

INTERVIEW WITH PAUL TRENTHAM, CONSULTING ENGINEER
By Scott Robertson, Pneumatic Options Research Library
www.AirCarAccess.com

RE: Paul Trentham, PE
7342 Old Scenic Dr.
Joplin, MO 64801
417-623-5459
tigertrentham@4state.com

4/14/04

I called Paul Trentham, a consulting engineer in Joplin, Missouri because I had his name in connection with the Terry Miller/Toby Butterfield air car project from the previous decade. I wanted to find out if he knew the fate of the project, and especially what happened to the three air cars I knew of that Terry had built. The interview was not recorded, but I have summarized it below based on notes from our conversation.

Paul Trentham is a consulting engineer, among whose accomplishments is that he worked on the Apollo engines for the moon shot in the 1960s.

Paul got involved with the Joplin air car project about the time Terry got out of it. (Editor's note: Terry was the inventor, and Toby his business partner; Terry gave his share to his daughter, Teresa Robbins. Terry and Toby are now deceased.) Toby called Paul and explained that he and Terry had come to an impasse, that the partnership was not working out, and that Terry had lost interest in pursuing it. Paul was asked to make an analysis of the invention to determine if there was any practical use in continuing it. Paul only met Terry once, and was not well acquainted with Ms. Robbins, Terry's daughter. His dealings were with Toby.

Regarding the air cars that Terry built, Paul recalls only the blue Chevy Sprint (editor's note: there was also the famed "Air Car One," a three-wheeled workbench on wheels that Terry showed from coast to coast (1980s), and a red compact car, probably either a Chevy Sprint or a Ford Festiva (1990s, called "Miss. Rexroth," the blue car was the "Spirit of Joplin")). Paul met Teresa Robbins, Terry's daughter, at a meeting where the project collapsed and everyone went their separate ways. Ms. Robbins has moved away from the Joplin area. The project had no tangible assets at the time of its dissolution, and the blue car was mashed for scrap. Paul never saw Air Car One. He still has a number of high pressure air tanks, originally made for CNG usage, and would like to sell them. Most have never been used.

Paul wrote his report in about 1992 or 1993. The good news was that he found a definite use for compressed air as a motive power for vehicles. The bad news was that he felt Terry's way of going about it was all wrong. In Paul's opinion,

which was based on computer models and other research, multiple expansion is impractical because it can only be optimized at one set of conditions: one speed, one cutoff. He is convinced that the 2nd, 3rd, and 4th expansion stages on Terry's engine were actually dragging on the 1st stage, instead of augmenting its power. Paul tested the car with a simple Prony Brake placed on a front driving wheel, the other driving wheel on the ground. The power of the engine was measured and found to be pulsating and unsteady, falling to zero and rising to about 1.5 hp. This seemed reasonable with the knowledge that all of Terry's cars needed pushing to get them started, even on a flat surface. He felt that compound engines could work well for a steady speed stationary engine, but less so for locomotion, and certainly not more than two stages total. He cited Norfolk and Western Railroad efforts with two stage compound steam locomotives based on the Mallet design originating in France. The compound idea was well known in The Steam Age, but never more than two stages in locomotives, and for good reason.

He felt it would be much more practical, in a vehicle engine, to use a single-stage engine with variable cut off. Some air is used inefficiently at long cut offs required for acceleration from zero, but the time is so short the loss is not worth the extra complexity of multiple compounding. The most economical use of air seems to be at a very short cut off of only 5%. To realize high efficiency at such a short cutoff requires near zero clearance space in the engine cylinders, and very good seals. Rotary valves help to reduce unwanted clearance space, and have no reciprocating mass problems causing vibration and wasted power loss.

Toby asked Paul to design a better engine, which he did. He determined that the most efficient cutoff point would be 5%, but in order to start and accelerate the car, something like 50-60% would be needed. At this cutoff range, the engine would develop enormous torque, as in steam engines, and no transmission would be needed. (Note that Terry's vehicles also had no transmission, but never achieved much torque or power due to the ineffective and complicated multiple compounding scheme.)

