



Hybrid safety

While there is no doubt that hybrids are considerably safer than traditional solid or liquid rocket engines, there is a popular misconception that they are totally safe, and never go boom. Sadly, an ill-designed hybrid, or one that is subject to mechanical abuse, will most certainly go bang. Several have, and lives have been lost.

The following is a guide to some of the issues concerning the safe design and operation of amateur hybrids, focusing on nitrous oxide hybrids in particular.

In complement, the United Kingdom Rocketry Association's safety code (version 5, section 5.2 gives some excellent advice on hybrid usage and safety. (www.ukra.org.uk)

Needless to say, in these days when uncurbed litigation is the biggest threat to democracy and the pursuit of happiness, we have to state that the following is solely our opinion, and we accept no liability whatsoever for accidents arising from following the advice herein, nor do we assume liability due to errors contained within this paper.

Part1: oxidizer choice

As far as rocketry performance is concerned, Hydrogen peroxide or just raw oxygen give better Specific Impulse and Density Impulse (packageability) than nitrous oxide ('nitrous'), but nitrous is so much more user-friendly than these, which is why it's so popular:

First off, nitrous is not highly reactive to humans like peroxide, nor excessively cold or shock-sensitive like liquid oxygen (Lox).

Nitrous is, however, a powerful anaesthetic and is used as such by the medical profession: inhale too much and you might never wake up again.

Inhale Lox or peroxide vapour, and say goodbye to your lungs: terminal frostbite or combustion.

You can carry bottles of nitrous in the back of vans (but not in cars, there should be a barrier between driver and bottle incase of a leak as nitrous is a powerful anaesthetic; stupidly we've all done it, but keep all windows open.)

Unless you want to be flame-grilled in an accident, you'd be crazy to carry Lox or peroxide in your own vehicle; they have to be pre-delivered to a proper test-site or launch-site which adds to the cost.

Nitrous has to be raised to a moderately high temperature before it will decompose and release its oxygen. In contrast, look at Lox the wrong way, and it'll auto-ignite your test-stand and torch the tarmac underneath it because bitumen is a hybrid fuel.

Part 2: mechanical safety

Manual versus remote fill as it affects Nitrous tanks

Any container that can safely withstand the pressure without bursting will do for a nitrous tank. Stand next to a vessel pressurised full of nitrous however, and your delicate bits are right next to a potential grenade; it's the shrapnel of the exploding casing of a grenade that does the ripping through everything bit.

The United Kingdom Rocketry Association (www.ukra.org.uk) quite rightly regards standing anywhere near a cylinder under pressure as potentially hazardous.

Their safety code only allows people to be close enough to manually fill a nitrous tank if the tank is deliberately designed with a high margin of safety to prevent bursting.



Commercial hybrids are available such as the Aerotech manually-filled hybrid system which has this kind of strengthened tank, but for experimental hybrids UKRA will rightly require sufficient proof of tests performed to verify the tank safety if anyone is to be near it.

Remote-controlled filling of flight tanks is preferred.

It doesn't really need saying, but **any homemade tank from a rocket that has suffered a recovery-system failure needs re-tested.**

Aspire's smaller vehicles (FLARE, ADV2a, and ADV2c/Rickrock) utilise manual fill.

Remote-filled systems allow the luxury of smaller tank safety margins, and so thinner-walled, lighter tanks, but the potential mass saving if using an ultra-thin tank is proportionately smaller as the vehicle diameter gets smaller.

For example, the number of fabric layers of a composite tank is an integer, it can't be a fractional number, so small composite tanks can't be made with an optimum composite thickness; they're over-heavy.

Similarly, small aluminium tanks suffer minimum gauge problems, and over-proportionally large bolt-holes which raise stress.

A manual fill system is simpler to construct, but involves a higher level of design and testing of all tanks and plumbing that will be pressurised; safety of the filling crew is the prime consideration.

Obviously, you *can* safely be close to the massively overstrengthened tanks used to transport nitrous from the suppliers; they're properly engineered and manufactured to allow you to move nitrous around the country after all, and they're tough unless you drop them on their necks and break the valve off.

Then you get a rocket alright.

Such a commercial container is safe enough to handle (though not idiot-proof) but is far too heavy to fly.

Thin-wall aluminium tanks

So just how strong do nitrous tanks have to be to be *reasonably* safe to be near without being too heavy to launch?

Military missile-design literature recommends a design safety factor of *at least* 2.0 times expected internal pressure on pressure-vessels that are to be manually handled while they're pressurised.

But this applies to a *production* tank; the fundamental point is that a batch of military production tanks have been **tested to destruction** to ensure that they really do burst at well over the 2.0 safety factor, and not a worrying 2.00001

Now we amateur groups don't tend to make batches of tanks, therefore we can't perform a suitable number of destruct tests.

Several rocketeers over the decades, making one-off tanks, have learnt *to their cost* that home-made thin-walled tanks, especially aluminium ones, need a burst safety-factor of at least **three** to handle the inevitable dings, scratches, and accidental alteration of the metal properties (typically inadvertant annealing) during manufacture.

Unexpected stress raisers can cause ally to rip apart at much lower *average* stresses than you bargained for, especially if you're brave enough to try welding the 6000 series aluminiums, as this locally kills their heat treatment which is what originally made them strong. They must be re-tempered.

So for manual filling, then Aspire's approach, based on the personal experiences and advice from engineers who make home-made tanks, is that you should **test** your hybrid's one-off tanks to ensure that they safely withstand **three times** the vapour-pressure of nitrous on a hot day without failure, or 3 times 60 Bar = **180 Bar**.

