Project SPECTRA

Experimental evaluation of a

Liquid storable propellant

Copenhagen Suborbitals

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Revision: 1.0

Revision date: 2012-09-11

Status: Released

1.1 Document history

Date	Revision	Editor	Changes
2012-09-11	1.0	Peter Madsen	Released according to review by Thomas Petersen

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3 Preface

This document is an attempt to unveil the practical pros and cons of a specific liquid storable propellant.

It aims at identifying the problems, features and other properties of a group of propellants that has found extensive use in the professional space programs.

The matter is treated form the advanced amateur experimental view, and in the context of Copenhagen Suborbitals needs in the field of propulsion.

4 Motivation

Since the dawn of the space age the cost of access to space has been exceptionally high, compared to any other logistic operation carried on by mankind.

Lt. Col. John R. London III, of the United States Air force has conducted a comprehensive analysis of the reasons of this high cost, and what can be done about it.

The reasons, according to John London, are that current launch systems are optimized for high performance and compact design, not low cost. This is because current launch systems almost without exception are derived from the first generation of Intercontinental ballistic Missiles, and the design guidelines used in these military systems, are still largely used in most space rockets of the modern age.

John London´s theory is, that if rockets were designed for low cost, specifically with crude, pressure feed, liquid propellant propulsion systems, the cost of space access could be brought down dramatically.

His ideas are not new. In the 1960ties Robert Truax, of the US Navy came up with similar concepts, but in the race to the moon with the Soviets, few considered high cost an issue.

Nobody has ever tested this theory with a full scale practical experiment. The closest we can get to a test is ironically the Soviet / Russian designs for space launch vehicles – that are relatively crude, by western standards, and are among the cheapest and most reliable in the world today.

However – a “clean low cost big dumb booster design” has never been tested. To do so is a major goal for Copenhagen Suborbitals.

5 Liquid propellants

Liquid propellant rocket engines is by far the most common type of rocket used in the worlds space programs today.

Hundreds of exotic combinations of fuels and oxidizers can be imagined and many have been tested. However, remarkably few combinations are used at large scale. Roughly there are three types of liquid propellants in large scale use:

Earth storable hypergolic: Typically N204 / hydrazine deviates.

Mild cryogenic: Typically LOX / RP-1

Deep Cryogenic high energy: Typically: LOX / LH2

When these technologies must be adapted to Copenhagen Suborbitals use, typically propellants that comes at high cost, and low availability are the first to be ruled out. Next, ease of engine design is favored over high performance. Finally, the special condition that off-shore launch gives us is applied. This adds special extra layers of demands such as sea water solubility and associated environmental issues.

CS has made extensive testing of LOX / alcohol / water propellants. This combination is as old as liquid propellant rocketry itself and for good reasons. The alcohol fuels can be mixed with water to reduce the thermal load on the engines, simplifying engine design to the level where combustion chambers may be build form mild steel. The combination is non-toxic, but mildly cryogenic.

In theory, the -183 C cold LOX might not seem that difficult to deal with, however it puts some demands on the practical rocket mechanic:

Typically we must bye and transport 200 % of the nominal propellant load in extra LOX to make up for evaporation losses, and to be able to top op in the event of a launch delay.

Typically the exact amount of LOX onboard, or used during a burn, is not known with any high accuracy. This affects ISP measurements, and accurate synchronizing the fuel and oxidizer depletion times.

Typically helium is the only practical pressurization gas.

Typically a pyrotechnic igniter is needed.

All valves that come into contact with LOX must be absolutely dry, or problems with freezing may prevent the use of the valves.

If somehow a storable, hypergolic, high density propellant combination could be identified, some of these problems could be solved, yielding a simpler, safer, propulsion system.

5.1 Example

During the Apollo moon program, all three types of liquid propellants found use in different parts of the Saturn V / Apollo CSM stack.

All of the engines in the Saturn booster could fail with survivable outcome – but the engines needed for the flight in deep space, and for the actual lunar descent and ascent had to work perfectly.

Unlike the complex J2´s and F1´s of the booster, the CSM and LM engines had no pumps, and very few moving parts. They needed to be fired in some cases several times during a lunar mission. Failure to deliver the needed delta V, would in almost all cases result in mission failure and the loss of the crew.

So, the Apollo engineers looked into the use of simple pressure feed, storable engines with hypergolic ignition.

Such a system can indeed be very simple, and extremely reliable.

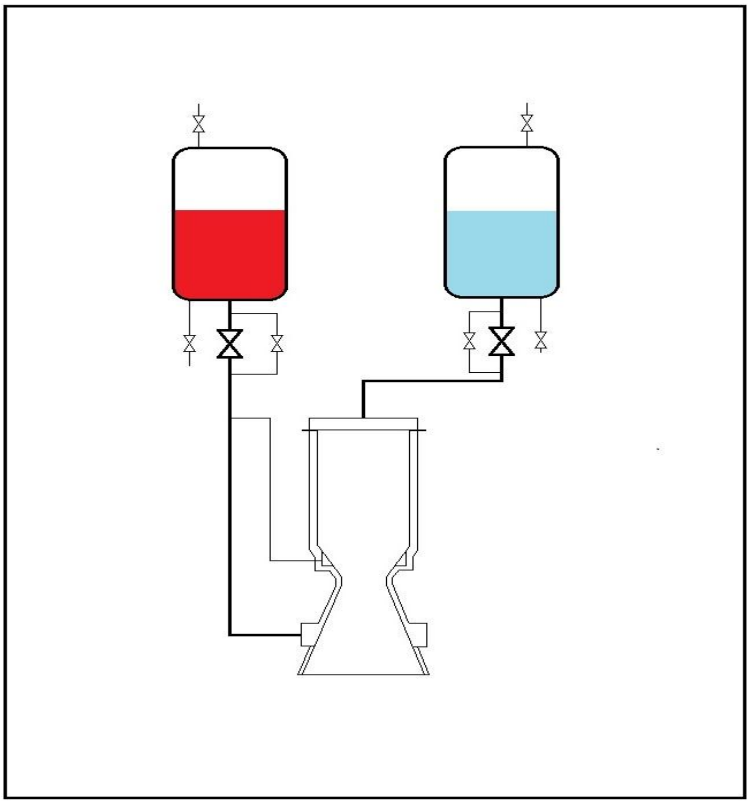
During the entre Apollo program the CSM / LM engines worked perfectly, even when asked to do things they were never designed for.

6 System design

Like in the case of the CSM / LM engines very simple systems are possible.

Since the suborbital mission profile allows decay of thrust during the burn, a pressure blow down system is used. In such a system the pressurization gas is stored at flight pressure inside the same tank as the propellant.