Paul designed and built a variable cutoff engine over the next three years, converting a Honda 500cc V-twin motorcycle engine to run on air. He moved the equipment from the Joplin air station to his home and built a garage and shop to house the project. He invented a rotary valve to eliminate complicated reciprocating valve parts, which allowed faster engine speeds than the old-fashioned expansion engines were capable of, and a simple cut off control valve. One rotary valve took care of intake and exhaust, (flow to and from the cylinder) while another small variable cut off valve ahead of the intake/exhaust valve adjusted the cutoff (the amount of stroke during which the inlet valve was open.) Although he was not happy with the seals on the valves, it did work. It developed about 9.5 horsepower at 5% cutoff, and was operated up to 800 psi. Higher pressures were not used due to the leaky valve seals.

He accidentally discovered that the engine would function well at up to 14,700 rpm, by opening the engine full throttle from rest, with no load. The engine jumped almost immediately to that speed, and ran at that speed with almost no vibration. The compressed air was entering the engine at the pressure tank's ambient temperature of 83° F., but he had trouble measuring the exhaust temperature at 5% cutoff because the expanded air bottomed out his temperature gauge, which couldn't go below -75°. He has a VHS tape somewhere, showing that if you blew across the engine's exhaust stream, the moisture in your breath would freeze and fall to the ground as snow. The engine ran smoothly down to about 30 rpm.

The University of Washington, Seattle, got interested in the engine. The Aerospace Engineering Department had been working on a liquid nitrogen car, which used a marine auxiliary steam engine they had found and adapted for their purposes by installing it to run a small mail truck. They invented and patented a triple-pass heat exchanger that warmed liquid nitrogen up to nearly ambient temperature, using the free energy of the atmosphere to do the warming. Paul spoke very highly of their heat exchanger, saying that it did not freeze up and functioned very well. After trying the former steam engine, they had some grant money left, so Paul sold the engine he had developed to the U of W and they put it in their cryogenic car. The young professor working on the project was Dr. Carl Knowlen, whose address is U of W College of Engineering, Aerospace Building Room 136, Seattle, WA. The head of the department is Dr. Adam Bruckner, and his predecessor, Dr. Abe Hertzberg was the founder of the nitrogen car project. Dr. Knowlen wrote SAE papers on the car, but the project ran out of grants.

Paul questioned the use of liquid nitrogen by the U of W project, rather than liquid air. The U of W was concerned about using liquid air because they thought the oxygen would separate and cause a fire hazard in an accident. Paul says that since the molecular weights of oxygen and nitrogen are very close, the cost of a stirring device to keep them from separating in storage would be insignificant. Dr. Knowlen studied the use of cryogenic air and nitrogen and the economics and safety issues, and delivered a paper at the Society of Automobile Engineers conference in Los Angeles. This was during the popularity of battery powered cars, so it did not get a lot of attention.

Paul still thinks that air is the way to go. He never got to finish what he wanted to do with his engine. He is now working on a rotary valve for internal combustion engines, with fully variable timing. He has been granted two patents for his rotary valve and has another patent in the works.

The seals on the original short cutoff engine limited the pressure and therefore the effectiveness and efficiency of that engine. A different approach on the seals would be used if further air engine designs were undertaken.

Paul notes that a cryogenic car can be run on ordinary compressed air by bypassing the heat exchanger, although the inverse is not true. He states that the cryogenic car has the advantage over the compressed air car, in that it can store 2.5 times more air in a given tank at a given pressure. Therefore the cryogenic car can exceed the range of the pneumatic car by more than twice. The cost of doing that is to have a U of W type heat exchanger on board to warm the cryogenic air up to near ambient, with the "free" ambient energy. It is this ambient energy converted back to useful driving energy that extends the driving range of the car by double over the compressed air concept. Another way of stating it is that the car can carry twice as much mass of air as a liquid, but it all comes out to the same impressive gain in on board energy storage. You get air conditioning as a side benefit whether the car is running on cryogenic air or highly pressurized air.

Paul is still interested in working on air engines and would be willing to be hired on to do engineering work on either cryogenic or pneumatic systems. He strongly believes in the superiority of the cryogenic system, which would need to be supported by tanker trucks transporting liquid air to cryogenic air stations, because of the greater range between fill-ups compared to the compressed air car.