CO₂ paintball-gun tanks, for example, are designed to be carried around during such adult tig-tag, bashed off trees, and people have sometimes fallen on them, without injury.

These tanks are all pre-tested to around *five* times nitrous pressure, and are stamped to say as much; so a bad batch will fail during factory testing well before reaching the shops.

So AspireSpace have been comfortable enough with manual filling of hybrids that use such paintball tanks, such as our highly successful FLARE and ADV2a vehicles.

Paintball tanks are a good safe choice, but they're somewhat overheavy.



Also, most (Luxfer) paintball tanks use a 5/8ths-18 UNF internal thread on their necks; sourcing a suitable tap can be tricky.

Composite tanks

The general advice from composite manufacturers is that DIY home-made composite tanks have resulting properties that are far too variable from tank to tank to predict: **use remote filling only**.

More to the point, when composites are damaged, the ensuing micro-cracks are rarely visible on the surface, so the tank may rupture next time it's pressurised without any visible prior warning.

If you treat your composite tank like eggs from the moment it's made, then throw it away after its first flight then maybe...

But the whole point of all the hassle of a composite tank is to go for absolute minimum tank mass, so there's absolutely no point in building a composite tank that isn't remote-filled.

Composite tanks need a separate internal liner because raw composite leaks, and can cause nitrous to 'explosively' decompose as we'll see in part 3. But even thin-wall aluminium liners are not thought to provide the whole structure with enough uniformity to allow anyone to be near one when pressurised.

Plastic liners are lightweight, but you must ensure that the plastic is one that isn't a fuel or catalyst: using a polythene liner for example turns the tank into a potential hybrid if blowback of chamber gasses upstream occurs! Use the fluorocarbons such as PTFE or PET. Materials suitable for nitrous oxide are listed at the end of this paper.

Tank testing

No pressure-vessel, nomatter who or what company made it, is at all safe until it's been pressure-tested.

Until somebody's tested it, don't use it.

If there's no information stamped on its base, or if some rocketeer who you know is bad at recovery-systems sells you a scarred and pitted second-hand tank, regard it as dangerous until you've tested it.

Don't even assume that a tank specifically sold for nitrous hybrids will take full nitrous pressure; some are only designed to take the lower pressure that you get with a permanently-open vent-hole system.

Remember to test the tanks to the safety-margin that they'll need: at least 180 bar for any tanks you'll ever be near.

Many CO₂ fire extinguisher bottles are tough enough even to transport nitrous around in, but beware secondhand ones: test them first.

A safer testing method

The *only* safe (safer) way to test a high-pressure system is hydraulically: never use compressed gas or you're just making a gas-pressurised grenade again.

Buy a hydraulic hand-pump and some hydraulic jack-oil from an auto-store (such as Halfords or the like). Before pumping the tank up, make absolutely sure you've bled all the air out of the system (no bubbles) by separately filling the tank and pump completely full of oil before you connect them.

For safety, arrange to have at the very least a solid brick wall between you and the tank during testing, or preferably the corner of a building.

You don't need to be able to see the tank anyway: any leaks will show up as a steady drop in pressure on the hand-pump's pressure-gauge, their location revealed afterwards as a green stain on fresh newspaper.

And if the tank bursts, the loud splurt of a soggy explosion sounds exactly like an enormous aquajet going off.

Bits of burst tank won't go very far under fluid pressure, because fluids can't store energy in compression nearly so well as gasses, but jack-oil is impressively messy: the whole area gets slimed.

Make sure nobody else can wander into the danger area while you're testing, and take extra precautions if you're testing a large tank.

After testing is finished, **thoroughly clean the inside of the tank because jack oil is a fuel**. Cleaning procedures are covered in part 3.



Remote fill systems

Sadly, tanks that can *safely* withstand 3 times nitrous pressure can be too heavy for some vehicles. If this is the case, then you should resort to developing a safe remote-filling system.

If nobody's *ever* going to be near a tank while it's pressurised, i.e. only remote filling and dumping throughout the whole life of the tank, then the safety-factor on burst can be 1.0001, or however lucky your rocket is feeling.

1.5 times the expected nitrous pressure is a reasonable remote-fill margin for a reusable tank, but pressurise the tank and plumbing a few times to this 90 Bar before first flight to be sure.

Pre-launch and aborts

Remote-fill systems must be designed to fail-safe, i.e. will empty the run-tank if electrical or pneumatic/hydraulic power is lost.

Otherwise, excepting a sniper, there's no way to depressurise a remote-fill tank if the remote-fill system dies and the hybrid didn't launch.

You can't approach the pad without serious risk to yourself, so the pad could be out of bounds until the pressure lowers the following winter!

The simplest approach is the one commonly used; the vent-hole's secondary function is a deliberate leak to slowly lower the tank pressure in the event of an abort.

A deliberate leak is a good idea even on a vent-free system, and the time it takes to depressurise the tank is entirely up to you. (Evacuate the pad for an hour though, and the RSO may become displeased!)

Below 20 Bar as read on a pressure-gauge through binoculars, gives the required safety factor of 3 again on the original 60 Bar, and you can then approach the pad.

For safety, vent all remaining nitrous in an aborted fill, and wait 15 minutes before re-filling otherwise the tank will be excessively cold and thrust will be lost (see our physics of nitrous oxide article).

Launch

The remote-filling mechanism absolutely must disconnect from the rocket at or before launch, otherwise half the pad gets carried aloft and the rocket vehicle crashes.

