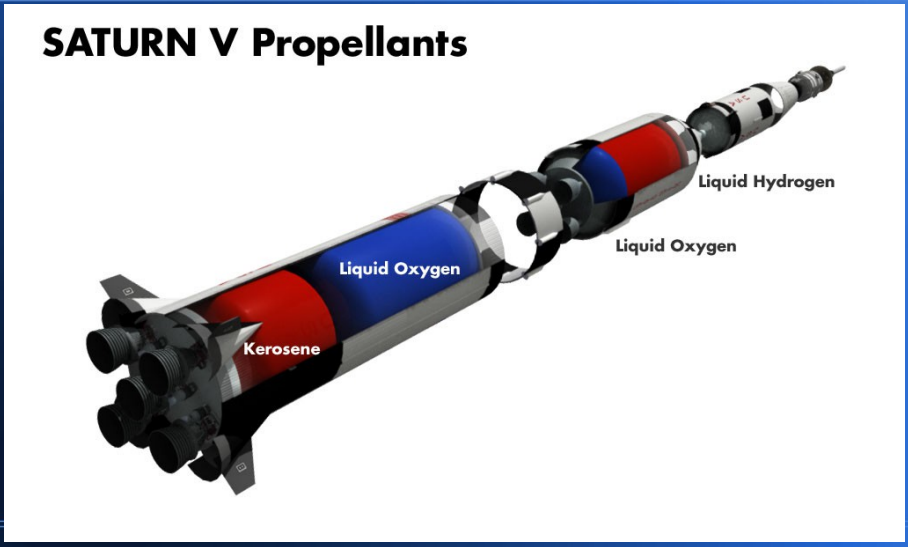
- Rockets always use telemetry because black box recorders add weight and are not often recovered
- Elon tweeted very quickly that an overpressure event occurred in the second stage LOX tank – at the top of the rocket
- Other evidence was confusing, and seemed to contradict some other data
- The focus homes in very quickly on second stage Helium storage tanks, INSIDE the LOX tank

Helium use on rockets

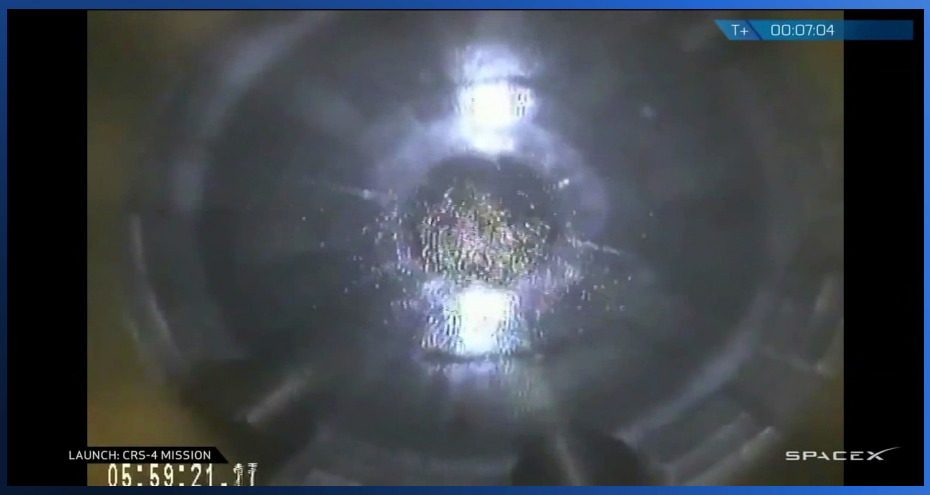
- Light weight
- Won't liquify
- Versatile

- Helium is a very useful gas in rocketry because of its light weight, and it doesn't liquify until it's colder than the coldest liquid on board – liquid oxygen, at -183 degrees C, -297 F.
- valve actuators, engine start-up sequence in the turbopump, landing leg extension cylinders, and mostly – filling empty space in propellant tanks as fuel and LOX are consumed. Otherwise the fuselage tankage would crinkle up and collapse.