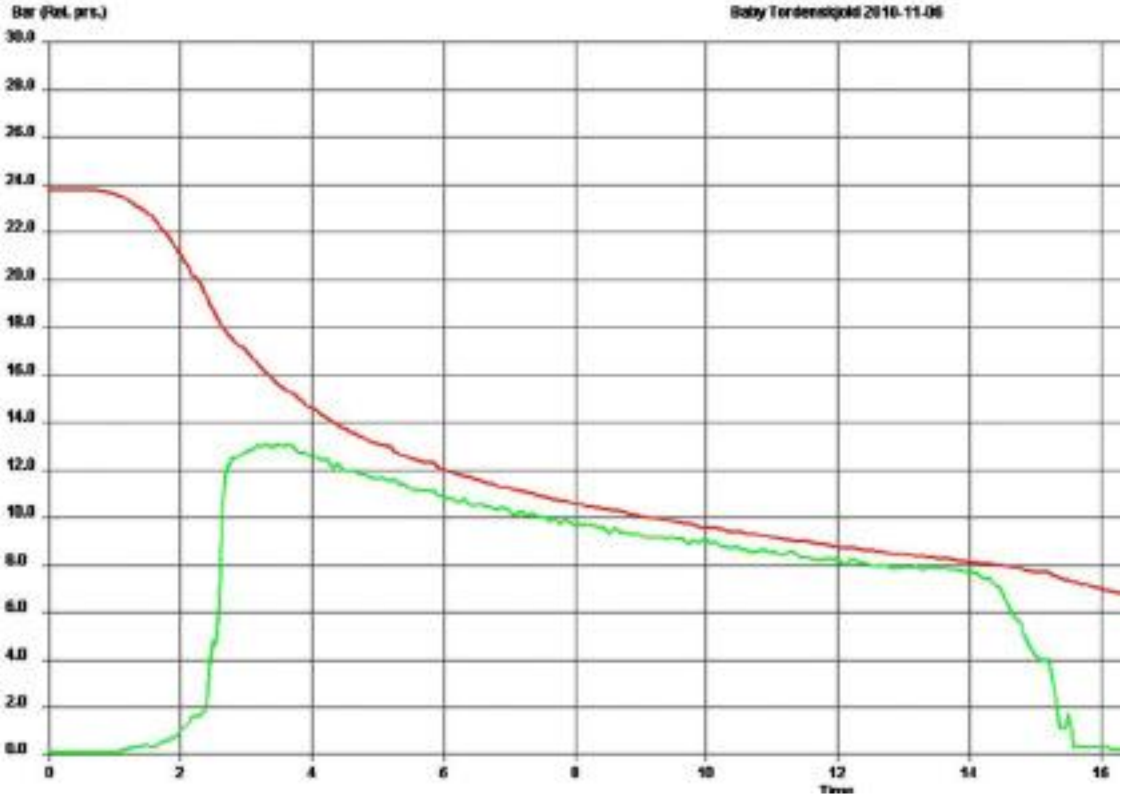
This is the simplest possible system, and the one with the fewest moving parts. Surprisingly it is also the system that typically offers the best mass ratio.



During the expansion of the gas in the propellant tanks, the pressure gradually drops. This in not necessarily a drawback, as the vehicle mass also drops, causing the acceleration at burnout to stay at moderate levels.

During 2010 the XLR-3B test engine used such a pressure blow down system.

The figure below shows the pressure time history in one of the tests.



The red line is the propellant feed pressure, the green the chamber pressure.

As it can be seen the engine starts out at just above 12 bars, this was the engine design pressure – and burns out at about 65% thrust after 12 seconds.

The two storable propellants are stored under nitrogen pressure in their tanks. It is fairly simple to make the pressurization process remotely operated, but in theory its pressure vessels like any other, with all the normal demands it puts on design and non- destructive testing.

The propellants can be carefully measured and loaded at exactly the proportions that the injector demands. The propellants can be stored for periods that may be years, but in space mission the positive effect of storability is most felt by going from hours, to days and weeks. For storability measured in years special measures must be taken that the propellant not corrodes the rocket tanks beyond certain limits.

The tanks can be filled to any level from about 65 % and downward, meaning that if a short burn is required, the tanks may simply be filled less.

This is a very practical option for CS, as some tests does not need at full duration burn.

Ignition happens on contact of the two fluids, so no ignition system is needed. This also allows multiple firings of a given engine during a given mission.

The pilot valves seen in the diagram are inserted to prevent hard starts that may damage the engine.

The pilot valves are opened a few seconds prior to full ignition, to allow the hypergolic reaction to happen at low propellant flows – typically in the order of 25 % nominal flow.

This corresponds to the same system used with the LOX / Ethyl alcohol engines, but the ignition system and the ignition system detection can be omitted.

The pilot valves are only needed if the valves are operated with pneumatic actuators. If an electric linear actuator is used, and the valves are properly designed they can be omitted. Slow opening, and gradual thrust build up is putting the least strain on the engine.

7 Propellants

There are a number of storable chemicals that can serve in this type of propellants. The most widely used is of the N204 / hydrazine deviate type. These have excellent performance, comparable to LOX / RP-1 and instant reliable hypergolic ignition. The practical handling of N204, and the cost and availability of this material is however prohibitive for it to be used in a “big dump booster” – and the hydrazine is far worse.

H202 at high concentrations can do the same, with a catalyst providing the hypergolic effect. E.g. the British Black Arrow satellite launcher was using RP-1 and H202 in a simple pressure feed design. This launched Britain’s first, and last, satellite. However, again, the cost and most important availability of H202 is prohibitive. The safe handling is difficult due the unstable nature of this material.

That leaves us with combinations of concentrated nitric acid and furfural alcohol.

We will take this propellant combination under investigation.

7.1 Properties of Nitric acid and Furfuryl alcohol

Concentrated nitric acid or WFNA is a clear to light yellow, fuming liquid. In concentrations from 97 – 99 % it has a density

of 1.510 kg / m3. It is highly corrosive, and can only be stored in glass containers. For short periods however stainless steel like AISI 304 and pure 1000 series aluminum can be used.Tyically this allows storage for months. For shorter periods, such a days or weeks aluminum alloys like AlMg3 may be satisfying. Small amounts of HF tend to inhibit the corrosion, but introduce HF to the exhaust gasses.

WFNA is available via distillation from 62 % commercial grade nitric acid. No practical other small scale source has been identified. However the process is manageable and has been managed by amateurs in this country on a fairly large scale.

If heated, if exposed to air, if quickly diluted and in the contact with metals and organic matter WFNA may decompose. It is not an exothermal process, so it does not explode or decompose into hot gasses. However the byproducts of the breakdown – NO and NO2 and HNO3 fumes are highly toxic gases.

The maximum acceptable limit in breathing air is 5 ppm.

The danger is further increased because some very dangerous symptoms are delayed by as much as 24 hours. Extensive care must be taken to prevent any exposure of personnel to propellant fumes. The fumes are very clearly seen. It has a powerful odor, so detecting the fumes is not difficult. Protection may be a filter mask, PVC rubber gloves and a protective suit. This is only needed if in contact with the material. All personnel not directly involved with oxidizer handling can stay at distances where it is uncritical.

All oxidizers have problems, some more visible than others. WFNA looks nasty and will be treated respectful. Other oxidizers may seem benign, while being high explosive and shock sensitive in contact with fuels.

Furfuryl alcohol is a slightly viscos liquid. Furfuryl alcohol is mildly toxic, comparable to most other alcohols. It has a very high density at 1.130 kg/m3. The liquid reacts violently with most strong acids, and with nitric acid it is reliably hypergolic at acid concentrations of about 97 – 98 %. Open cup ignition happens at 15 – 20 msec, even faster than hydrazine fuels, and fast enough to be useful in combination with a staged or slowed valve open ignition. The material is hypergolic at up to 15 % water in the acid. Ultra dry acid, at concentration above 99 % is less hypergolic.

