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Book Review:

Ignition!

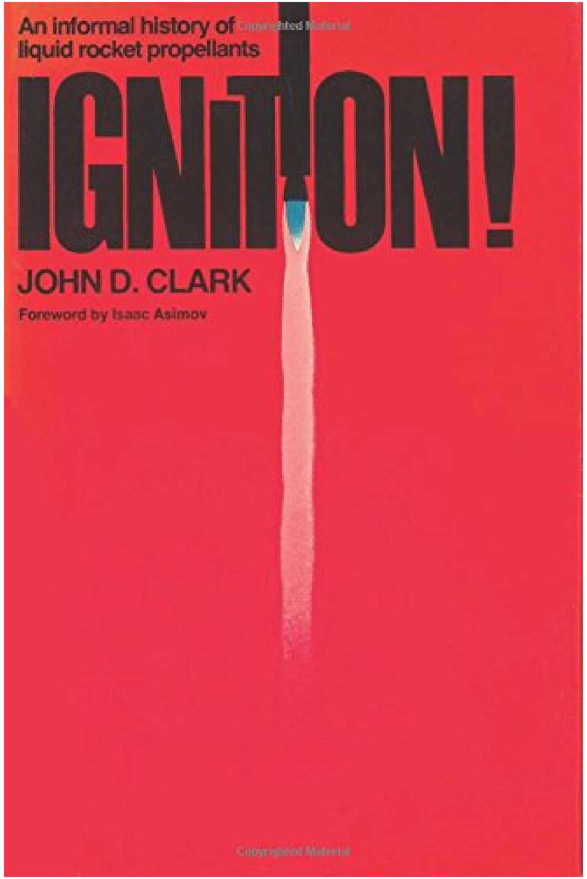
An Informal History of Liquid Rocket Propellants

by John D. Clark

Fred Mora - System Engineering, Datto

Why this book?

- This is the classic “rocket science” book (more like rocket fuel science)
- It is extremely entertaining
- It was out of print
- Its publisher, Rutgers University Press, finally decided to re-issue it (release date: May 2018)
- You can pre-order it today.



That’s nice, Fred. What’s the IT angle?

- This book was written on a typewriter
- It contains only references to IBM-360 computing
- So why review it?

- Because history of science is good for you
- Also, *Ignition!* contains lessons about engineering project management
- It shows how to handle hazardous R&D and stumbling blocks in complex projects
- And it’s much more fun than process and management books!

Clarke credentials

- Joined the Navy rocket fuel R&D in 1949 (Naval Air Rocket Test Station, or NARTS)
- Led the lab for 17 years until 1970
- Developed propellants that satisfied civilian and military rocketeers
- Never had a serious injury or death on his watch, in spite of:
  - Demanding customers
  - Angry chemicals
  - Novel, uncertain science
  - Careless personnel

- Clarke picked the stuff that rocket scientists pump into their tanks, no question asked.
- This book tells you *why* these propellants were chosen among all the thousands of substances that could apparently do the job.
- More importantly, it hints about how to do your job in a high-stake environment.

Why we IT guys should respect rocket scientists

- When we goof, we loose time and money
- And sometimes data
- If we are unlucky, we'll botch an electrical job on a data center and burn a few racks
- What raises our heart rate: The latest patch crashes our servers.

- When they goof, they loose time, money, and limbs
- And sometimes colleagues.
- If they are unlucky, they will receive posthumous honorific distinctions
- What raises their heart rate: An unknown liquid pooling under a storage cabinet, and they have no dog.

What’s so special about that job?

- To quote Isaac Asimov:

  “[Some chemicals are explosive. Some are inflammable. Some are corrosive. Some are poisonous. Some stink.]
  As far as I know, only liquid rocket fuels have all these delightful properties combined into one delectable whole.”