Paul's own written explanation of the advantage of cryogenic-over-compressed air is reproduced here:

"Liquid air is much denser than pressurized air. We were using lightweight tanks designed for and used by the CNG (compressed natural gas) cars. CNG burns cleaner than gasoline, and is used in some places, but has much lower energy availability, generates Carbon Dioxide, etc., so it probably won't ever be THE solution. These tanks are good for, I believe, 4000 psi. Because cryogenic air (liquid air) is a liquid, instead of a gas, it is much denser, or about 2.5 times as heavy as even the highly pressurized air at around 4,000 psi. (I hope my numbers are right, it has been several years since I went through this). You see, air is quite light at atmospheric pressure, but it gets more dense as you pressurize it. If you pressurize it to two atmospheres, that is to say, about 30 psi instead of 14.7 psi, then it is twice as dense, because you have twice as many molecules in the same volume. And so forth. And when you go from high pressure (about 3500 or 4,000 psi) to liquid, you get about 2.5 times as much liquid air in the same volume tank that held the high pressure air. Above 4,000 psi, it is not practical to pressurize air and haul it around in a tank, it is generally agreed it is too dangerous if ruptured, it is like a damn big gun exploding. So that is sort of the agreed on upper limit for hauling around pressure vessels of anything safely on the highways, air included. Plus the tanks get to be very heavy walled, and expensive, and weigh a lot.

"Liquid air is made in large plants by pressurizing the air, and then removing the heat caused from the pressurization, and then doing it again and again, until it collapses from the gaseous state to a liquid, and it is very cold, I can't remember, lousy memory, but it is around 200 degrees F below zero. Now it is not under great pressure as a liquid, but will vaporize and turn back to gaseous air as ambient heat leaks in through the tank, and that causes the pressure to rise, so you have to insulate the container, and that is often done by making a Dewar flask, which is like a thermos bottle. Fortunately there are some really good insulators from the past few years, and you can insulate a tank with stuff like glass foams that do a great job of keeping the liquid air cold. Even so, there is a little heat leaks in, and I think they figure on losing about 5% in a week, due to heat leaks, and having to vent the excess pressure off.

"Dr. Knowlen and I looked at this several years ago and he wrote a paper on it, so you guys might call Washington U in Seattle and ask him for a copy. I got one somewhere, but it is filed away in the junk, but I remember that we found out from the big suppliers that it costs about 15 cents a gallon to make liquid air. Carl figured it out for reasonable mileage and storage, and I think it came out that liquid air was the equivalent, economically, of operating a gasoline powered car at \$1.30 per gallon. So you see, the economics are not at all bad, and no gas price wars with the Arabs and Californians driven by environmentalists to not build more refineries, etc.

"Liquid cryogenics, mostly Oxygen, Nitrogen, Argon, and CO₂, are hauled all over the country in those long shiny tank tractor trailers, and I have never heard of a bad accident like you have with gasoline tankers. The big liquid air plants are expensive to build, so they haul their product hundreds of miles. They crack off Oxygen, Nitrogen, Argon, etc. from these plants much like you do in a petroleum refinery, based on their liquification temperature. They don't explode, not even Oxygen, because there is no fuel to ignite when the tank breaks. Remember, the pressure is not high!!! Oh the oxygen will burn anything organic it touches, like gasoline, that is how the Moon rockets worked, and you don't need a spark plug. But by and large it is safer to store liquid air than it is to store gasoline, in my opinion.