The high density, some 50 % higher than LOX / ethanol, allows for excellent mass ratio. The ISP is slightly less than LOX / ethanol, but this is largely compensated by the larger amount of propellant that can be loaded.

The cost of WFNA is a combination of raw material costs and the work that goes into the refining. However, it is slightly more expensive than LOX, but one kg WFNA is one kg WFNA, while one kg LOX rapidly becomes 0.5 kg LOX.

Nitric acid is a dangerous chemical in all concentrations. At rocket grade concentrations, protective gloves, breathing protection and eye protection are needed. In designing WFNA systems, it is always to be preferred to handle the propellant inside tubes and flexible hoses – exposing personnel to directly handle it, is not recommended if a closed system is possible. In the case of LOX, eye protection, clean suits and special gloves is normally needed. However, today at CS, we handle this inside closed lines and metal hoses – giving a large improvement in personnel safety.

The same is highly recommended with WFNA. In short, if you can visually see it, something is wrong with the procedure.

8 Engine design

A number of amateur rocketry projects have made reliable rocket engines with the combination. Most have used ablative or even uncooled combustion chambers.

At CS we need engines to run for extended periods up to, and above 100 sec, and for this use, simple combustion chambers with no, or only ablative cooling becomes unacceptably heavy.

However, a pressure feed rocket engine will typically operate at very low pressures – below 20 Mpa. In this region, and with relatively cold burning propellants, it is not very hard to make a true regenerative cooled engine work.

The LOX Ethyl alcohol engine TM65 was using regenerative cooling system, and its performance during the first burn can be seen on Steen Andersen's measurements:

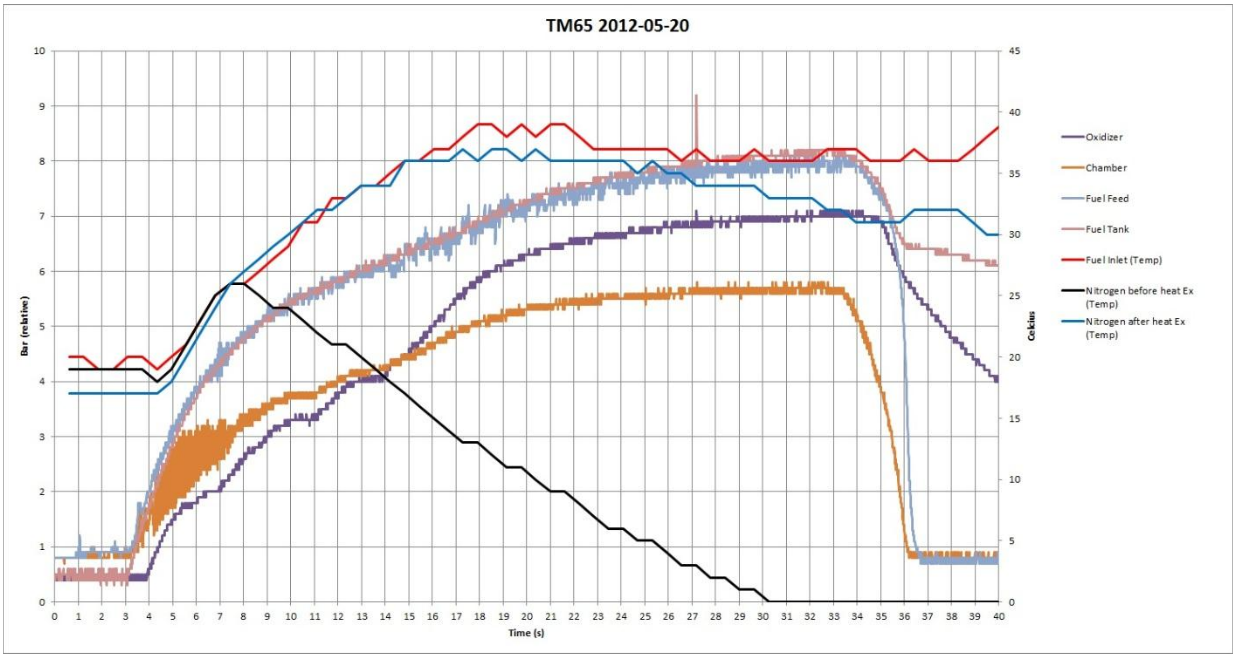
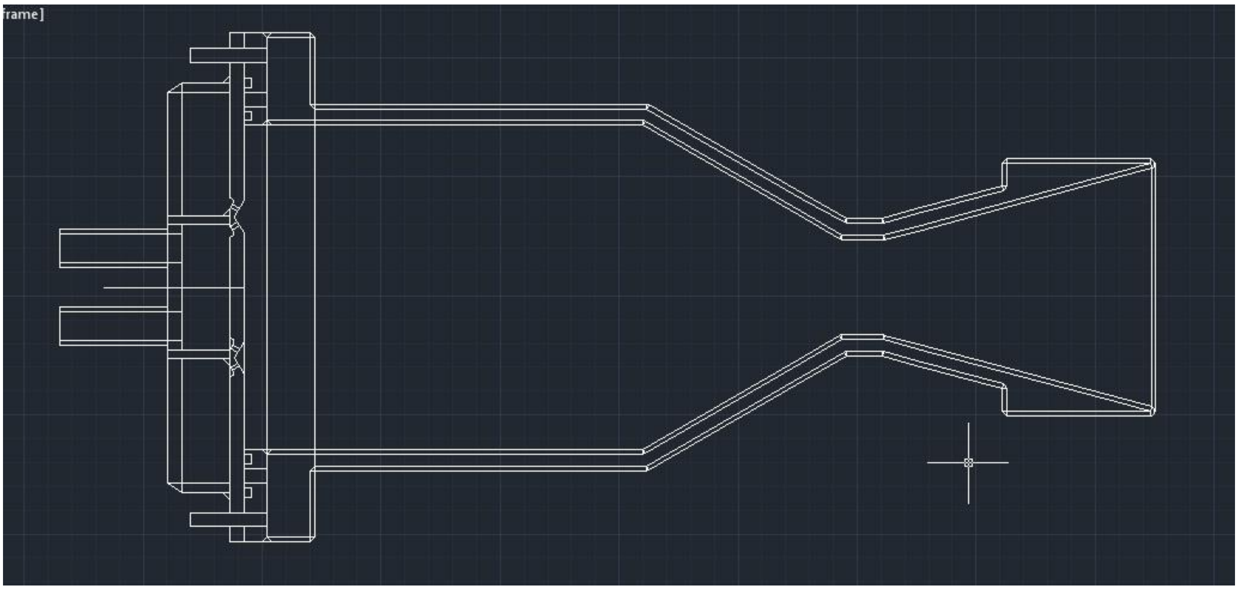
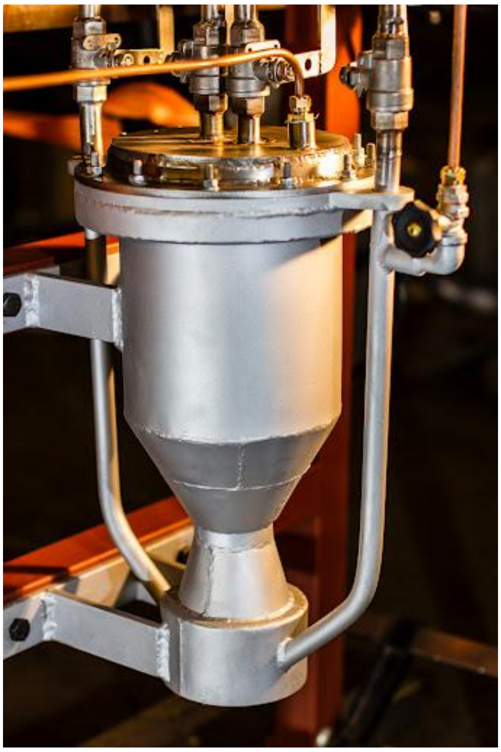


Figure 1 Measurements on TM65. As it can be seen the temperature on the skin of the engine drops slightly after reaching main stage at T + 10 sec. The blue and red lines are surface temperatures.

