Everest Parajet Engines - The Development Story

By Giles Cardozo – Parajet International Ltd

Why is it difficult to make an internal combustion engine powered aircraft fly at High Altitude?

As altitude increases, so air pressure drops. At 15,000ft there is two thirds of sea level pressure and at 29,037ft at the summit of Everest there is only one third of sea level air pressure. An engine combines oxygen in the air and fuel to create the explosive charge that drives the engine. At sea level the oxygen content is approximately 20%, at 30,000ft the oxygen content percentage remains the same but due to the lower air pressure is equivalent to 6.5 %. Such a low volume of oxygen is insufficient for a standard internal combustion engine. Take a normal 2-stroke or 4-stroke paramotor engine to this altitude and it will simply stop running. In fact it will stop running at around 24,000ft as it simply can't produce enough power to even push the piston up and down any more. Theoretically, with a third of the oxygen at 30,000ft an engine should produce a third of the power, however, the mechanical inefficiencies of the engine remain the same as at sea level and therefore draw a large percentage of the total power produced. This result is an engine that produces about 8 times less power and in most cases…especially for light weight aero engines…they just stop running.

To prevent this from happening the engine needs to be force fed air, either by means of a supercharger or a turbocharger. These can produce up to three times the ambient air pressure, therefore at 30,000ft an engine will receive a simulated sea level air pressure and can therefore theoretically produce it's standard sea level power rating However, a typical supercharger will absorb around 10% of the engines total power output.

Another important factor that must be taken into account is the engines fuel/air mixture ratio and the dramatic reduction in air temperature with the increased altitude. The ratio of fuel to air is absolutely critical to the performance of the engine, too much fuel and the engine will be underpowered, too little and the engine will run too hot and potentially destroy itself. So as the engine increases in altitude so the fuel delivery needs to be adjusted and the quantity reduced to maintain this critical ratio. At 30,000ft the air temperature is between -40 and -50 degrees Celsius, vaporized fuel and air mixture freezes extremely quickly at these low temperatures, causing fuel starvation and ultimately the engine will cut out.

In the case of an internal combustion aero engine we also need to take into account what happens to the aerodynamics of the aircraft and propeller. An aerofoil flying at 30,000ft will fly 1.6 times faster, yet maintain it's designed glide ratio, the sink rate will increase by 1.6 times also. A propeller driving an aircraft at this altitude will therefore be flying through the air 1.6 times faster and to produce the necessary thrust to keep driving the aircraft upwards the propeller must increase the blade pitch and also spin approximately 1.3 times faster.

Therefore, everything is working against an internal combustion engine and propeller at high altitude, it just becomes exponentially more difficult the higher you try to fly. Saying this, all the technology that was required to make such flight possible was well established by the 1950's. Rolls Royce used superchargers on aero engines as standard. It was important to fly high, the airspeed goes up as does the fuel efficiency…high is the place to fly! But not for paramotors and paragliders, they are just too inefficient to benefit from high altitude.

So why is making a paramotor and engine capable of flying to 30,000ft so difficult?

Ultimately, because nothing like it has ever been done before. There's nothing that already exists, and no one alive who can really tell you how to do it and what you'll need….because no one knows.

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From a purely engineering perspective it's worth taking into account that there have been no engines in history ever designed to be powerful enough to fly to 30,000ft yet light enough and compact enough to be worn on a pilots back. Secondly, that there are no engines in the world designed to automatically compensate for high altitude yet light enough and small enough to be worn on a pilots back.

This meant that we needed to start from scratch and deal with all the hurdles as they arose.

Firstly it was just about research and working out all the parameters required:

1. How much power is required?

Having calculated that 1.6 times the power is required to fly and climb at 30,000ft we can work out the rest from known facts about flying paramotors at or about sea level. If 20 horsepower is enough to climb at 400ft per minute at sea level, 32 horsepower will therefore be enough at 30,000ft. Obviously making a paramotor engine produce 32hp at sea level is hard enough, given that all paramotor manufacturers struggle even to make 22 hp from their engines before pilots start complaining about too much weight. The average paramotor barely produces 15hp. Now consider making a paramotor engine that produces almost twice the power and do this at 30,000ft. This meant it needed to produce nearly 90hp whilst fully supercharged with 2.4 bar pressure at sea level. Once you take into account that 10% of the power output is absorbed by the supercharger and that once you reach 30,000ft the supercharger will struggle to provide the engine with sea level air pressure of one bar the power out put is reduced by more than half….from 90hp you end up with around 32hp from a fully supercharged engine at 30,000ft. An incredible drop in power that's practically unavoidable given the design and weight constraints of a paramotor.