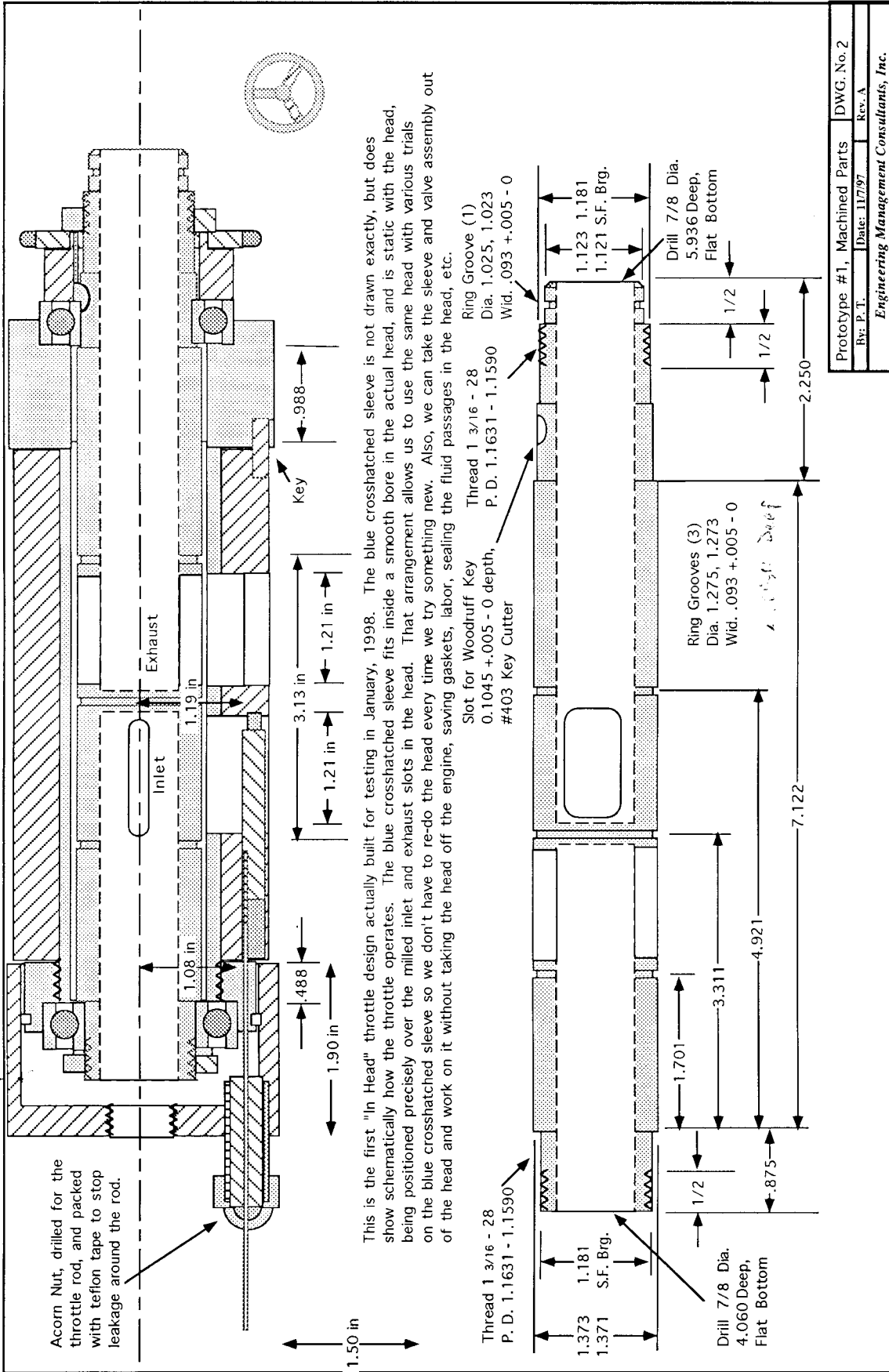
"You could have filling stations just like you have now, only they would have insulated liquid air tanks. They get filled once a week by the big highway tankers. Special nozzles used to fill the liquid air tank in your car, not a big deal, and not at high pressure like the

pressurized air tanks. If you have a leak, so what? The liquid air quickly vaporizes, and turns into air, and it is much cleaner than the air in LA, because liquifying it takes out all the dirty stuff. Neat, huh?

"Still won't have as good mileage range as gasoline powered cars, but about double what you will have in pressurized air cars. And if you are remotely located and don't have a liquified air station, just use your handy dandy high pressure air compressor and run the car at half its liquid air range. The liquid air tank will probably have the same pressure rating as the high pressure air tank.