Following the advice of NASA literature on remote disconnection systems, consider backup mechanisms in case the primary disconnection mechanism jams.

Too many backups decrease reliability (the KISS principle) but *one* backup increases reliability greatly.

For example, if the tie-down strap on the commercial Hypertech system breaks or wasn't installed properly, then the backup is that the fill-line burns through almost instantly, before the rocket has left the pad.

The Reaction Research Society has launched rockets using an ingenious re-rig of a standard hydraulic quick-disconnect coupling:

The coupling's release-collar is tied to a stake in the ground, and the male part is fixed into the rocket pointing aft.

When the rocket pulls upward on the coupling at launch, the lanyard tied to the release-collar goes taut and the coupling disconnects automatically.

This is a good design for the backup release, which Aspire have adopted as ADV2b's backup disconnect.

Note that some couplings can't be disconnected before de-pressurising the line.

Hydraulic overpressure, the headspace

Pick up any fresh bottle of camping-gas or CO₂ and give it a gentle shake; the sound of waves sloshing inside reveals that the bottle hasn't been completely filled with liquid, there's obviously a small amount of gas in there as well.

This small 'head space' of gas is in there for a purpose, because after filling, the liquid's density will change with any future changes in temperature.

Infact just-subcritical fluids like nitrous, CO₂, or butane can change density rather a lot with temperature if they're around room temperature.



The danger is that if the temperature increases, the liquid density will drop (see our physics of nitrous article).

If the tank was completely full of liquid, then the tank's fixed volume now won't be enough to contain the mass of liquid as it expands. (i.e. increases its volume)

If the tank is stoppered, the liquid will then self-pressurise.

Liquids don't compress easily, so the ensuing hydraulic self-pressure can often be enough to burst the tank, or any closed-off feed plumbing downstream of the tank.

To prevent such an accidental hydraulic overpressure, then just as in nature's design of the egg, a small percentage of the tank volume is deliberately left free of liquid to allow for expansion with temperature. This gas pocket can then compress to absorb reasonable volume changes without overpressuring the tank. (Seriously large run-tanks benefit from either a relief-valve, which is a commercial safety valve designed to open at a set over-pressure, or a commercial burst-disk that is designed to burst at a set over-pressure.)

This 'head space' of gas is often created by situating a vent-pipe a little way below the top of the tank, so that the liquid never fills above the level of the vent (see our physics of nitrous oxide article).

As every excess gram of run-tank matters, what is a reasonable minimum volume of head-space? Using tables of nitrous properties with temperature (Ref. 1) the Aspire run-tanks are designed to absorb the liquid expansion caused by a 10 degree C increase in nitrous temperature after the vent is closed at the nominally British climate's 15 degrees C.

This requires a 12% ullage (12% of the tank volume is vapour) which reduces to 0.7% at 25 degrees C. In practice, we use 13% to 15% depending on how accurately we know the tank internal geometry. (See our physics of nitrous oxide article for the required calculation.)

Leaks:

Leaks show up in any pipe-joints carrying the liquid phase of nitrous as regions covered in ice; the nitrous sucks heat out of the atmosphere as it leaks out to atmospheric pressure and vaporises (see our physics of nitrous oxide article), freezing the water-vapour in the air around the leak.

It'll freeze your hands or face too if they're near a leak: **wear goggles and gloves when you work with nitrous.**

Cryopumping (sort of)

As the first syllable suggests, this pitfall should only occur at cryogenic temperatures such as when you use Lox, but it caused the demise of our first nitrous hybrid Rickrock flight (ADV2c), so is worth mentioning.

Rickrock 1's manual-fill system used a manual vent-valve, this was a simple banjo-bolt that was screwed shut after filling.

On this occasion, we didn't realise that it had frozen partly open due to a phenomenon akin to cryopumping up the threads of the bolt during a pause in the filling operation.

This caused a leak that slowly lowered the run-tank pressure, and Rickrock 1 sailed away on a low, flat trajectory that broke the recovery system due to too high an apogee airspeed.

Cryopumping occurs when the metal of some cavity is chilled by cold fluid in contact with it.

The cold reduces the local pressure, and increases the density, of the air in the cavity, and so more air flows into the cavity from outside.

Despite any previous purging of the cavity by inert gas, this air flowing in from outside contains water-vapour, which freezes on contact with the cold wall.

Although the term cryopumping implies cryogenic temperatures, vaporising nitrous will also chill metal components sufficiently for this to occur.

We've since redesigned the vent-valve for Rickrock 2.



Part 3: Nitrous oxide decomposition hazards

The day the hybrid world changed

On the 26th July 2007 a terrible accident occurred at Scaled Composites' hybrid test site in the USA. Three of our fellow hybrid rocketeers died when a very large flight-weight run tank of nitrous exploded, and they were all too close to the tank when it happened.

This accident sent shockwaves around the world; many amateur rocketry groups became scared of nitrous and either halted their research or switched to a different oxidiser.

After the accident, research and evidence was uncovered which showed that nitrous has a dark side to its nature that we were unaware of. A lot of this research was done years before the Scaled explosion; it would have been nice if those researchers and 'professional' rocketeers could have been bothered to pass on their findings to Scaled and to us *before* the accident.

But I think the world has over-reacted to the Scaled accident. Now that we have more knowledge of nitrous we simply have to incorporate the new findings into our hybrid designs. There's no need to demonise nitrous; it's still one of the safest rocketry oxidisers.