2. What type of propeller, how fast must it spin, what diameter and how many blades are required?

The easiest way to work this out is by using already known specifications from propeller manufacturers. Helix propellers amongst others provide graphs that plot prop rpm against thrust against power input required. They didn't know what happened at altitude though but this can be calculated to some degree…I couldn't find anyone or any manufacturer who really knew the answers…I just had to experiment both in a hyperbaric chamber and by flying extremely high. After carrying out much of the initial testing with a 1.3 metre 5 blade prop I ended up using a 1.4 metre 3 blade Helix propeller. The reason for this was that 5 blades were heavier, more difficult to balance and more expensive to replace in case of bad take-offs.

3. How to make the fuel delivery system compensate for altitude?

The fuel delivery system must compensate automatically for altitude, there was no way that the pilot was going to make the carburetor adjustment by hand whilst flying so high in the mountains and in such extreme conditions. However, altitude compensating carburetors do not exist for small engines and rarely for larger aero engines, they are heavy and far too big to be useful in this application. The only solution was to use a computer controlled fuel injection system specially designed to compensate for altitude and to run a micro sized rotary engine.

4. What type of fuel is required and how much?

Due to the severe lack of oxygen in the air and the amount of power required from the engine it was necessary to use an oxygenated fuel. This type of petroleum is chemically combined with oxygen atoms during manufacturer and provides 10% more oxygen per combustion cycle. A high octane fuel was also required to prevent the volatiles in the fuel vaporizing when subjected to such low air pressure. This was a problem discovered when running tests on fuel in the hypobaric chamber, ordinary petrol starts boiling at around 24,000ft. The fuel used was 109 octane, similar to that of AvGas. An 18 litre tank was required on the Parajet as the engine consumed up to 11 litres per hour on full power.

5. What's best, a supercharger or turbocharger ?

Whilst driving a turbocharger is much simpler than driving a supercharger, there is no commercially available turbocharger light enough and small enough to be used on a paramotor. A supercharger was therefore the only option, what type of supercharger was the next important issue. There are many types of supercharger…all of which I discovered were too large and heavy to be contenders apart from one. The most compact, light weight and efficient of all was the miniature centrifugal supercharger manufactured by Rotrex in Denmark.

6. How can the engine deal with the extreme temperatures?

Normal aero engines suffer from problems with carburetor icing, this happens even at low altitude. Firstly by using a fuel injection system this helped over come part of the problem, but secondly by placing the supercharger upstream of the fuel injector the freezing air was heated rapidly on being compressed so icing never became a problem.

The Engineering problems encountered:

How do you make an engine light enough to carry on a pilots back yet twice the power of an average paramotor, and it's got to do all this while flying at 30,000ft?

The first answer was not to use a conventional piston engine at all, after looking around the market for small, powerful piston engines, it became clear that there was nothing that could produce the power we needed and do so reliably. As I was already developing the world's first wankel rotary engined paramotor, it seemed only natural that I should want to prove this technology by putting the engine through the hardest test of all. My partner in the Parajet rotary engine project Paul Woelfle from Aixro in Germany had already designed a larger Rotary engine for kart racing and this seemed like the perfect choice. It weighed 17kg and produced 48 horsepower. By the time I had finished taking every extra component off it such as the clutch, carburetor, fuel pump, engine mounts, gear drive, and machined the weight out from every conceivable other component, including the main drive rotor, balancing shaft, side plates, exhaust and manifolds, I had a 254cc engine that weighed only 11kg, produced 48 hp at 9000rpm and was only 130mm wide, front to back. It is an incredible and tiny engine which produces zero vibration so it's ideally suited to the light weight airframe of a paramotor.

Now it was time to make it produce almost double the power. This was achieved by fitting the Rotrex supercharger, by forcing air into the combustion chamber under high pressure, this engine could actually produce more than double the power and because it already had a low compression ratio of 11:1 it wasn't necessary to alter the engines mechanical components, ratios etc.

Where it seemed simple to just add a supercharger to an engine to receive the desired effect…I was proved dramatically wrong.

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There were so many problems that I discovered when putting this idea into action.