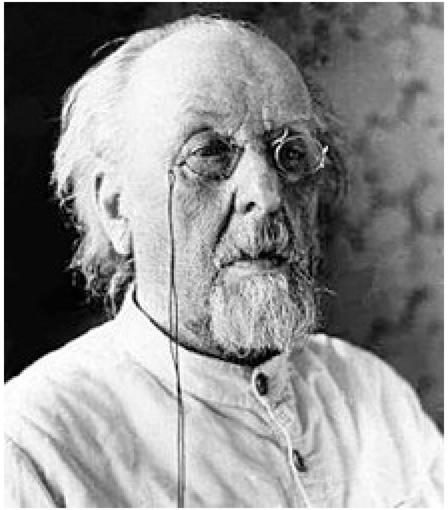
Managing failed tests

- Clarke sometimes heard about failed projects or accident
- He read the reports
- Then he headed for the local bar, looking for a dejected scientist
- He asked (and obtained) the unsanitized version of the events
- He carefully made notes about what really went wrong

- LESSON: When things go South, the failure is generally not heralded
- Communication, if any, tiptoes around the subject
- You need to know what on Earth happened because you could hit the same problem
- Unless it’s too enormous to be hidden, your only chance to get the straight dope is to network with the persons responsible for the failure.
- Make notes about what went wrong and heed the warnings.

The early pioneers

- **1903**: Russian Konstantin Tsiolkovsky publishes a seminal paper about rocket propulsion in space:
  - Describes the famous rocket equation he discovered in 1897
  - Brings up the propellant topic
  - Calculates that gunpowder is too weak – take that, Jules Verne!
- Article went unnoticed until much later
- Tsiolkovsky carefully keeps his work theoretical.



Konstantin Tsiolkovsky

The early pioneers

- **1926:** American Robert H. Goddard flies the first rocket with liquid propellants: liquid oxygen (LOX) and gasoline
- Goddard worked in secrecy, so his work was only rediscovered later
- He had to lower the ratio of LOX in his mix to avoid burning out his motor
- This is another recurring theme:
  - The best combos are the most energetic
  - They are hard to use because they are *too* energetic!

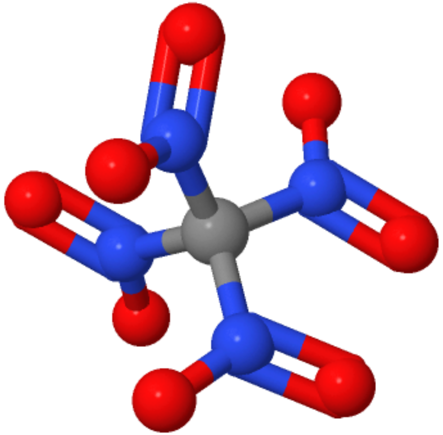
Robbert Goddard
NASA - Public domain

The early pioneers (cont’d)

- **1930:** Frenchman Robert Esnault-Pelterie (eh-noh paylteree) write his treatise *L’Astronautique*
- Convinces French government to fund ballistic missile research for bombardment.
- Experiments with tetra-nitromethane as an oxidizer
  - Perfect chemical on paper
  - In practice, impurities make TNM very unstable – a recurring theme with oxydizers
  - Esnault-Pelterie loses 3 fingers in accident
  - French gummint loses all interest.
- TMN is very attractive on paper, so it was manufactured. It claimed a lab in Germany and a factory in the US.

Esnault-Pelterie
Bain News Service, publisher
Public domain

TNM. Count your fingers.



Von Braun and Peenemünde

- Peenemünde is a Baltic Sea island were the V1 and V2 were manufactured
- One propellant used was 80% peroxide
- One of the ergol mixes used in missiles was alcohol and LOX
- “Why not mix alcohol and peroxide?” asked one scientist. “Let’s run a burn test!”
- The resulting explosion killed him
- High-grade peroxide has a justified bad rep
- Remember that next time you find your job boring. Boring is good.

- Remember TNM?
- A spy working in Germany planted the fake info that a TNM compound was mass-used for rocketry in the US.
- The Germans managed to manufacture *eight tons* of it without accident but nobody wanted to touch it.

The JPL

- Started as “Dr. Malina’s group”, a CalTech bunch of rocket tinkerer, in the mid-30s
- They got kicked out of the campus due to an explosion.
- Contracted to produce a reliable JATO rocket for the Navy. No unstable stuff or cryogenics, mmmkay?
- 1941: They picked red fuming nitric acid (oxidizer) and gasoline (fuel) - the combo is self-igniting
- They (re)discovered the hard start problem, a.k.a. Puddle of Death:
  - Incompletely burnt fuel pools in the firing chamber and then explodes
  - Engine coughs, sputters, then detonates
- This problem is one of the main propellant science headaches.