For use as an experimental test article the SPECTRE rocket engine has been designed. It is a small, simplified version of the TM65. At a rated pressure of 1.2 Mpa, its thrust is 1.8 kN, at an expected ISP of 180 sec.





Engine Data:

Sea level trust at 1.2 Mpa:	1.8 kN
Mass flow of propellants:	1.0 kg/sec
Mass flow of WFNA:	0.72 kg/sec
Mass flow of Furfuryl alcohol:	0.28 kg/sec
Nozzle throat area At:	12.56 cm2
Nozzle exit area Ae:	78.00 cm2
Nozzle expansion ratio:	6.20
Combustion chamber volume:	2400 cm3
Specific length:	200 cm

Some of the above data is based on decisions that may change as we get into testing. However the choice of 200 cm specific length reflects our belief in imperfect mixing that requires extended stay time to complete combustion. The decision to use an expansion ratio of 6.2 reflects the interest in observing just how long the nozzle may be without experiencing flow separation. For high altitude operation, combined with sea level liftoff we are interested in making the nozzle as long as possible. With the high expansion nozzle the vacuum specific impulse exceeds 250 sec. The nozzle expansion ratio is a compromise, since the engine must be able to work in a number of different ambient pressures.

ISP is not a function of chamber pressure, but of the pressure difference across the nozzle. Therefore the ISP penalty of choosing low chamber pressure is only felt at low altitude, in the high atmosphere and space, chamber pressure only dictates the engines output, not its ISP. However – the nozzle must be short enough not to separate at sea level, and long enough to make use of low ambient pressure in the later part of the burn.

8.1 Injector design

The challenge in the design of the injector is that the SPECTRA system, with its pressure blow down system will never operate in

Complete steady state conditions. During operation the feed pressure steadily drops, and especially when the tanks are filled to capacity – 65 % during such burn the feed pressure close to MECO will be some 25 % of the initial feed pressure.

To maintain stable combustion over such a wide range of feed pressure the initial injector pressure drop must be fairly high.

Spectra is designed so that a chamber pressure of1.2 Mpa is defined as 100 %, but initially it will operate above this, at the end of the burn well below. 100 % or 1,2 bars is called the engine nominal operating pressure.

A design injector pressure drop of **0.**45 Mpa is chosen. This is fairly high, but must be so, because of the pressure blow down system.

Tank initial pressure is therefore 2.0 Mpa.

Using G. P. Sutton, Rocket propulsion elements we can calculate the injector total area:

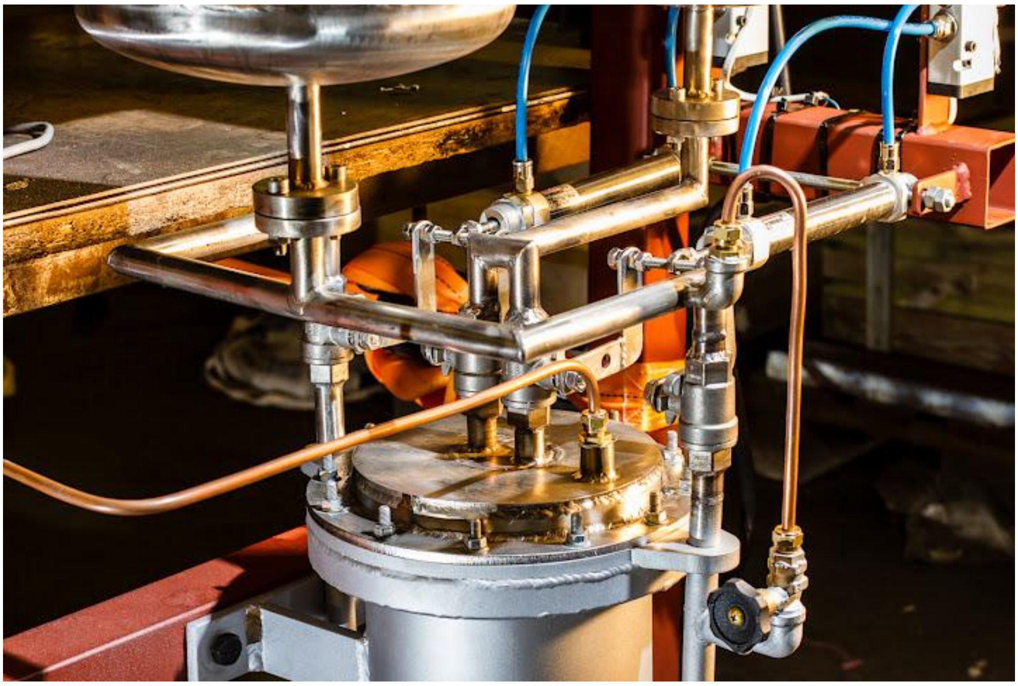
The input is:

Oxidizer density	1.51
Expected discharge coefficient:	0.8
Design pressure drop:	0.45 Mpa
Design mass flow:	0.72 kg/sec
Fuel density	1.12
Expected discharge coefficient:	0.8
Design pressure drop:	0.45
Design mass flow:	0.28 kg/sec.

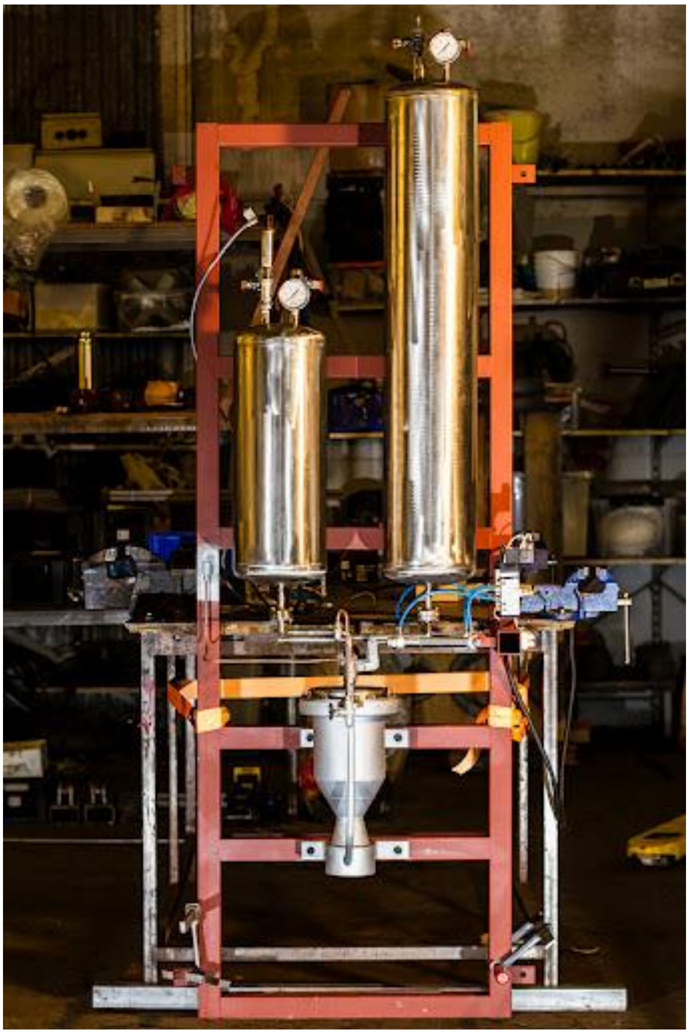
These inputs give the following results:

Oxidizer injector area:	24,3 mm2
Fuel injector area:	9,4 mm2

One must remember that this is the product of a very crude mathematical modeling of at complex flow. SPECTRA was specifically designed to allow for simple flow calculations. This was done by making the propellant feed pipes and cooling passages with 5 – 10 times larger area than the injector orifices. This means that almost the entire feed system pressure drop occurs in the injector orifices, thus making an engine that is very close to the crude mathematical model used.



In reality eight oxidizer holes was drilled with a diameter of 2.3 mm. In the fuel system eight 1.6 mm holes was drilled. This makes up eight pairs of like on unlike impingement pairs. They form a single ring on the face of the injector with a diameter of 55 mm. The impingement angle is symmetrical, both fuel and oxidizer holes are drilled with a 60 degree angle to the injector plane. The oxidizer flow has a larger inertia because of the larger mass flow. Thus, the spray pattern inside the combustion chamber will be a diffuse cone that opens up towards the nozzle end of the chamber.



The complete feed system was subjected to water flow tests. This was done by filling the tanks 1/3 with water, and the remaining 2/3 with hp air at 0.6 Mpa. The simulated propellants were subjected to the engine, and the time from valve open to propellant depletion was measured. Also the change in feed pressure during the blow down was measured. The process was done for both fuel and oxidizer side of the system.

During the blow down, tank pressure dropped from 0.6 Mpa to 0.365 Mpa, and the average pressure was used. This is again crude, but since it is done in the same way in both tanks, and since it is the relative flows in both tanks we try to control, less than the absolute flow, it was found adequate.

The two tanks followed an expansion curve that was very similar to each other. It took 17.96 seconds to deplete the five liters of water from the fuel system, and 16.97 seconds to deplete the ten liters from the oxidizer side.

Using Sutton we can calculate that this would mean the fuel side behaves as if it had an area of 11.1 mm2, and the oxidizer side as if it had an area of 23.6 mm2.

The actual areas is 16.08 mm2 and 33,23 mm2. This simply indicates that the discharge coefficient is closer to 0.6 than 0.8, and that there is some pressure drop in the feed lines and cooling passages. This all fits what we already know, and must expect.

Due to the toxic and corrosive properties of the real propellants, the tests is performed with water as simulated propellant.

When re-computing for actual propellants, again using Sutton, the actual system, with its actual pressure drops ought to behave like this:

A flow of 0.72 kg/sec of WFNA is to be expected at a pressure drop of 0.47 Mpa in the oxidizer feed system.

A flow of 0.28 kg/sec of Furfuryl alcohol is to be expected at a pressure drop of 0.44 Mpa in the fuel feed system.

This is close to the desired pressure drop of 0.45 Mpa. This is so close to desired values that the combined inaccuracy of pressure measuring, depletion timing and measuring of fuel volume makes it unlikely to be worth improving.

The water flow test tells us that if the ISP of the engine is 180 sec @ 1,2 Mpa chamber pressure, the engine will operate at this pressure when the feed pressure is 1.67 Mpa.

The SPECTRA engine is not very different from the Pacific Rocket Society design for a simple WFNA / Furfuryl alcohol engine. Its ISP was 176 sec, and it produced it with a much lower specific length and an even more crude injector, with only four pairs. This engine operated at 1.3 Mpa initially with pressure decaying as it fired. Burnout would happen at 0.4 Mpa, but at elevated altitude.

The 180 sec ISP value at 1.2 Mpa, is quite a likely result.

Because of the non- steady state conditions we will start at a feed pressure of 2.0 Mpa, or 120 % of the engines nominal feed pressure. Then, as we travel down the expansion curve of feed pressures it will pass 100 % output and below. In a full burn with 65 % loaded tanks, it is likely that we are at 45 % – 65 % power at burnout.

With less propellant loaded the change will be less.

8.2 Cooling system

The cooling systems purpose is to deplete the combustion heat absorbed by the engine. The highest heat loads exist just upstream from the nozzle throat.

The cooling is done by taking the fuel into the engine at the nozzle and pass it around the combustion chamber in an helix. The helix is made by welding a 5 mm solid rod of steel around the engine. The desired flow speed for this engine is in the order of 5 m/sek, with a 7 m/s peak just at and above the nozzle. The fuel flow is 280 gr/sec, and the volume flow is therefore 250 cm3 pr sec. The distance between the inner and outer chamber wall is 5 mm, so in the areas where 5 m/sek is required each turn of the helix will be 10 mm apart. In zones where higher flow speed is desired the distance must be less.

8.3 Thermal expansion joints

During operation the Inner wall becomes significantly hotter than the outer wall. The thermal expansion of the inside chamber wall would generate high compression stresses in this structure if not compensated for. The upper part of the fuel inlet ring, just above the cylindrical portion of the nozzle acts as an expansion joint. So does the even bigger similar plate on the lower side of the injector flange. The movements are measured in small fractions of a millimeter, but the inside wall might bend of crack during multiple heat cycles. Such cracks were found in the XLR-3B test article rocket engine.

8.4 Tank system

The Spectra system has two tanks made from 204 x 2 mm stainless steel tube. This tube can handle test pressure up to 5.0 Mpa, if cycled during first pressurization. During the hydrostatic test cycle, the metal is hardened, and AISI 304 has excellent properties in this respect. However, for this use, hydrostatic test can end at 3.0 Mpa, requiring no pressure cycling.

The tank domes are welded to the tanks using TIG welding, and with the use of inert gas filling of the tank to provide a clean, corrosion resistant inside surface. Maximum operating pressure is 2.0 Mpa.

Each tank has very few connections.

There is a filling connection, a pressurization connection and the connection to the engine. Finally there is a small connection on each tank for the placement of a pressure gauge.

8.5 Main propellant valves

The main propellant valves are of the ball type design. As this system uses non cryogenic propellants ordinary single piece stainless valves can be used. All connections in the system is welded, to out rule the possibility of leaks via bad seals.

There are four propellant valves. The one set of fuel and oxidizer valves are used for starting the engine, and the second two valves are used for main stage operation.