1. Firstly, creating an extremely reliable drive system from a single rotor engine to a supercharger is extremely demanding on the mechanical components. This is due to the intense power strokes received by the drive system once every revolution. The power pulses are so intense as the engine fires that the drive belts shatter and break up. Belts that were designed to take up 50 horsepower were disintegrating in minutes, the belt tension was critical to the longevity of the belt and there was no belt specialist who could provide the answers to this application. The speed at which the supercharger needed to be spun at also created a massive problem. To create sea level air pressure of 1 bar at 30,000ft the supercharger impeller needed to be spun at 200,000rpm, (that is an incredible 3333 rotations per second) Getting a drive belt to run the system this fast just added to the problems we were already experiencing with the power pulses. It took 4 months of relentless redesigning and rebuilding to come up with a system that truly worked. And the interesting thing is that it had nothing to do with what all the belt and transmission specialists from around the world suggested should be done.
The final design of supercharger drive system was fundamentally different to anything they suggested. I ended up with a drive system that was simpler, lighter and more reliable than any recommended system and one that ran the transmission belts at more than double there maximum designed speeds.

2. Secondly, I discovered that the engine over heats very rapidly the moment the supercharger really starts to kick in. It took some time and huge amount of experimentation with alternative methods to discover that the only way to reliably remove the heat from the incoming air was by intercooling it before the air reached the engine. An intercooler works like an air radiator, it passes the hot air blown from the supercharger through a series of vanes, each cooled by the air flow passing into the aircraft. I ended up making a small 2500cc intercooler which fitted directly into the airflow yet positioned as close to the engine as possible so as to keep all the air ducting reliable. The results were impressive, air that previously would heat up to over 100 degrees Celsius when drawn through the supercharger was now being cooled to 40 degrees, a very acceptable level, considering this was at sea level ambient air temperatures of 25 degrees. At 30,000ft we'd be looking at an inlet temperature of around 20 degrees. So the intercooler solved all the problems and kept the engine running impressively cool.

3. Achieving the correct supercharger pressure ratio against engine rpm is extremely critical to the gas dynamics involved, if the flow rate of the engine is not matched with the delivery rate of the supercharger then the impellor blades stall and the whole system ends up worse than if you just left the engine normally aspirated. This was a very real threat to the performance of the engine especially at high altitude. The drive speed could only be experimented with, neither the supercharger manufacturer or anyone else could offer a calculation that could determine the ideal ratio. Projects such as this take engineers out of the comfort zone, they just don't know what happens at high altitude as they've never done the tests. The only way to discover was trial an error and this meant spending hundreds of hours making different drive ratios and then testing them in a hyperbaric chamber where we could simulate 30,000 ft air pressure (equivalent to 0.3 bar). In the chamber we could monitor the engine extensively in a controlled environment. I had a sensor for everything and all the reading s could be viewed outside the chamber in a control room. The engine was totally remotely controlled from in here, in particular I could monitor pressure and temperatures at different stages along the airflow into the engine. Eventually I settled for a ratio that provided the engine with just enough air pressure, not as much as I would have liked but it was the only ratio that could work. This drove the supercharger at 171,000 rpm and delivered 2.4 bar of pressure. Just enough to keep the engine happy at 30,000ft.

4. The supercharger inlet orientation was critical to it's performance. The initial design had the inlet pointing down stream of the airflow, which meant it was effectively drawing in air from a space slightly void of air. It was impossible to place the supercharger the other way around, firstly because the drive system would be impossible, but also because it would have spun it the wrong direction. So the position was fixed, it was a question of how to get the airflow in the right direction which in the end meant re-casting the air inlet manifold to have a 90 degree turn immediately before the impeller, then splitting the inlet airflow either side of the intercooler, and into the incoming airstream, drawn both by the prop and the direction of flight.

5. To make the supercharger deliver enough boost pressure to the engine it had to be driven 20% harder than it was designed to. This meant that it too got very hot. This extra heat caused the impeller blades to expand slightly. The impellor blades are spun extremely close to the air inlet housing to ensure the air is pressurized efficiently, the problem was that these micro tolerance blades ended up expanding enough to touch the stationary housing which destroyed the supercharger more than once. The distance was critical, the housing had to be re-machined, but only by trial and error as the rate of expansion was impossible to calculate, finding out the actual temperatures of the vanes was just too complex.