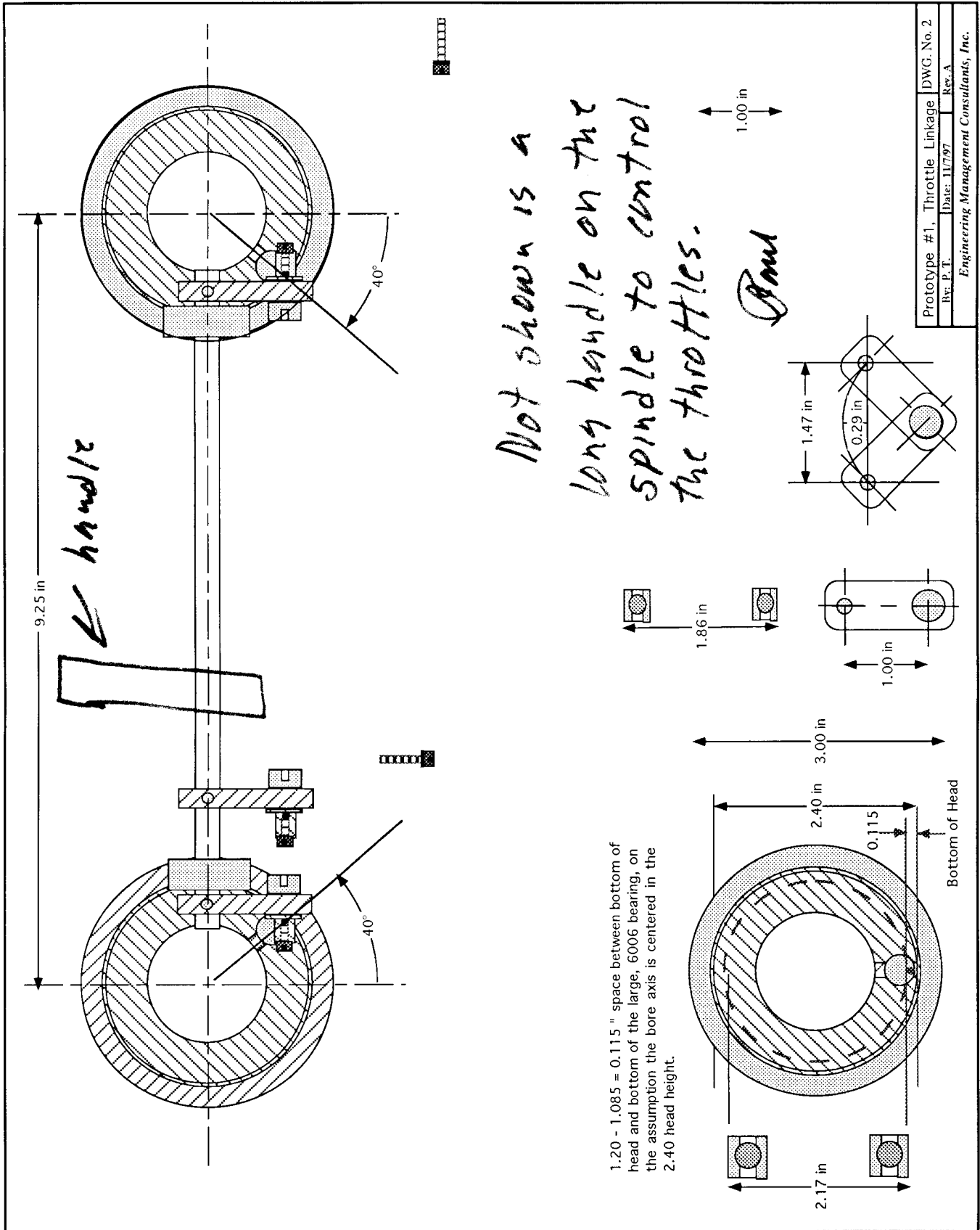
"A word about air conditioning. You don't get the AC from the very cold liquid air, you get it from the expansion of the air in the cylinder. So you get A/C whether the car is liquid air or pressurized air tank. I was taking air at about 80 degrees F from a pressurized tank and putting it through my engine at several hundred psi, and it was expanding to do work in the cylinder and coming out the exhaust at below 75 degrees below zero and you could make it snow by blowing your moisture laden breath across the exhaust. My seals were not very good, so I only ran at 300 to 700 psi, and that is not very efficient use of the air, but the engine ran as high as 14,700 rpm, and, by the way, there was almost NO vibration, and it would run nicely down to about 30 rpm. You do not need much if any transmission in a "steam" (Rankine thermodynamic cycle) engine. Lots of torque when you need it for short time, though inefficient at long cut offs.