Liquid Fuel Propellant tanks



Camera inside a SpaceX LOX tank



Trivia Question #6

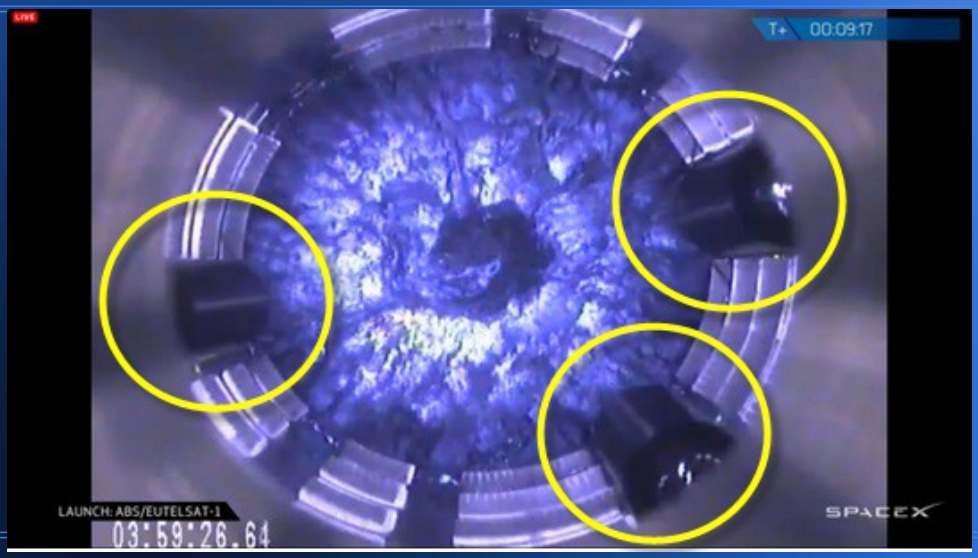
- When the LOX starts floating around when the engine cuts off, what TV show does that remind you of?

The Stargate “Sideways Toilet Flush” effect when the gate opens

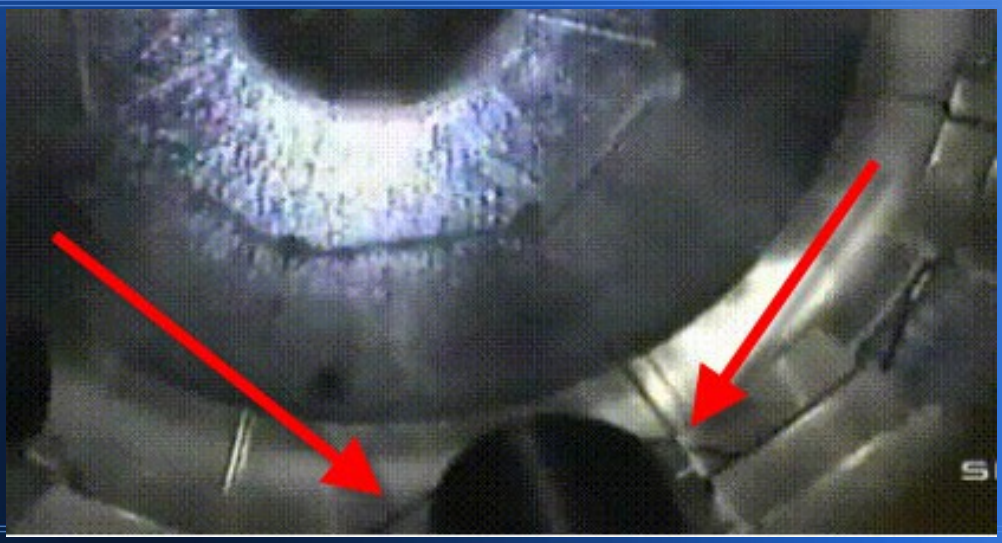
The Stargate “Sideways Toilet Flush” effect when the gate opens