What happened?

So what exactly happened at Scaled? The complete answer may never be known for sure, but there are several theories.

The facts are that a large composite tank had been filled with nitrous in preparation for a flow test of the hybrid injector. This test was cold: there was to be no ignition of the motor. Either just before or during the flow test, a large portion of the nitrous spontaneously decomposed into nitrogen and oxygen gas, with a large release of heat from the decomposition (the casualties suffered severe burns) that raised the run tank pressure. This overpressurised the run tank, and as there were no pressure relief devices on the tank such as a burst disc or pressure relief valve, the tank burst.

Although a lot of damage then occurred to the test area, it was significantly less damage than would have occurred had there been a detonation of the nitrous. The definition of a detonation is that the flame front spreads through the nitrous at supersonic speed. In fact no evidence has yet been uncovered to suggest that nitrous will detonate.

The data suggests that spontaneous decomposition can occur, spreading through the nitrous at a rapid pace, but significantly slower than a typical fuel-air deflagration.

It appears that only the nitrous vapour is the culprit, liquid nitrous doesn't appear to support continued decomposition because the surrounding liquid soaks the heat out of the reaction (this is called quenching): all attempts in the literature to ignite liquid nitrous have failed.

I reckon that the damage at Scaled was caused by a BLEVE event.

This stands for Boiling Liquid Expanding Vapour Explosion.

When the nitrous vapour decomposed and ruptured the tank, the tank pressure suddenly dropped to the pressure of the atmosphere outside the tank. This caused all of the liquid nitrous to flash-boil into vapour, expanding enormously in the process.

This expansion provided the energy for propagation of further cracks in the tank wall (shrapnelling) and then propulsion of these fragments of tank at very high velocity.

The expansion was further enhanced by a greater number of moles in the decomposed gasses and their increased compressibility factor (a so-called 'real' gas effect).

As this was happening, the now greatly increased amount of nitrous vapour decomposed, causing a release of heat which caused further gas expansion.

Complete decomposition of the nitrous in a run tank will theoretically cause a 20 times increase in pressure, though the tank will have burst long before reaching that pressure.

The key question is, what caused the nitrous vapour to decompose?

It turns out that nitrous is a good solvent. The Scaled run tank used a composite tank liner, so bare composite resin was in contact with the nitrous, as well as the waxy deposits that you get on the surface of composites. This became the fuel, or possibly the catalyst, for the decomposition. Plastic saturated with nitrous can decompose 'explosively' when ignition energy is provided.



Static discharge

What provided the ignition energy?

It was a hot (38 degrees C), very dry day in the desert test area that day, which is conducive to the buildup of static electricity. Our nitrous hybrids typically have metal tanks and combustion chambers, so they're earthed when in contact with our metal test-stands. But the Scaled hybrid had a composite tank and chamber. Assuming that the injector plate was metal, then this could have built up a large static charge as the nitrous flowed through it. The electrical conductivity of nitrous is low enough that with flowing nitrous it is theoretically possible to produce a large enough static discharge to initiate decomposition.

As liquid nitrous flows through an injector, nitrous vapour appears. This vapour can be easily ignited by an electric spark at typical tank pressures, and even a very feeble spark will do it (0.14 joule).

One rocketeer from Arocket recounts: "I can tell you from personal experience that a big spark will set off nitrous."

Scale effect

Another issue with the Scaled (sic) hybrid was its large size; probably the largest nitrous hybrid ever tested.

As hybrids get larger, the decomposition hazard increases with increasing system scale due to tank wall surface-to-internal volume scaling.

And there's the quenching effect: the radius of the feed pipes of many of our small amateur hybrids are smaller than the quenching distance. This is a size (around 7 mm for pressurised nitrous, though it changes with pressure) below which the metal walls of the pipe are near enough to soak up any rouge heat energy from decomposition, stopping the reaction dead.

In Ref. 8, the researchers could only get nitrous vapour to sustain a reaction in a ½ inch diameter (12.7 millimetre radius) metal pipe by heating it prior to ignition (204 degrees C and 55 Bar). In a 1-inch pipe and larger, there was no quenching at typical nitrous pressures.

Rocketry use of nitrous

Nitrous has many uses, from medical anaesthetic to dispensing whipped cream, and it's been used for over 100 years. There have been very few accidents. (Excepting the poor souls who's colons exploded during surgery due to catalytic decomposition of nitrous anaesthetic reacting with intestinal chemicals. Farted out of existence is a sad way to go.)

But the rocketry use of nitrous is a new thing, we're still in the learning phase.

Rocket propulsion is unique in that large quantities of nitrous are stored at room temperature in thin-walled flight-weight tanks.

The combustion chamber is closely coupled to the run tank. This is a significant source for ignition which does not exist in other applications.

Nitrous oxide can be safely handled in extreme conditions in the liquid state, but hazards exist in the vapour state at elevated temperatures and/or pressures.

The release of thermal energy is by exothermic molecular decomposition; this has a handy side-effect in that it helps motor combustion stability.

There is a large energy release upon decomposition, about double that produced by an equivalent weight of TNT.

Despite its potential decomposition hazard, if handled properly, nitrous is one of the safest rocketry oxidisers.

To minimise the risk of decomposition, SpaceDev stores its nitrous in liquid form at -18 degrees C (zero degrees F).

Let's look at the hazards:

Contamination

The presence of even a small amount of fuel or catalyst material in tanks and feed plumbing can greatly reduce the energy threshold required for initiation of nitrous decomposition.