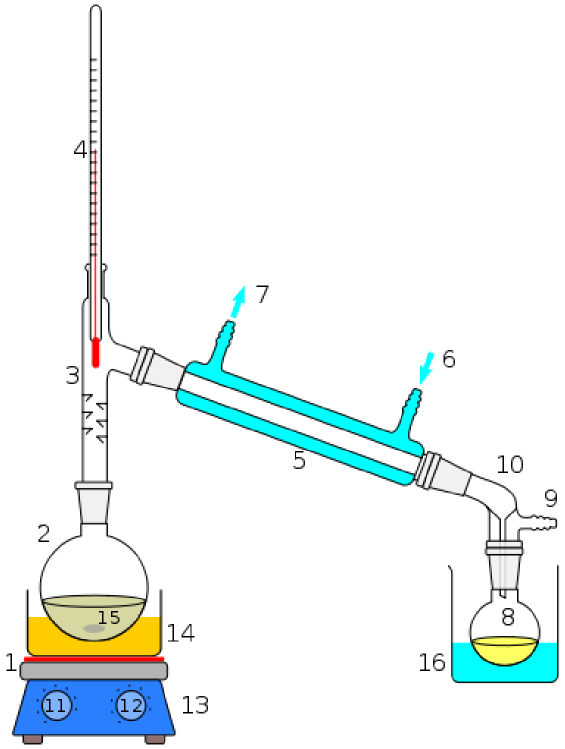
The starter valves has a orifice equal to 1/8 the injector area, and will be opened to allow hypergolic ignition at low flow. The two others are unrestricted. The tubes feeding the valves are 12 mm inner diameter giving a fuel flow speed of 2.5 m/sec, and an oxidizer flow speed of 5 m/sec. This yields all in all very low pressure drop. The injector holes on comparison, gives a flow speed of 30 m/sec. This means the total pressure drop will almost only be in the injector.

8.6 Propellant supply and refining

Furfural alcohol is commercially available at low cost. In our case it is purchased in 240 kg drums at a cost of 3300 eur / ton.

Nitric acid is commercially available in 62 % concentration. The cost is of this is 1000 eur pr. ton.

In order to be used as a rocket propellant it must be concentrated to 98 %. This is done in a distillation process.



As water and nitric acid distills at a constant concentration of 68 % concentration, the distillation process uses sulfuric acid as a drying agent. This means the distillation process starts by mixing 1:1 volume nitric acid 62 % with sulfuric acid 96 %. The mixture is heated and at 86 degrees C, the WFNA comes out as steam. It is condensed into WFNA liquid in a water cooled condenser. The sulfuric acid can be reused after heating till all water is removed too. The cost of the finish WFNA ends up at 2000 Eur pr. ton.

The laboratory scale plant shown above can do this, in principle, however, we use an semi industrial pilot plant with a production capacity of 10 liters pr. hour.

In the case of very large amounts are needed it may be possible to purchase the 98 % acid directly. However, it is a bulk chemical, shipped only in very large amounts, and used almost exclusively in the production of explosives. This makes is fairly difficult to obtain. However low concentration nitric acid is available for metal treatment and cleaning – and is a commodity in most industrialized countries. No other storable liquid hypergolic oxidizer is commercially available.

Like in the case of LOX an entire infrastructure is needed to accommodate a propellant. The final part of the WFNA infrastructure is the storage tanks. The storage tank for use with Spectra is one 25 liter tank made form 99.5 % aluminum, with a thickness of 4 mm. It is equipped with a connection for at flexible stainless hose, and valves for slight pressurization to 0.3 Mpa.

The tank hangs on a balance during the loading process, and the oxidizer is loaded in a completely sealed system with no exposure to the personnel. Basically all the personnel ever sees is some hoses, tanks and valves that are operated to make the balance tell them that they have loaded the required amount of oxidizer. This is not some high tech thing – just the natural continuation of LOX processing. The air that must be removed from the tank is passed via a filter to prevent any exposure.

At all times large amounts of water is available for quick and simple removal of any spill. Water is the simplest and only measure against WFNA exposure or skin contact. The personnel where protective garment, gloves and has filter masks. However – exposure is not a normal part of the loading process.

9 Going operational

The hope of the Spectra experiment is to evaluate the practical properties of a storable, high density, hypergolic propellant.

WFNA / Furfuryl alcohol is as hypergolic as N204/UDMH, and has a similar density. The ISP is 10 – 15 % lower. However, at a slight cost in ISP, it is far less toxic, and far cheaper. This is the reason for taking it through a comprehensive practical evaluation. It compares in scope and concept to the twelve XLR3B tests done with LOX /ethanol during autumn 2010.

9.1 Procedures for the static test

As we move SPECTRA from the laboratory and into the battlefield of the test stand many questions arise.

The following section will attempt to outline the procedures for static testing of this engine.

The operation of an experimental liquid propellant engine is a potentially very hazardous process. Every step of the preparations, checkout, fueling, firing, and post burn operations must be very carefully planned. The purpose of this is the safety of the test conductors. However, it also serves to establish the operational rules for the engines future use in a launch vehicle.

When writing the procedures, it is important to remember that it is only the sequence of pre firing events that can be manipulated – such as deciding if fuel or oxidizer is loaded first. Somewhere along the way the engine will be fully loaded, pressurized, and ready. As a result – it is also very dangerous in the event of accidental firing.

From the start, the SPECTRA engine and feed system is designed for maximum safety. The tanks, valves, propellant feed lines and

Combustion chamber have been hydrostatic tested to and above 1.5 times flight pressures.

The primary safety system is a mechanical arming pin, that blocks all propellant valve operation when inserted. Second, the valves are designed to close in the event of electrical failure. Thirdly, it is possible to block engine operation but removing the HP air the opens the valves.

9.2 Static test procedure for SPECTRA

9.2.1 Pre burn checkout

The system is mounted on the test stand, and the umbilical lines for HP air is connected. The control cable is connected to the control box. Pressure transducers for fuel, oxidizer, and chamber pressure is connected and checked out for function.

A low HP air pressure is submitted to the empty tanks. 0.6 Mpa is recommended. A simulated firing is performed. Valve functions are verified.

The control cable is disconnected, and the plug is removed from the command post. It is guarded during the following procedures.

The valves are closed with HP air force, and the arming safety pen is inserted. To have positive closing force on the valves, HP operating pressure is maintained during the fueling.

The desired amount of fuel is submitted to the fuel tank. To allow for the filling (priming) of the cooling system of the engine 0.65 kg extra Furfuryl alcohol is submitted to the fuel tank.

A low nitrogen pressure of 0.3 Mpa is submitted to the fuel tank. The engine is primed, by opening the primer valve until drops of fuel are observed below the nozzle. After engine priming the HP nitrogen is blow out and the valve closed.

The oxidizer loading personnel donnes suits, boots, protective goggles and rubber gloves. A hose with fresh water is ready or flowing. Filter masks are ready, but not donned unless needed. The system is closed, so under normal conditions no oxidizer fumes is present. Donning masks puts considerable stress on the personnel, and it is used only when the personnel is close to sources of fumes.

The desired amount of oxidizer is loaded into the oxidizer tank. The loading takes place by submitting a low HP nitrogen pressure to the storage tank, and connecting it to the oxidizer loading valve. During the oxidizer loading the storage tank is hanging form a load cell, and the amount of loaded oxidizer can be measured from the mass loss of the storage tank. The air trapped inside the oxidizer tank will escape at the oxidizer loading valve. This air will contain fumes of oxidizer, and must be avoided by the loading personnel. It is high above the test stand, and no personnel are needed in the vicinity.

When oxidizer loading is complete, the oxidizer loading hose is removed and the oxidizer loading valve is closed.