The JPL (cont'd)

- JPL solved the hard start problem by replacing gazoline with aniline
- They got a clean burn
  - They also got the headache of handling aniline, a very toxic liquid…
  - …That freezes at -6C (21F)!
- The Navy was quite upset but they had no other JATO.
  - A JATO in a take-off crash would add a toxic cloud to the disaster scene
  - Any leak could lead to a carnage
  - Well, the propellants are not unstable, are they?

- LESSONS:
- The customer's unwritten requirements are often just as important as the written specs
- Even if you deliver the specs, the users might revolt.
- There is no pleasing some people.

Hypergolic: remember that term

- Ideal rocket propellant is a hypergolic mix (that is, self-ignites when mixed)
- Without it, igniting an engine requires some special measure, e.g., pyrotechnics or hypergolic lighter
- SpaceX's February 6th flight: Falcon Heavy's booster ran out of "lighter fluid" and couldn't restart its engines.
- The search for hypergols drove rocket scientists to despair: They even tried mercaptan, a.k.a "skunk juice".
- Ten years later, the test site still stunk.

Early 1950s: The kerosene dead-end

- The Air Force buys and handles huge quantities of jet fuel (JP-4, a NATO standard)
- Of course they wanted their rockets to use JP-4 instead of exotic chemicals
- No cryogenics! So that mean nitric acid instead of LOX for oxidizer
- With JP-4 + nitric acid, all you get is Puddles of Death and exploding engines.
- Kerosene composition varies a lot – fine for jet, not for rocket engines!
- It took years to admit that LOX was the only practical oxidizer for kerosene

Kerosene (cont'd)

- The Air Force insisted on kerosene (JP-4 jet fuel) because it had lots of it and could easily buy more for continuing operation.
- Kerosene is actually a mix of many different molecules in variable proportions. Which makes it a headache for rocket propulsion.
- Jet fuel decomposes and creates bacterial sludge. Also lots of soot in rich mixes.
- But in strategic ICBMs, do you really need to care about refueling?
- Chances are, these will be the very last rockets you ever fire because the other SOBs on the other side are doing the same.
- After a few hundred warheads have been exchanged, "the problem of fuel for later salvos becomes academic." (Ignition!, ch. 8)
- In 1957, the Air Force grudgingly conceded that a specially formulated fuel, RP-1, might be used for ICBMs.

- LESSON: A customer might insist on a certain technology because of logistics and habits.
- You should always question these requirements by looking at the expected use cases.
- In that case, "we need to fuel more ICBMs after WWIII" turns out to be a debatable requirement.

The taming of nitric acid

- Oxidizer hunt: If LOX is out, nitric acid is the next best choice, particularly red fuming nitric acid.
- The acid corrodes stainless steel or aluminum containers and is unstable…
- … And produces gas oxygen as it degrades!
- So missiles could not be pre-filled with NA.
- Breakthrough: Adding 0.5% of HF (the dangerous hydrofluoric acid) reduces steel corrosion greatly…
- … But speeds up titanium corrosion by 8,000x and makes it explosive.

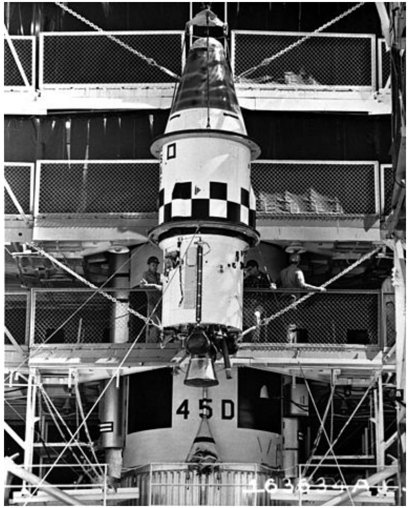
    Dec 29, 1953: Titanium samples immersed in nitric acid detonated. One dead. Nobody wanted to touch titanium for years afterward.

- In the end, they produced a nitric acid mix that could be stored safely in steel missile tanks for years.
- The Air Force published the HF breakthrough in spite of the author’s objections. It was a boon for the Soviets – Their hydrofluoric acid manufacturing boss had been sent to the Gulag.