A mixture of nitrous and 9% hydrocarbon (ethanol) initially at only 40 degrees C exploded in a lab.



I've listed compatible and non-compatible materials at the end of this paper, though an awful lot of materials have still to be tested: if you google on nitrous material compatibility you'll find that most of the websites are way behind the current research.

The way to deal with contamination issues is to give the system a damn good clean; equipment must be thoroughly degreased before use.

Professional rocketeers working on manned nitrous hybrid systems have, in my view, been forced to go completely overboard on their cleaning since the Scaled accident. They're using the strict procedures used for *oxygen* rocket systems. If you're going to all the bother of full oxygen cleanliness, you might as well use oxygen in your hybrid as it'll give you a higher specific impulse.

Here's one of their 4-step cleaning procedures; it goes beyond the procedure we at Aspire use on our H2O *Lox* hybrid:

- Dust and loose contaminants removed by scrubbing, then cleaned with oxygen cleaner, then rinsed in water.
- Ultrasonic cleaning.
- Rinse and soak in de-ionised water 3 times to remove oxygen cleaning agent.
- Dry the parts with nitrogen.
- Inspect cleaned parts, re-clean if fail:
- Visual inspection looking for loose contaminants or grease.
- Wipe with a white lint-free cloth (check that the cloth remains clean).
- Ultraviolet lamp inspection.
- Store all cleaned parts in sealed plastic bags and re-inspect just prior to assembly.

In my personal opinion, an adequate cleaning procedure for us amateur nitrous rocketeers is to wash your run tank and feed plumbing in 'trike' (old-style dry-cleaning fluid) or chloroform, then acetone, then rinse with good clear Highland water. (Okay, so trike is frowned upon because it damages the ozone layer, but there's *nothing* that beats it for cleaning.)

Bear in mind that thousands of grubby HPR nitrous hybrids get assembled in muddy fields and lobbed skyward without incident, though the quenching size might be saving them.

Incompatible grease

Although a properly installed O-ring in a properly designed groove will seal perfectly when dry, it's become an amateur and HPR rocketry habit to smear some grease around the O-ring, primarily to give a sacrificial heat-proof coating.

There have been several instances of people reaching for their solid rocketry supply of petroleum jelly/vaseline and smearing nitrous hybrid engine O-rings with it.

A little thought reveals that such grease is a fuel, whilst the nitrous is an oxidiser: sure enough **their hybrids blew up upon ignition.**

Use only oxidiser-compatible greases: these fluorocarbon greases can be bought from SCUBA diving suppliers or rocketry vendors.

Adiabatic compression

This is also called 'water hammer' (even though there's no water), and until recently we all thought it only occurred with pure high-pressure oxygen (gox). Aspirespace had to design against it for our H2O *Lox* hybrid.

What happens is that if a run valve is opened suddenly, gox rushes down the feed pipe until it hits another shut valve or obstruction such as the injector. The gox's momentum piles it up against the shut valve, and the temperature rises purely because of the compression. This self-heating can reach the ignition temperature of the pipework, and start a fire.

In nitrous' case, the self-heating can reach its auto-decomposition temperature.

Here's a note from XCOR: "We had a few milligrams of fuel in a Snaptite valve which we didn't know about; we had some nitrous in it as well, and we hit it with a water hammer. Adiabatic heating made the fuel/nitrous mix diesel, and that was enough, in that small space, to set off the nitrous. The result was a very loud CRACK! and a thoroughly ruined Snaptite valve."



The way to prevent adiabatic compression is to avoid sudden rushes of oxidiser: open run valves slowly and reduce the deadspace downstream of valves: dead volumes in the feed lines (e.g. a tee fitting) are prone to adiabatic compression.

Reduce the pressurisation rate of your run-tank as you fill it to no more than 20 psi per second (Ref. 10) to avoid adiabatic compression. The way to do this is to reduce the diameter of both your fill pipe and your tank vent.

Bruno Berger at the Swiss Propulsion Laboratory (Ref. 11) understandably worries about imploding cavitation bubbles of nitrous vapour, because when they implode, they can generate very high temperatures.

As the liquid nitrous flows down the feed pipe between tank and injector its pressure drops, which causes some of the liquid to flash into vapour (2-phase flow) causing lots of little vapour bubbles. If you get an adiabatic compression in the feed line or at the injector, these bubbles could implode. If there are enough of them imploding then the froth could generate decomposition energy faster than the liquid nitrous can quench it, leading to the feed pipe overpressurising (blows up).

Reverse flow

This is thought to be the main hazard to nitrous hybrids, the most likely hazard to occur.

There are two different times when this could occur: before the liquid nitrous has run out, and after when there is only vapour left in the system.

Taking the before case first:

Terminal flatulence

We all want the highest chamber pressure to get the biggest specific impulse; as close to the tank pressure as possible, but there's a practical limit.

A common trend is to use too large a hole/holes for the injector, in order to minimise the pressure-drop across it, but this is a very dangerous practice.

The pressure drop is there partly to prevent very hot combustion chamber gasses having the potential to flow back upstream into the feed system or tank if there is a chamber pressure pulse. Too low a pressure drop across the injector encourages such audible forward-reverse flow oscillations in the chamber:

Screaming hybrids are NOT cool, they're dangerous: hot gasses could get back into the feed system and decompose the nitrous there, blowing up the feed pipework and starting a fire.

Use a smaller orifice size to get the chamber oscillations under control.