6. The problem with testing the engine at sea level is that you end up working the supercharger harder than it should be and in turn blasting the engine with too much air, infact more pressure than it can withstand and you end up blowing the seals. To stop this happening an electronically operated pressure release valve was installed before the intercooler to release the pressure at 2.8 bar. Safe guarding the engine. It had to be electronically operated as spring operated valves work on the pressure differentiation so are not accurate as the outside pressure increases

Finally all the supercharging problems were overcome, this core component was finally running reliably after well over 100 times of dismantling and re-building the engine. But this was actually just a small part of the engine design, the entire computer control system had to be created before the supercharger could actually do anything.

The Engine Computer control system:

The Everest engines were operated entirely by computer, the ignition timing, fuel injection timing, manifold pressure monitoring , liquid cooling and of course the automatic altitude compensating system. An engine such as this had never run with a fuel injection system before, this was all new territory for, plus the fact I didn't really know what fuel injection was or how it worked. I had to learn a lot in small space of time to get this system working properly and harness the brains of a lot of electronics and fuel injection specialists to make it possible.

I ended up using an MBE chip as this was easily programmable and had a facility to incorporate manifold pressure based fuel delivery. This was a simple way to make the engine understand what to do as the altitude increased. By measuring the exact pressure and temperature in the manifold after the air had flowed through supercharger and intercooler and the precise engine speed at the same moment, it was possible to tell the fuel injector exactly how much fuel to inject. As the pressure decreased in the manifold so the computer knew that it must be increasing in altitude, and providing the engine revs were still the same it knew it must inject less fuel. The really critical part, once the system was working was to work out how much fuel needed to be injected. This process took 2 months of flight trials and ground testing the engine on a thrust rig both in and out of the hyperbaric chamber.

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The fuel injection system:

The problems associated with making a fuel injection system for a rotary engine were tiresome. Starting with selecting the correct injector by calculating what the maximum mass flow will need to be and find the right fuel pump that is light enough and yet powerful enough to vaporize the fuel adequately whilst the manifold air pressure is almost 3 times ambient. To find out what was required I attached a fuel pressure gauge and as the revs of the engine increased and the altitude increased discovered that I needed an 11 bar fuel pump. This meant that all the fuel line, the connectors and injector housing would have to be extremely strong and absolutely floorless in quality. A slight imperfection at this pressure would mean a fuel leak and this could be dangerous. I found a submersible fuel pump from Walbro and by placing a regulator valve in the fuel line which was linked to the engines air inlet manifold I was able to regulate the fuel pressure according to the inlet manifold pressure.

Powering all the onboard engine electronics:

The engine consumed a lot of electrical power. The liquid cooling system, ignition system, injector, fuel pump and ECU together drew 15 amps. I had to develop a tiny 3 phase generator as any conventional alternator that was readily available was far too heavy and meant more drive systems. The tiny system was driven attached directly to the rear driveshaft after the supercharger transmission system. It consisted of 12 Neobidyumidium magnets mounted around a small magnetic stainless rotor. This spun on the shaft inside a specially wound stator, coil and regulator. The result was a reliable 14.4volt charge to the tiny 3 amp 12volt lead acid gel cell that I used to keep things as light as possible.

The engine cooling system:

The rotary engine is liquid cooled, this makes it more efficient and lighter than an equivalent air cooled rotary engine. It did however make things more complicated, at high altitude the air density is so low that cooling radiators need to be made larger than at sea level. Although the air temperature is lower this does make up for the cooling inefficiencies of low pressure air and the radiator had to be made 50% larger and mounted directly in the most exposed position in front of the propeller.

Starting the engine:

The first engine was designed and built with the start motor and electronics incorporated into the design. After all the design issues were discovered with the supercharger and the weight penalty of a basically redundant starter motor was established, the starter motor was removed and the supercharger moved into it’s position as close to the engine as possible. I used an external hand held starter motor instead which was more reliable and powerful and fitted onto the rear of the engine during the start up procedure.

The propeller re-drive system:

This was a critical part of the engine design and I wanted it to be as integral as possible. The drive system bracket was CNC machined from 6082 T6 aluminium and fitted to the machined front face of the engine. It was designed to become a structural brace for the supercharger as well which was critical to the reliability of it’s drive system.

The End Result:

After 7 months intensive research and development the engine flew to 20,890ft in 42 minutes over Salisbury Plain in Wiltshire. The climb rate was over 800ft per minute at this altitude and the engine was only running on two thirds throttle. Further testing using a hypobaric inlet pressure moderator showed that the engine could continue to produce sufficient power up to 33,000ft. This was even better than expected.