This completes propellant loading. With the arming pen inserted, and HP air force closing the propellant valves the system is safe.

9.2.2 Final procedure and engine firing

Both fuel and oxidizer tanks have each one a pressurization hose. These connects the nitrogen high pressure reduction valve to the pressurization valves on the tanks. The HP nitrogen storage tanks is placed on the back side of the concrete wall of the test stand. From here, the pressurization of the tanks is controlled.

First, the fuel tank is pressed up to 2.0 Mpa flight pressure. Then the pressurization valve on the tank is closed, and the hose disconnected. For static test purposes the hose may remain connected. With the fuel at flight pressure a last visual check for leaks at the engine is done.

The tanks are hydrostatic tested to 1.5 times or more (in this case 1.9 times) the pressure submitted to them. Therefore the pressurized propellant tanks are no more dangerous, and no less dangerous than any other pressure vessel. Comparing a pressurized WFNA tank to a pressurized water boiler is quite accurate. In both cases, rupture of the vessel will result in severe burns and injury to bystanders. However this does not mean that steam locomotives are only operated by remote control. It simply means steam locomotives and pressurized propellant tanks must be operated by trained personnel, following careful procedures only.

Oxidizer pressurization is done. Again this tank is brought up to 2.0 Mpa. The oxidizer pressurization valve is closed. The pressurization umbilical hose may, or may not be removed. A final visual check for leaks can be performed.

The safety arming pen may now be removed. It can be done at a distance using a lanyard, and it is important to remember that the system is designed so the arming, that is removing the safety pen is impossible if one of the valve sets were in a condition where it would open.

With the arming pen removed, and the test stand cleared the control box can be checked. It must be in position “off” Then the control cable can be connected.

The engine is now armed, and ready for ignition. At this point it is important to remember that the main feature of the family of propellants is storability. The test conducted may now spend whatever time needed to verify everything is ready or solve whatever problem that might be with range safety or cameras.

Engine ignition. The ignition occurs when the control box lever is moved from position off, past position armed, and to position “pre-stage” in this condition the engine will ignite and fire at 10 % propellant flow. When visible flame is observed, the engine can be brought up to 100 % power and above, by moving the control box lever to its extreme position.

It is always preferred to allow the system to self-deplete all loaded propellant. The feature of this is that when the propellant is depleted, all pipes, valves cooling passages and the injector is blown clean of propellant with the stream of HP nitrogen.

9.2.3 Post burn procedure

With the engine empty of propellants and burned out the post burn procedure starts. First, the test personnel saves their data. The tanks will depressurize and be clean form propellant residue.

The propellant loading crew will return to test stand. If any fumes is observed the mask will be donned. The area below the engine and the engine itself is hosed down with the fresh water hose.

The propellant valves are closed and the control cable disconnected. The plug is removed from the command post.

The propellant tanks loading valves can be reopened, and propellant loading procedures may be repeatet for a second burn.

If not the fuel tank must be flooded with water, and and oxidizer flooded with water. Note that when in contact with water WFNA may decompose and release fumes. More water solves this. When both tanks are filled with water, they can be emptied via the injector.

In all propellant handling fresh water is the key to disarming the dangers of the propellants. When thinned out to the thousands the propellants become benign, and will no longer be dangerous. In the event of skin contact again water is the sole means of first aid.

10 Static test

On September 9th 2012 the Spectra was taken through its first static test.

Much of the motivation for the Spectra was to gain practical experience in the handling of WFNA compared to LOX. To make handling safe, the loading of propellants carefully planned and the necessary equipment produced.

The fuel component was we loaded manually using a funnel and a can. This material is very benign compared to the oxidizer. The crew wore protective garments and rubber gloves for the process.

3.6 kg was loaded in a few minutes. This tank was then closed, and pressurized to 11 bars. The primer valve was opened and 0.6 kg of the fuel was allowed to fill the engines cooling system. The full condition was detected by the fuel dripping out of the nozzle. After this the fuel tank was taken up to 20.4 bars, and sealed. The pressurization umbilical was removed.

The WFNA oxidizer component was transferred form the aluminum storage tank via flexible hose and under 0.5 bar nitrogen pressure. In this manner the process could be completely contained, and all the crew needed to do was to connect the hoses, and operate the valves. The amount loaded was monitored by hanging the storage tank in a load cell. In all 7.3 kg was loaded.

Figure 2 Propellant is loaded. Note storage tank under load cell. Photo: CS

After oxidizer loading this tank was taken op to 20.2 bars, and sealed. With the engine ready for ignition, the test stand high speed camera´s was turned on, and the crew left the test stand for the bunker.

The last man to leave Spectra removed the arming pin, and retreated to the bunker.

The countdown started at T-60 sec. At T-4 sec, the pre-stage knob was activated. A cloud of reddish brown smoke puffed out of the nozzle, but no ignition. The test conductor expected ignition at less than 100 msec delay, so he turned it off for about a second. Then a new opening was done, and this time fire was seen and the main stage knob was turned. The engine throttled up and reached main stage in less than 0.2 sec.

During main stage there was no reddish smoke generated and to all we know the engine operated the way it was supposed to do.

The chamber pressure stated out at 13 bars and dropped to 11 bars during the burn.

After 7.5 seconds high speed cameras detected an anomaly in the exhaust. Iron sparks was ejected. At TBD seconds into the burn, the inner chamber wall failed just above the nozzle throat, and a hole of about 80 mm2 was burned in very short time. This area is very large compared to the 9 mm injector area. As a result, the fuel flow increased to more than ten times nominal, and the fuel was depleted in in about one second. As the fuel is not burned inside the chamber but outside, it does not contribute to the chamber pressure. It therefore decayed very rapidly to almost zero. The WFNA continued flowing at close nominal rates, and decomposed on contact with the hot concrete flame deflector.

Figure 3 The above picture is the “smoking gun” in finding out the exact cause of tests outcome.

Figure 4 N204 fumes formed from the spill of 3 kg WFNA. Photo: CS

The spill of WFNA was about 2.5 kg, but it still generated a large cloud of propellant fumes. Most of this is NO and NO2. It is not an unusual sight using this form of propellants.

Post burn the area next to the test stand was cleaned with fresh water and no damage except for the throat was detected on the engine.