Ref. 2, in line with most injector design practices, advises a pressure drop across the injector of 20 percent of the chamber pressure at the end of the burn (when the liquid has just run out) when the tank pressure is at its lowest.

On a particularly cold day in the UK (i.e. a low tank pressure), a commercial hybrid with too large an injector orifice (causing too low an injector pressure drop) went boom.

The Space Propulsion Group have had several nitrous hybrid feed pipe explosions while still with liquid in the tank, believed to be caused by reverse flow into the feed system.

For example, at the end of the burn, our Aspire nitrous tanks are at about 36 Bar, so we tune the nozzle throat size so that the chamber pressure is no higher than 30 Bar at the end of the burn as 30 Bar times (100+20) percent = 36 Bar

The injector pressure drop is therefore 36 – 30 = 6 Bar

Firstly, make sure that the upstream feed pipe (between run tank and injector) is suitably wide enough (large enough cross-sectional area A_{pipe}) that the flow velocity within it is less than 10 metres/second (i.e. effectively stagnant) to minimise pressure losses in this pipe, otherwise you'll get an unwanted pressure drop along the pipe which reduces the injector pressure drop.

To check the flow velocity use: $v = \frac{\dot{m}_{nitrous}}{A_{pipe}}$ (The mass continuity equation)



Then use the following equation to design the number of orifices required by the injector:

$$n = \frac{\dot{m}_{\text{nitrous}}}{A_{\text{orifice}}} \sqrt{\frac{K}{2\rho_{\text{nitrous}} \Delta P}} \quad (\text{from the continuity equation inserted into Bernoulli's equation})$$

Where n is the number of orifices, \dot{m}_{nitrous} is the nitrous mass flow rate in kg/sec, A_{orifice} is the internal cross-sectional area of one orifice (metres²), the liquid nitrous density ρ might be around 880 kg/m³ at the end of the burn, and ΔP is the injector pressure drop (Pascals) at the end of the burn.

We've experimentally determined the energy loss constant K for nitrous to be approximately 2.0 as the nitrous partially vaporises within a sharp-edged injector orifice. (Length of the orifice divided by its diameter is around 4)

Flashback through vapour

Flashback of hot chamber gasses into the nitrous vapour after all the liquid has run out is thought to be a greater hazard (Ref.9) than before the liquid runs out. This is because there's much more vapour in the feed system, and this vapour goes all the way up and into the tank, so the tank can go boom too.

Hybrids have exploded when the liquid nitrous has run out, and a chamber pressure spike has reversed the flow.

Here's a picture of the remains of a run tank (thanks to Troy from Arocket) after a flashback event at the end of a run resulted in an explosion of the vapour from within the tank:



Another way to blow up the feed system is to let hot igniter gas back-flow through the injector. Don't let this happen.

Inadvertent liquid engine, a hard start:

One of the biggest bangs of recent years in the UK professional (defined as getting paid for it) rocketry field occurred when a nitrous hybrid engine accidentally became a liquid engine, and then blew up.

The nitrous **must not** be in liquid form once it's inside the combustion-chamber because of the danger of it pooling in corners of the motor; molten plastic fuel may be pooling in the same corner.

In this case, the nitrous was injected tangentially into the chamber instead of axially for several promising technical reasons, but centrifugal effects re-compressed the nitrous, and at the higher pressure it reverted into a liquid again. A design oversight allowed molten plastic to occupy the same area, and it did the classic liquid-engine 'hard start' upon ignition.

This bang was compounded by the fact that the feeble igniter was situated at the nozzle instead of where you ought to put it: close to the injector, so the chamber could happily fill with unburnt nitrous.

One way to fill the chamber with liquid is to use too large an injector orifice, with its resultant too low a pressure drop. This could keep the nitrous from vapourising properly.

Arocket have seen "a very scary explosion of a thin-walled steel nitrous oxide tank due to a hard start with a paraffin hybrid. When the pyro (run) valve failed, a much larger volume of nitrous entered the preheated, flame-filled combustion chamber, and decomposed. Bits of combustion chamber went everywhere; we never found the injector."

Pacific Rocket Society, Black rock desert, November 1995: a fill line leaks inside the combustion chamber, saturating the HTPB fuel with nitrous. Upon ignition the chamber blows up.

Warming the run tank

On cold days, the run tank has to be heated in order to get the nitrous pressure up (see our 'physics of nitrous oxide' paper).

It goes without saying that care has to be taken to avoid hot-spots that could decompose the nitrous. If you're using an electrical tank heater, don't let it overheat.



Hot-spots within heat exchangers have been found to set off nitrous: use a heat exchanger coil with a uniform wall temperature such as a coil submerged in a water bath to warm nitrous.

Now that we know the hazards, what can be done about them?

The decomposition process

Know thine enemy: it's instructive to review the decomposition process. See Ref. 9 for a very detailed theoretical model, the results of which are summarised below:

Nitrous decomposition is a marginal reaction with just enough heat released to sustain itself. It is easily quenched: either nearby metal pipe walls or a diluent gas added to the vapour act to absorb heat and quench the reaction.

The decomposition rate of nitrous vapour is 6 orders of magnitude slower than peroxide decomposition, making it a safer oxidiser: it's less sensitive. This abnormally low reaction rate is partly caused by "the non-adiabatic spin-forbidden transition elementary unimolecular decomposition process" (it's a quantum thing: I don't understand a word of it either!)

All attempts in the literature to ignite liquid nitrous have failed (unlike liquid peroxide).