Synthesis of red fuming nitric acid. Photo: “Chemist by Destiny”

The taming of nitric acid (cont’d)

- Thus was born “Inhibited Red Fuming Nitric Acid”, the standard nitric acid oxidizer of the rocket industry.
- The US Agena rocket engine used for 30 missions used JP-4 + IRFNA – that is, kerosene and nitric acid.
- Used to this day in short-range missiles such as the Scud and Silkworm.
- On impact, unburnt IRFNA forms poisonous, irritant clouds.



US Agena rocket engine Photo: US Air Force - Public Domain

Scud missile. Photo: Military Today

Trying to dodge LOX

- To avoid liquid oxygen – a Pentagon requirement -- truly terrible substances were tried.
- Example: ClF3, Chlorine Trifluoride or CTF, a very strong oxidizer without the forgiving, laid-back qualities of nitric acid.
- Very toxic, combusts anything.
- Corrodes teflon and gold.
- Very hypergolic with any fuel including safety equipment, tank seals, glass tubes, and technicians.
- Also nicely burns water, sand and fire hoses.

Test: ClF3 drops on safety mask

T = 0

T = 2 s

Source: old French chemistry safety institutional short.

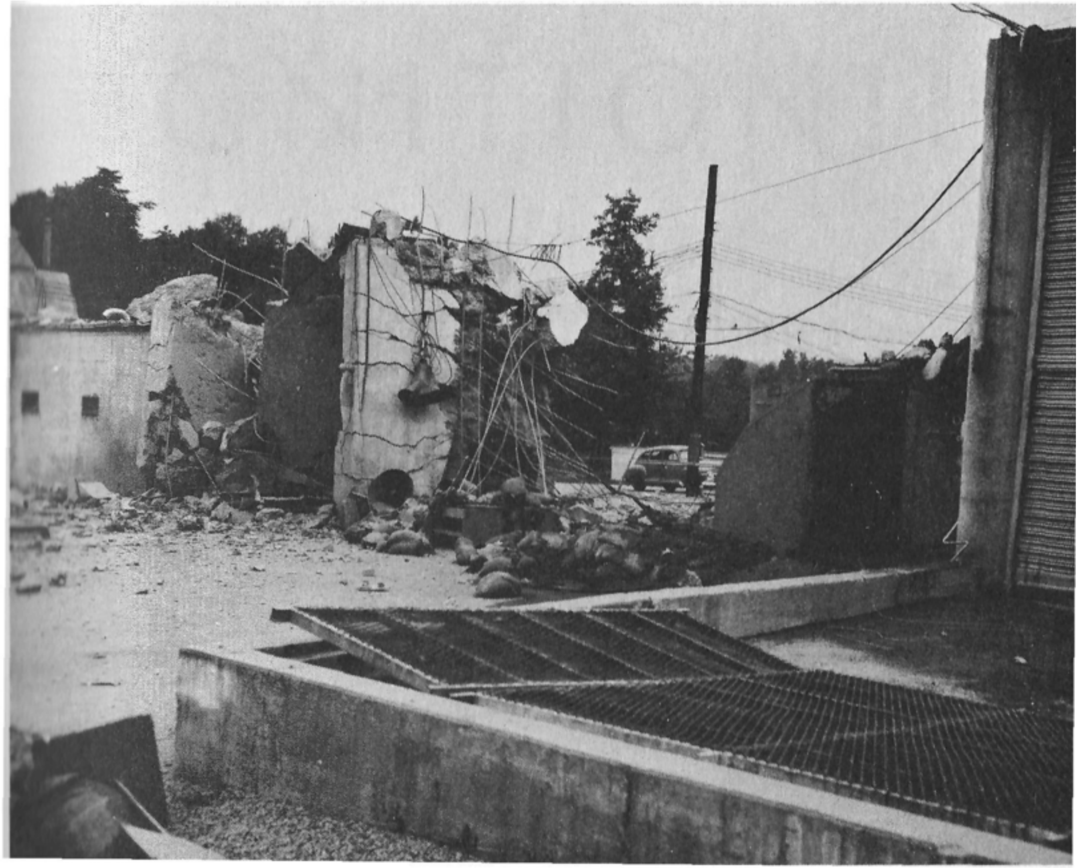
Trying to dodge LOX (cont'd)

- The book describes the effect of a one-ton spillage of chlorine trifluoride due to a steel container cooled with dry ice that broke when put on a dolly.
- Happened at the General Chemical Corp. facility in Louisiana, date unsure.
- The CTF burned through 12 inches of concrete floor and "dug a 3-foot hole in the gravel underneath". Fumes corroded the whole building.
- The dolly operator reportedly fled and died of a heart attack.
- LESSON: Sometimes, a requirement is just taking so much effort that it is not worth implementing.