"Cryogenic air doubles your tank range, and it is safer than high pressure air. You can use the same vehicle and tank for high pressure air, it is just a little bigger with the insulation. I would rather hit a cryogenic tank full of liquid air, than a 4,000 psi air tank. The difference in explosive power and potential hazard in an accident is enormous. Spilled cryogenic air on asphalt, might or might not burn the asphalt, I don't think so, as 80 percent of the liquid air is Nitrogen, and non flammable. It boils off to become air very rapidly. That is why you want to use liquid air, rather than liquid oxygen, and you don't need to go all the way to liquid Nitrogen to make it safe, but some tests would be needed."



This is the first "In Head" throttle design actually built for testing in January, 1998. The blue crosshatched sleeve is not drawn exactly, but does show schematically how the throttle operates. The blue crosshatched sleeve fits inside a smooth bore in the actual head, and is static with the head, being positioned precisely over the milled inlet and exhaust slots in the head. That arrangement allows us to use the same head with various trials on the blue crosshatched sleeve so we don't have to re-do the head every time we try something new. Also, we can take the sleeve and valve assembly out of the head and work on it without taking the head off the engine, saving gaskets, labor, sealing the fluid passages in the head, etc.

Carl, we got rid of the cap, and replaced the undesirable valve in the inlet side with a smaller bearing in an improved design, but have not built it yet. Paul



From knowlen@aa.washington.edu Wed Feb 23 10:25:03 2000
Date: Wed, 27 Oct 1999 14:07:05 -0700 (PDT)
From: Carl Knowlen <knowlen@aa.washington.edu>
To: LN2 -- abe hertzberg <plueagle@aol.com>,
Adam Bruckner <bruckner@aa.washington.edu>,
Carl Knowlen <knowlen@aa.washington.edu>,
Tom Mattick <mattick@aa.washington.edu>
Subject: LN2 leaks 2 of 2

----- Forwarded message -----

Date: Thu, 26 Aug 1999 16:48:20 -0500
From: Paul Trentham <tigertrentham@4state.com>
To: Dave Scanlan <daves@afmusa.com>, Carl Knowlen <knowlen@aa.washington.edu>
Subject: Re: Seals for UW Rotary valve application

Dave,

I was pleased at your quick response. I have tried to reach Dr. Carl Knowlen, UW in Seattle, who is our contact on that project, but he is out. We frequently correspond by e-mail or phone. UW has completed two DOE research grants on this project in the last 4 years, but currently have no research funding to continue work on it. Their physical effort has been to design and install a "vaporizer", which converts the cryogenic fluid to a gas. This is accomplished by using the warmth of ambient air to "boil" or vaporize the cold cryogen fluid, and it accomplishes this without freezing up the heat exchanger with the moisture in the warm ambient air. They have converted a small postal van as a "test mule", and have our rotary valve engine, or "expander", installed in it. They have an insulated flask on board to contain the cryogenic fluid, LN2, and also their "vaporizer", to provide the gas phase at pressure to our engine. It works, and they drive it around the UW campus in Seattle.

We sold them the engine last year before we had completed development of the seals. It works quite well, but the seals we used were not adequate, and should be replaced and re-designed. This approach is unique, in that it uses the warmth of the ambient air to recover energy removed from the working fluid in the cryogenic cooling process. As a an added benefit in some applications, the gas gets quite cold again as it expands through the engine, and provides on board air conditioning as a natural consequence without further energy usage except for a fan and heat exchanger.

Dr. Knowlen and others in the Aerospace and Energetics department at UW have written several papers on this concept. His most recent paper was presented last week at the SAE meeting in Costa Mesa. It is available through SAE or UW. In this paper, He explores the economics and physics of using Liquid Air rather than Liquid Nitrogen, as is currently being used in the "test mule", and the theoretical results are encouraging. The economics are also quite encouraging, as it turns out that the cryogenic cost is dependent primarily on the cost of electricity. The cryogenic suppliers routinely transport liquid Nitrogen and Oxygen in bulk in insulated transport trailers hundreds of miles. Storage in dewars appears to be quite safe, and the leakage or boil off can be quite low.