Small concentrations of diluent gas added to the nitrous vapour increase the ignition energy of the vapour, making the mixture extremely difficult to ignite at dilution levels greater than 30%. Adding extra gas to the run tank is sometimes called 'supercharging', and has the side effects of raising the tank pressure slightly, and reducing the tendency for 2-phase flow in the feed system.

Reference 9 defines two distinct modes of nitrous decomposition:

Local thermal ignition

This is regarded as the most common mode/ greatest hazard expected in nitrous rocketry, since it requires only small localised quantities of thermal energy. This starts a self-sustained deflagration wave in the nitrous vapour (starting at the injector, once all the liquid has run out) that travels up the tank, causing havoc (decomposing the rest of the nitrous vapour).

The rate of increase of tank pressure (the violence of the explosion) that this causes depends upon this wave's flame speed. The inherently slow decomposition of nitrous results in a low flame speed of only 15 cm/second at 41 Bar. The flame speed decreases with increasing pressure and increasing dilution of the vapour.

The quenching distance is around 7 mm for pure nitrous at 27 degrees C (300 K), and increases with dilution:

Figure 11 shows the quenching distance estimate for N_2O/O_2 mixtures at 40, 50 and 60 atm for an initial temperature 300K. Note that the quenching distance for pure N_2O is around 0.7 cm and it increases with increasing level of dilution as expected.

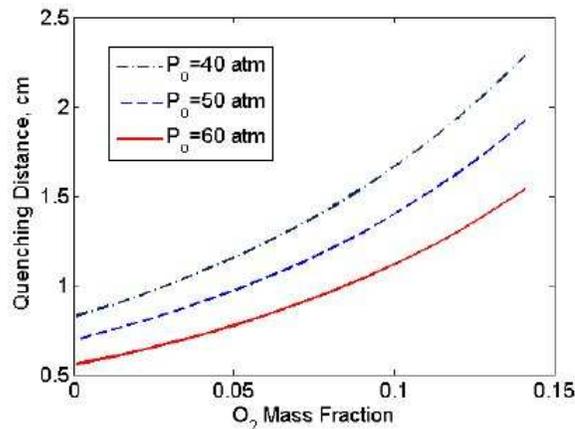


Figure 11: Quenching distance for N_2O/O_2 mixtures at 40, 50 and 60 atm.



The minimum ignition energy for pure nitrous vapour is very roughly 100 millijoules (not a lot). There is a *big* effect on local thermal ignition if you dilute the tank vapour: dilution by 30% gox raises the ignition energy to roughly 500 Joules, making ignition virtually impossible.

(Note: as yet I'm not sure whether this dilution figure is based upon the mass of vapour at the end of the burn, or is based on the total nitrous mass at the start of the burn: I'm waiting to hear from SPG.) Dilution with nitrogen is expected to have a similar effect, and helium is expected to be better: have the same effect at lower dilutions because heat gets conducted away more easily in helium. Ref. 8 suggests you need 4 times less helium compared to nitrogen.

It may seem odd that adding gox to the run tank actually makes things safer. I assume it adds a bit to the specific impulse as well.

The time taken for local thermal ignition-caused decomposition of the tank vapour to occur is surprisingly slow: a typical time to maximum overpressure is 5 seconds, (time to typical flight-weight tank burst is 2 seconds).

This is slow enough for an automatic safety system to react and do something.

Dilution doesn't really change the maximum overpressure.

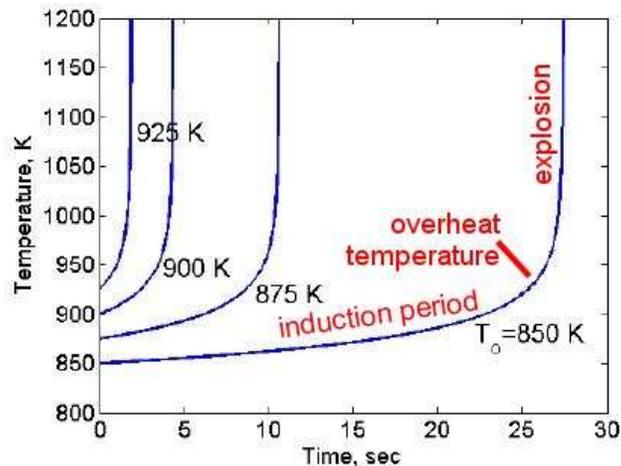
Homogenous ignition

This is simultaneous ignition of a sizable bulk of the nitrous vapour when sufficient energy is added (high temperature, such as caused by a fire). It's regarded as the less likely of the two types.

Above a certain high temperature, the heat produced by the exothermic decomposition reaction exceeds the heat loss to the surroundings and the temperature rises.

A slow increase in temperature begins (an induction period). This is followed by an exponential growth in temperature (causing very rapid gas expansion) once the temperature reaches the overheat temperature.

As this graph shows, below around 850 Kelvin, the induction period is too long for propulsion systems (the nitrous has drained out of the tank and/or feed system by then) so auto-ignition is not going to happen.



Induction time as a function of initial temperature, no heat loss case.

Homogenous ignition is most likely to occur in the feed system due to reverse flow or adiabatic compression. It's unlikely to occur in the run tank due to the need to heat the whole of the nitrous to its high 'auto-ignition' (short induction period) temperature.

The effect of diluting with inert gasses is small: even 80% dilution only raises the 'auto-ignition' (short induction period) temperature by 30 Kelvin.