"*[…] rocket people started working with CTF […] and proceeded with a degree of caution appropriate to dental work on a king cobra.*"
J. Clarke, Ignition, ch. 6

U.S. Navy photo

This is what a test firing *should* look like. Note the mach diamonds in the exhaust stream.



U.S. Navy photo

And this is what it may look like if something goes wrong. The same test cell, or its remains, is shown.

Rocket science tutorials

- Clark excels at explaining how rocket scientists work
- The *Performance* chapter amounts to tutorials on how rocket scientists performed their calculation by hand, even if he does not go into all the details.
- It is a lesson on how to teach a terribly complicated subject.
- Clearest explanation of specific impulse I ever read!
- His revolutionary quick, simplified method of fuel efficiency calculation took only 15 minutes!
- Clark talks about using FORTRAN programs and their well-known poor user interface.
- Turns out missile engineers are never happy with the results anyway.

And there is one disconcerting thing about working with a computer—it's likely to talk back to you. You make some tiny mistake in your FORTRAN language — putting a letter in the wrong column, say, or omitting a comma — and the 360 comes to a screeching halt and prints out rude remarks, like "ILLEGAL FORMAT," or "UNKNOWN PROBLEM," or, if the man who wrote the program was really feeling nasty that morning, "WHAT'S THE MATTER STUPID? CAN'T YOU READ?" Everyone who uses a computer frequently has had, from time to time, a mad desire to attack the precocious abacus with an axe.

John D. Clark, Ignition, ch. 7

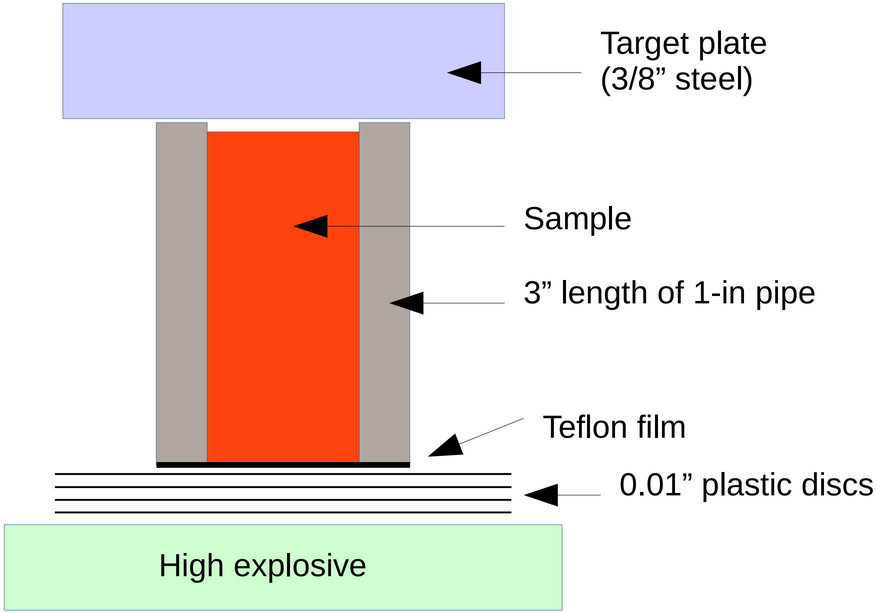
Meanwhile, back at the LOX range

- The Navy hated LOX, but it gave good results
- The first supersonic plane, the X-1, burned alcohol with LOX.
- Turns out that barrels of ethanol (drinkable alcohol) “evaporate” quickly on ships due to numerous “testing”. Also, a bit weak.
- The famous X-15 burned LOX and an ammonia-based fuel. The motor development was troublesome.
  - During a flight to California, the head engineer for the motor, Lou Rapp, reportedly was asked about the engine’s reliability by his seat neighbor.
  - Rapp went on a rant and described it as an accident waiting to happen.
  - The seat mate turned out to be Scott Crossfield, the designated X-15 test pilot!