STARGÅTE
SG·1

Three Helium storage tanks inside the second stage LOX tank



Mounting struts pointed out in red

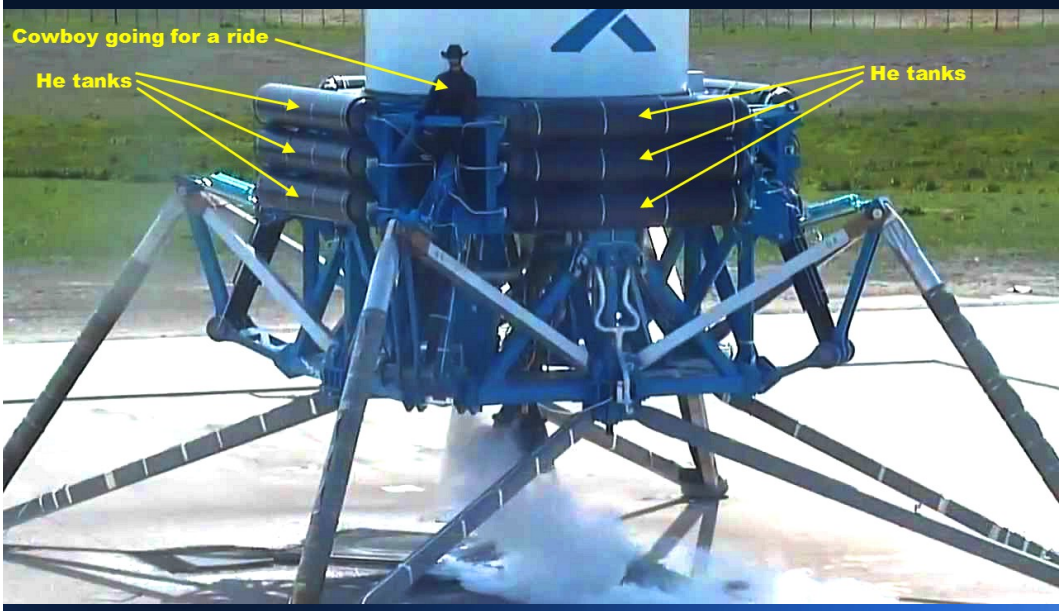


Struts also seen behind Elon in a tank under construction

Carbon (fiber) Overwrapped (titanium) Pressure Vessel

- COPV tank recovered after a second stage re-entry
- Other commercial tanks

COPV Helium tanks used on Grasshopper test vehicle



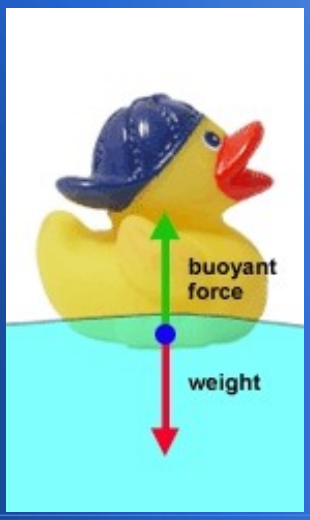
Helium tanks inside the LOX tank?

- **SHRINKAGE** at cryogenic temps
- Up to FOUR to ONE
- ~5000 PSI like a SCUBA tank

- Every gram counts on a launch vehicle
- The more Helium you can cram into each COPV tank, the fewer tanks you have to carry.
- COPV tanks can take 3000-6000 PSI. Like a SCUBA tank but even more.
- Helium is used around 50 PSI to pressurize the propellant tanks as they're drained (LOX and RP-1)
- At LOX temperature, you can fit about **FOUR** times as much gaseous Helium as you can if the tanks were at outdoor temp. Huge efficiency gain.
- COPV tanks are extensively tested, as are loading Helium and propellants and firing the engines, before launches.

So what happens during a launch?

- Helium tanks submerged
- Held down by struts
- Weight higher during launch acceleration
- But the buoyancy force is even higher!
- Funny behavior of helium balloon in a car



- COPV tanks are mounted near the bottom of the LOX tank, so they stay cool for a longer time during launch as the propellant drains
- mounted with 4-5 mounting struts as seen in the video frame grabs. 2 on the top sideways, probably two on the bottom sideways, and speculation is one to hold it down.
- Why down? During a launch, as propellant gets used up, G-force acceleration from the engines goes up, and shouldn't the tank weigh MORE?
- Counterintuitively, no. The tank has more upward buoyancy force than down weight, and higher G-force increases the buoyancy!
- Same thing happens to a helium balloon in a car. The air piles up to the outside of a turn, and the balloon floats the OTHER way!

Balloon in a car goes opposite direction to what you expect

Trivia Question #7

- **Why should we forbid the use of Helium in party balloons?**

Worldwide shortage caused by politics, and reduced production of natural gas

Worldwide shortage caused by politics, and reduced production of natural gas

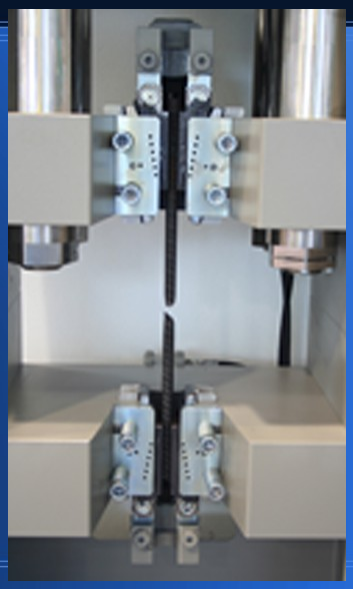
Got any math?

- Details are proprietary
- Buoyancy force estimated to be 4000 pounds
- Design margin estimate agrees with Elon's tweet – 10,000 pounds.

- Other on-line colleagues have done the math, but we really don't have hard numbers from inside SpaceX
- Given the assumed volume of the tanks from the intended uses of the Helium, and the expected G-forces, the estimated bouyancy force upwards on each tank near the end of the first stage firing is estimated to be around 4000 pounds!
- If there's a strut holding the COPV tank down in the LOX tank, with a decent safety margin designed in, it should be around a 10,000 pound rated strut.
- Amazingly, Elon tweeted that they were indeed 10,000 pound struts.

How did one break?