Flame traps

There's been talk on Arocket of the possibility of adding a flame trap to the feed line. Nitrous has a much larger quenching distance than typical fuel/air mixtures, so a grid of stainless steel tubes put into the feed line could be able to stop any decomposition that starts at the injector.

The quenching distance for nitrous is around 7 millimetres, so I reckon that a grid of 5 millimetre diameter tubes will work, and the tubes are large enough not to cause much of a pressure drop.



But I must stress that I haven't found any evidence of anyone having tried a flame trap with nitrous. This is a (potentially hazardous) experiment that needs doing.

Nitrous material compatibility

Use stainless steel!

As a general guide, materials that are oxygen compatible are suitable for nitrous.

It's worth pointing out that I haven't seen any evidence for a catalyst for nitrous that works at room temperature, they all seem to need elevated temperatures.

Metals

Aluminium, Stainless Steel: satisfactory

Copper and its oxides (and brass/bronze), nickel, and platinum, are highly catalytic with nitrous especially at elevated temperatures, so avoid their use.

Brass, copper, carbon steels are corrosive in presence of moisture: do not use corrosion-prone metals e.g. iron oxide (rust) is a catalyst.

Avoid rust contamination from steel fill tanks; use stainless steel filters in the fill line.

Plastics

Fluorocarbons such as Polytetrafluoroethylene (PTFE), Polychlorotrifluoroethylene (PCTFE), PET: satisfactory

Other plastics are an ignition hazard.

Nitrous can saturate plastics and composites turning them into 'explosives'.

HTPB fuel saturated with nitrous can be 'explosive'.

Elastomers

Think carefully about what material to use as your run-tank O-rings. Just because commercial HPR hybrids use 'rubber' O-rings doesn't automatically make it a good idea.

Fluorocarbon-coated O-rings (Buzak and Shamban catalogue) : use these where possible.

Unfortunately, they don't stretch very much.

Buna-N and neoprene degrade in nitrous liquid after several days.

Butyl (isobutene - isoprene) rubber (IIR): not recommended, possible ignition and significant swelling.

Nitrile rubber (NBR): not recommended, possible ignition and significant swelling.

Chloroprene (CR): not recommended, possible ignition and significant swelling.

Chlorofluorocarbons (FKM) (VITONTM) : not recommended, significant swelling.

Silicon (Q) : satisfactory

Ethylene - Propylene (EPDM): not recommended, possible ignition and significant swelling.

Silicone saturated with nitrous is an impact sensitive explosive.

Lubricants

Nitrous can form an explosive with many hydrocarbons and lubricants:

Fluorocarbon based lubricant (krytox): satisfactory

Hydrocarbon based lubricant: definitely not recommended, possible ignition.

Recommendations

- Keep everybody well back from the test area whenever nitrous is being loaded/is loaded into the run tank or whenever nitrous is flowing.
- Use a large-volume (large diameter) burst disk on the run tank. Mandatory for manned systems.
- For motor static testing, keep the run tank upright so only liquid gets to the injector at ignition.
- Keep it *very* clean: even very small traces of contaminating fuel can cause problems.
- Avoid the use of catalytic materials.
- Nitrous is a good solvent of hydrocarbons: grubby fingerprints, O-ring polymers, and valve seals.
- Venting nitrous through the combustion chamber should be avoided at all costs.
- Dilution of the nitrous vapour in the run tank is recommended.
- Avoid hard starts: fire the igniter before admitting the nitrous into the chamber.



- If using nitrous in a confined space use an oxygen sensor to monitor dangerous concentrations of nitrous which could be inhaled.
- Properly earth all ground support equipment (fill tanks and fill lines), and keep mobile phones switched off when anywhere near nitrous.
- Construct tanks and lines out of conductive material. For composites, work out a way of dissipating static (aircraft composites have metal foil as their outer layer to dissipate lightning strikes. Other approach is to embed carbon nanofibres or nanotubes within the resin.) Scaled are now using a metal tank internal liner.
- Avoid adiabatic compression: minimise feed-line dead volume downstream of the run valve, slow the valve opening.
- Prevent back-flow of igniter gas through the injector.
- Reduce the pressurisation rate of your run-tank as you fill it to no more than 20 psi per second.
- Use small enough injector orifices and widen the nozzle throat to get a good pressure drop across the injector right through the burn (a drop of 20% of the combustion chamber pressure as the liquid runs out).
- Develop safety procedures, and pre-chill the pump, if you pump nitrous from the fill tank to the run tank.
- Use pressure relief devices/burst discs on all trapped volumes of liquid nitrous to prevent hydraulic overpressure.
- Review all moving parts in the nitrous system (regulators, valves) for friction, impact, and static discharge.
- Avoid eddies or stagnation zones in the feed pipework due to sudden changes in cross-section. These can act as flameholders which prevent any decomposition from going downstream.



Glossary:

Feed system: the pipework between the run tank and the injector.

Fill-tank: the commercial container supplied with the nitrous.

Run-tank: the lightweight tank inside your rocket-vehicle that is filled from the fill tank.
(In a conventional hybrid, the term 'fuel tank' is just plain wrong as the fuel is the plastic in the combustion chamber.)

Quenching: when the heat necessary to continue the decomposition reaction is drained away into another source, stopping the reaction.

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Ref. 10: Zachary Thicksten, Frank Macklin, John Campbell, "Handling considerations of nitrous oxide in hybrid rocket motor testing" AIAA 2008-4830 44th Joint propulsion conference

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Ref. 12: N2O safety guidelines downloadable pdf, Scaled Composites

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Ref. 14: Arocket amateur rocketry forum