We hope to continue this research with UW, and need to improve the seals as one of the objectives in the next steps to be taken. Dr. Knowlen has also investigated adding heat to the cryogen by burning small quantities of fossil fuel. This approach provides an LEV or Low Emission Vehicle, compared to the ZEV, or Zero Emission Vehicle up to now. You may know that the Battery Cars are, for all intents and purposes, dead. They just did not work out for a number of reasons. Currently, Hybrid vehicles are receiving the most attention, and the LEV using some fossil fuel, CNG, or gasoline, based on the cryogen system looks very competitive. Burning a fossil fuel to heat a gas is much more simple and efficient in extracting the heat value of the fuel than in any 4 stroke engine as the other Hybrids are doing, and the exhaust emissions

X

are much lower.

To provide you with some dimensional data, I can tell you that the UW engine rotary valve diameter is 1.373/1.371 inches, with three ring seal grooves 1.275/1.273 inches, and 0.093 +0.005 -0 inches wide. The bore this valve rotates in is polished, and 1.375. Rotary valve and bore are aluminum. We are currently using 15% Graphite 85% Teflon solid rectangular section rings as seals, and the a dry film lubricant.

We are also experiencing considerable leakage at a stainless steel piston control valve. It has no seal at present, is 0.250 inch dia., and was made for a slip fit in an aluminum bore. We need a seal, or seals for it also.

We can provide some oil lubrication on the low pressure side of the rotary valve and the slideing piston control valve, if necessary. We have used Mobil One sythetic with no problems in the present engine.

The piston valve moves very slowly and only occaisionally. The rotary valve rotates at speeds up to 7,000 RPM. Pleas note that eventually the seals experience higher temperatures if the added heat of the LEV approach is used. I expect that those seals may require something similar to current usage in Turbochargers, where the first seal exposed to hot exhaust gases in similar to a piston ring, followed downstream (lower pressure) by a hot oil seal. We are using that concept in our latest work, and provide oil cooling at the second seal to cool the seal and the rotary valve surface it seals against.

Some very interesting industrial applications have arisen. I am not at liberty to discuss them at this time. We are very close to being able to disclose more proprietary information involving patents, but may require and non-disclosure agreement for the interim.

We look forward to working with you, if you think you can help. We expect some re-machining would be necessary in the existing seal grooves, new grooves on the control piston, and reworking the valve bore and control piston bore on the UW engine, and possibly some provision for seals lubrication.

I hope this is helpful in uderstanding our needs.

Paul Trentham, P.E.

Dave Scanlan wrote:

> Paul, we have many seals in many applications. I believe we will be able to
> help you if we can get more information on your problem. Our company is
> familiar with difficult applications and we are familiar with large volume
> of parts. I would be interested in looking at the application that you
> spoke of at the U of WA. We can handle AutoCAD DWG files or DXF format.
> Could you please give us your address or phone and we can start on your
> project. Dave Scanlan 206-575-1998 206-575-2122 fax
> daves@afmusa.com

>

> -----Original Message-----

> From: Paul Trentham <tigertrentham@4state.com>

> To: daves@afmusa.com <daves@afmusa.com>

> Date: Wednesday, August 25, 1999 12:22 PM

> Subject: Seals for Rotary vlve application

>

> >I have need for a number of circular seals for rotary valves. The
> >valves distribute air at temperatures ranging from -100 degrees C to
> >ambient. The seal fits in a groove on the O.D. of hollow stainless
> >steel cylinders approximately 2 inches diameter. (detailed DWGS can be
> >provided if you can provide the seals.) The inside pressure of the
> >cylinder is about 50 bar (800 psi) and is released into the seal cavity

> >during rotation of the cylinder. The seal purpose is to prevent leakage
> >from slim clearance annulus between the rotating valve cylinder OD and
> >the bore in which it is rotating. The clearance annulus is at ambient
> >pressure.
> >
> >We have a similar application, except the annulus is filled with hot
> >lubricating oil, and the pressure is 100 bar. High pressure gas
> >temperature is 150 C, and is petroleum combustion exhaust. Plurpose of
> >this seal is minimize leakage of the high pressure gas into the oil
> >filled annulus.
> >
> >Very high production quantities of these seals appear likely. We are
> >in a development program in support of a unique engine concept which is
> >being patented. One aspect of it is being tested at University of
> >Washington in Seattle as part of a Zero Emissions Vehicle program using
> >cryogenic air. That engine needs improved seals, which we hope you can
> >provide.
> >
> >If you have, or are interested in providing seals as outlined above,
> >please contact me.
> >
> >Paul Trentham, P. E.
> >
> >