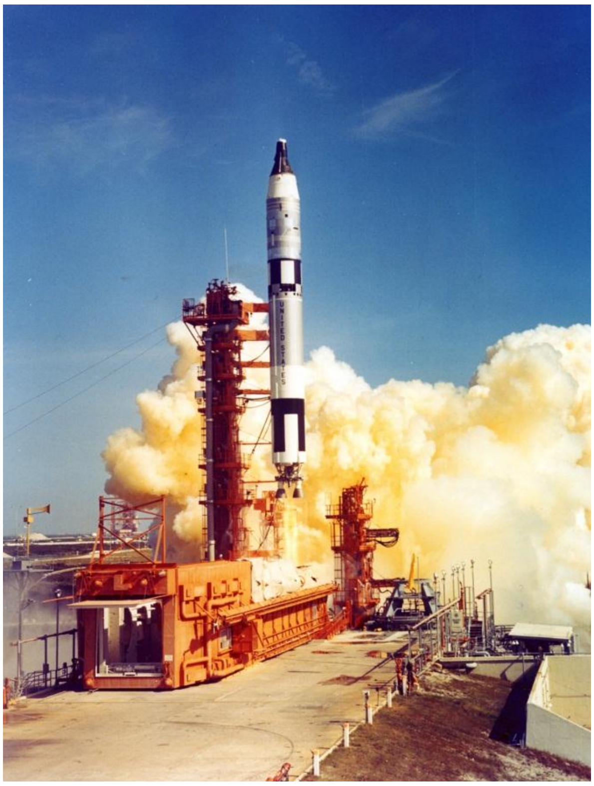
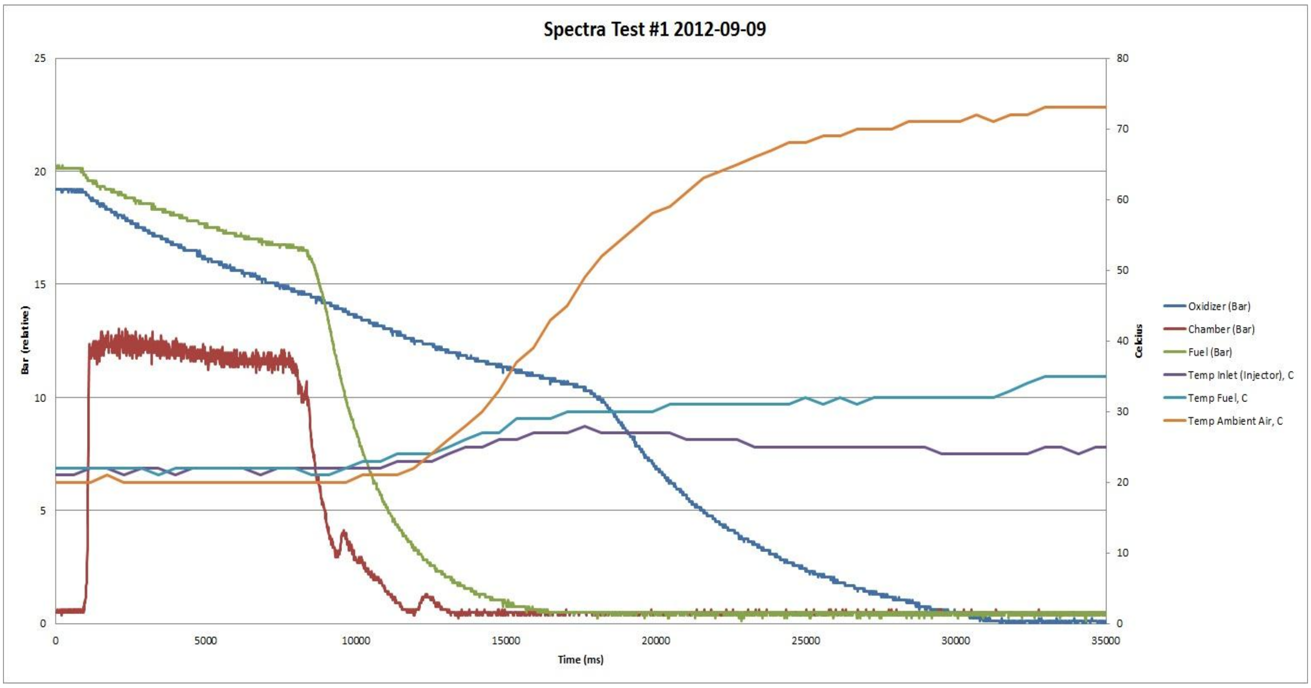


Figure 5 This 1965 Titan II launch picture tells a similar story. Photo: NASA. The color is very much the same because the composition of the cloud is very much the same.

11 Measurements

Spectra had pressure gauges in the fuel tank, in the oxidizer tank and in the combustion chamber. It also had thermal sensors on ambient air, on the fuel tank, and on the fuel manifold after the injector.

The measurements are depicted graphically below.



Because the nozzle throat failed 8 sec into the burn, some of the loaded 10.6 kg newer took part in the combustion or burned outside the chamber. This makes total calculation of the C star or ISP impossible. However we can still get an idea of how well the engine worked by looking at one point in the burn. The reason for this is that we know the injector´s hydraulic properties from the water flow tests.

At T+2.5 sec, the engine is working at its highest chamber pressure of 12.5 bars. At this pressure the Spectra will have a thrust of 1,96 kN or 196 Kp. This is assuming the Cf @ 12.5 bars is 1.25, but that is likely.

At this time the oxidizer pressure drop is 5.5 bars. This means that oxidizer flow rate is 0.77 kg sec. At the same time the fuel pressure drop is 6 bars, this means the fuel flow rate is 0.33 kg/sec

This means the engine is consuming a total of 1.1 kg/sec of propellant and generating a thrust of 196 kp at the flow rate means the ISP is: 178 sec.

This is a performance that is fairly close to what must be expected at the low combustion chamber pressure Spectra was designed for. The method is plausible if the injector has not changed at all after the water flow test. If any particle has plugged or obscured the flow the ISP will be higher, and, if anything have increased the injector area it will be less. However, while it is not completely unlikely that particles might have reduced the injector area, and increase of the area is unlikely. In this case, most likely, the injector was exactly in the same condition as during the water flow test. Therefore the ISP value is likely to be true.

If Spectra was to be fired at high altitude, where the ambient pressure was close to vacuum the nozzle would be too short to make use of the whole pressure differential. With the present nozzle the Cf would max out at 1.5 – 1.6 yielding a vacuum specific impulse of 225 sec. A longer nozzle could increase this. This corresponds to a Cstar value of 1450 m/sec.

What we can learn from this is that the combustion efficiency of Spectra was fairly high and within expected values. The engine worked as far as combustion is concerned. However, the failure of the cooling system is critical, and this must be addressed before more tests are conducted.

The cooling system failure caused the generation of the large cloud of N02 fumes, and it explains the shape of the pressure time curves of both of the propellants.

There are two cures to this. Either the cooing coil must have its distance cut down to increase the flow speed in the coil. Or, the engine most be outfitted with a film cooling system like the larger TM65. This may take the form of a curtain of injector holes near the chamber wall, or much better, at true film cooling system at the nozzle inlet. If this is added, very likely the Spectra engine can work with no damage, and with no burnout plume of NO2.

12 Conclusion

More tests are needed. Modifications to the engines cooling system are needed.

However, we have seen that the procedures during propellant loading functions very well, and that a spill of this propellant, is manageable at Spectra scale. The question that the Spectra opens after the first test is still if the benefits of hypergolic ignition, high density and earth storability offsets the danger of NO2 plume formation. The balance of this is not definitive.

For a first stage, the cumbersome handling and time critical launch procedure of LOX may be manageable. But, for a second stage or an orbit stage – the merits of storability may outweigh the problems of storable propellants.

After the Spectra test it is certainly proved that the launch pad procedures of WFNA can be clean and safe if the right equipment and procedures are in place. The problems of the Spectra test occurred after the engine shut down, and was well within the range that the crew was expecting and able to handle in a safe manner.

In future tests, the direction of the wind must be north or north-west to carry accidental plumes away from the control bunker.

The tests with Spectra ought to be continued, with the aim of providing CS with a potential high performance upper stage propulsion system. Other fuels than Furfuryl alcohol might be tested – such as turpentine that has higher ISP. Used with Furfuryl alcohol as an ignition propellant this is a good candidate for other than booster applications.