X-15. Main Engine burned ammonia and LOX. Thrust: 250 kN (57,000 pounds-force). Turbopumps and maneuvering jets used hydrogen peroxide.
Picture: NASA. Source: TheAviationist.com

The card-gap test (some people have all the fun)

- How do you determine the stability of a chemical?
- Answer: "Card-gap test". A metal tube filled with a 40-cc sample of the substance rests on 50-gram block of high explosive (tetryl), with 0.01"-thick disks of cellulose acetate between the two.
- A witness plate on top will be pierced if the sample detonates.
- Place the test rig inside an enclosure. The author's lab used an old destroyer gun turret.
- Detonate the explosive. If the sample does not detonate with zero disks between the two, it's considered totally stable.
- If it still detonates with 150 disks, forget it.
- And of course you need many explosions to run the test! At least a dozen per sample.



Monopropellants

- Monopropellants are products that generate heat and gas by themselves… Preferably without exploding.
- The burn is achieved with either a heat source or a catalyst.
- Hydrogen peroxide on a catalyst is still used for torpedoes, but very accident-prone.
  - August 18, 2000: Soviet sub Kursk lost with 141 on board due to peroxide leak in a training torpedo.
- Some compounds are too hard to burn (hard start problem). Others gum up the plumbing or decompose in storage.

Torpedo type 65-76

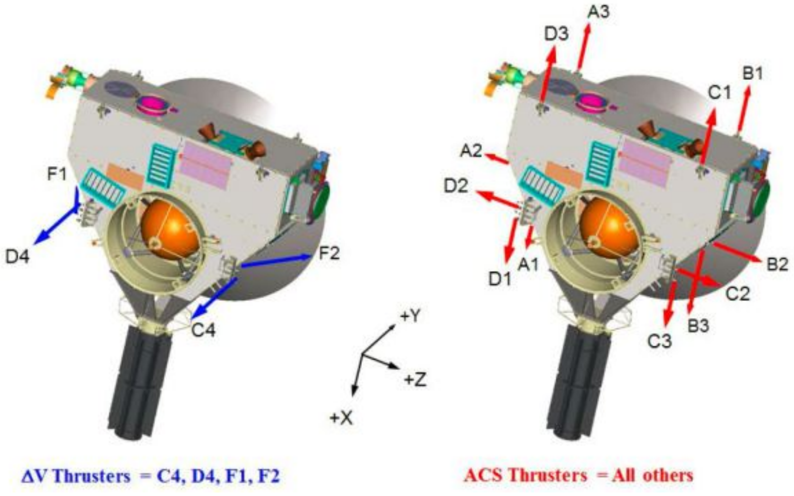
Monopropellants (cont’d)

- Some proposed compounds were staggeringly dangerous.
- A promising compound, propyl nitrate, burns nicely, passes the card-gap test at zero cards… but detonates if you close a valve too fast!
- In 1957, some chemists worked on a mix of LOX and liquid methane…
- … Which JPL showed will explode if you *shine a bright light* on it!
- Ten years later, the idea came back. Unsuccessfully, to the relief of all. Clark says it’s because engineers don’t read science papers.
- LESSON: Attend conferences and read. Otherwise, you will come up with bright new recipes for the same old disasters.

About colleague Bill Cuddy’s work: *[Perchlorate] esters were easy enough to synthesize, but […] he and his crew had never been able to fire them in a motor, since they invariably detonated before they could be poured into the propellant tank.*
John D. Clark, Ignition!, ch. 11.

Monopropellants today

- Monopropellants were also studied for very small motors used in satellites and probes.
- Clark wrote that high-energy monoprops studied in the golden space age were too dangerous.
- Only the relatively sedate hydrazine remains in use today, e.g. in space probes and satellite attitude thrusters
- The hydrazine is sprayed on a catalyst made of alumina grains coated with iridium.
- Clark foresaw the possibility.
- He noted that iridium was 40 x less abundant than gold and was mostly produced in USSR, thus making it a poor choice. But here we are.



New Horizons:

- *465 kg total mass*
- *77 kg of hydrazine*
- *Twelve 0.8-Newton thrusters*
- *Four 4.4-Newton thrusters*

[W]e propellant chemists have
worked ourselves out of a job.
The heroic age is over.
But it was great fun while it lasted.
J. D. Clark, Ignition!, conclusion.

Questions?