- "New Space" culture
- Trusting the vendors
- Strut violated spec
- There were others
- Elon tweeted: metallurgical flaw



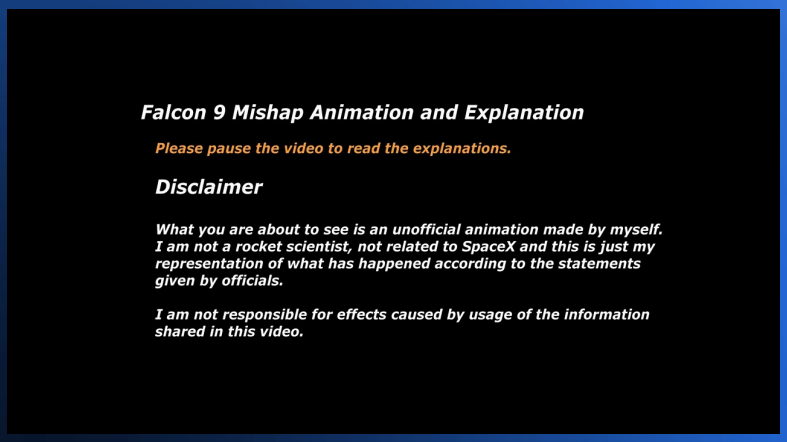
- The culture at SpaceX was to build everything they could in-house, but this was a commodity part they use a hundred of in each vehicle. They bought them from outside (like most screws and nuts), trusted the vendor, and didn't test each one to rated load or beyond
- That's one of the innovative but controversial ways they offer prices less than half the competition
- The telemetry data suggested one broke around 2000 pound force, releasing the COPV tank to pop upward at around 4000 pounds force!
- SpaceX pulled all similar struts from stock, set up a pull-testing machine, and indeed found other weak ones that failed well below the 10,000 pound specification.
- Elon tweeted they found a metallurgical flaw in bad units
- Could have been other bad struts installed in previous flights, perhaps none of them in an ultra-critical location like this one

Detailed sequence (professionally-informed speculation)

- Weak strut failed
- Helium tank tore loose and shot upwards
- High pressure leak into the LOX tank
- Contradictory telemetry data
- Helium tank punched through LOX tank dome
- Dragon capsule popped off
- Telemetry radios taken out

- Strut broke around 2000 pounds force during maximum acceleration as first stage was almost depleted.
- Second stage M-VAC engine chill-down had begin, consuming a small amount of LOX to flow through the engine parts, so Helium was flowing
- Tank tearing loose allowed high pressure helium to enter the LOX tank, which has only about 3% empty space at the top since it hadn't been started yet.
- Confusingly, Helium plumbing pressure went down, then back UP. Possibly the loose tank bent and crimped the broken pipe?
- Loose tank was in the process of shooting to the top of the tank – rupturing the upper dome and starting the massive LOX release into near-vacuum.
- Since the top dome was just underneath the Dragon's trunk area, the Dragon popped off.
- Since most rocket failures start around the engines at the bottom of each stage, the guidance computers and telemetry radios are on top of the uppermost propellant tank. In this incident, that was the first to be destroyed, handicapping the telemetry data analysis.

Quickie video simulation by Youtube user “SpaceFX”



The post-failure process

- Initial response
- Accident Investigation Process
- Fault Tree Analysis
- Corrective Actions

- Save all data, cancel the post-launch party, interview all staff
- Execute the pre-defined Accident Investigation Process
  - Involves SpaceX staff, NASA, and the FAA
  - Other customers will also expect full briefings on the accident and corrective actions
- Conduct fault tree analysis to examine every possible cause, eliminating ones with proof that they aren't involved.

- Following all possibilities in the fault tree – this is the first accident investigation most of the staff have been involved in.
- Engineers have buddied-up to have colleagues go over their designs and calculations in a "deep scan"
- Other issues that might not take down a vehicle, but are easy to fix while they're in a stand-down mode – get fixed.
- Elon's said the end of the process is in sight

Upcoming payloads

- **SES9**, Société Européenne des Satellites, Luxembourg
  - Communications/TV satellite
- **CRS8**, NASA - ISS resupply mission
  - Cargo Dragon
- **Jason3**, NOAA
  - Ocean Height Sensing mission

- SES9, SES, Luxembourg – Communications/TV satellite operator with fleet of 53 assets in geosync orbit. 11,684 pounds.
  - NET (no earlier than) November 20 from Cape Canaveral AFS, FL.
- CRS8, NASA - ISS resupply mission using a Cargo Dragon
  - Possibly Dec/January depending on ISS VV (visiting vehicle) planners
- Jason3, NOAA Ocean Height Sensing mission
  - Launch from Vandenberg AFB, CA possibly December

SpaceX goes BOLD!
How many in jokes do you count?

Trivia Question #8

- **In the video, there's a headstone for Elon on Mars. What's the funny saying about his own old-age plan?**

  " I think it would be great to be born on Earth and to die on Mars. Just hopefully not at the point of impact."

- http://shitelonsays.com/

Thanks for coming: Hope you're as excited about SpaceX as I am!