From knowlen@aa.washington.edu Wed Feb 23 10:24:51 2000
Date: Wed, 27 Oct 1999 14:05:44 -0700 (PDT)
From: Carl Knowlen <knowlen@aa.washington.edu>
To: LN2 -- abe hertzberg <plueagle@aol.com>,
Adam Bruckner <bruckner@aa.washington.edu>,
Carl Knowlen <knowlen@aa.washington.edu>,
Tom Mattick <mattick@aa.washington.edu>
Subject: LN2 leaks 1 of 2

----- Forwarded message -----

Date: Tue, 10 Aug 1999 11:31:53 -0500
From: Paul Trentham <tigertrentham@4state.com>
To: Carl Knowlen <knowlen@aa.washington.edu>
Subject: Re: greetings

Dear Carl,

Sorry about your lightning zapped system, and hope everything is working without any "twitching". I have been looking at the drawings of the UW expander to see how (1) the leaks can be fixed, and (2) how a variable cut off can be added, and (3) what changes would be required to use a target pressure of say 1000 psi. Perhaps you can get a lab machinist working on the leaks, with a minimum of your time and help from me advising.

(1) Leaks: I have all the possible leakage passages identified, and have a plan to fix them. The biggest leak is at the back of the throttle cylinder. The throttle cylinder bore exits the head, and is barely covered by the head sleeve cap and the external polished Aluminum cap. We need to add a threaded plug in the outside end of the throttle bore, with a hole through it for the throttle drive wire. With a close fit, hole to wire diameter, leakage should be very small, but you can pack the inside of the pressure end if you like to further seal it. I don't know why one side is leaking, and the other is not, irregularity in the sealing surfaces probably, so fix both sides anyway.

The rest of the leaks are theoretically solvable with a circular seal. We tried a nearly solid rectangular section Teflon and 15 % Graphite seal, but these are what is in the engine now, and they are not very effective, and should be replaced with a new type of seal. The worst case is the single seal groove in the middle outside of the valve between intake and exhaust ports. Leakage here goes directly to exhaust in a short path, and you can hear it "hiss" through the open exhaust port. I wish there was axial room to put a second and third seal at that location, but there is not.

What is required to improve this seal and the other circular seals on the valve is to abandon the Graphite Teflon, and make the seals from either Buna N, (I think brake cylinder seals are made from this), or pure Teflon. Standard hydraulic seals may be available in the size you need, or modifiable, or you can machine them from Teflon with small chevron skirts that will flex slightly under pressure to provide closing force around the sealing surface. Teflon should provide improved wear under rotating conditions, and your lab machinist can machine it directly from stock. This is the same cross section geometry of the typical rubber pressure seals in hydraulic systems, for example the brake cylinders on cars with the old drum brakes. The only difference here is that we also have the surface rotating in the seal, so it is more like a shaft oil seal. You will note that we have no oil supplied at present to the present seals, because we were trying to do it with a dry lubricant on "hardcoated" Aluminum surface, but that has not worked very well. The seals proposed herein will probably require a more fluid lubricant, such as a low temperature grease or oil. An oil drip into the sealing space should work quite well. Bore and tap a hole through the top of the head into the seal space, put in a few drops of oil, and then screw the plug back in. If it works well, it will not use much oil. The seal lip triangle should be small and rather thin, on the order of 0.005 or

0.010 thousandths of an inch. Be guided by the form and size of the typical brake cylinder seals. It should be thin enough to bend and conform to the seal surface, yet long enough radially not to be blown double back through the clearance space between the two sealing parts. Care should be taken in assembly to get them in the right direction according to pressure, and to get them in the bore without folding them over.

I know that you do not have a Student (Academically Indentured Servant!) to work on this, but I doubt that you need one. Most of them would just be in the Machinist's way for what is required, because what is really needed now is a good lab machinist and a stick of Teflon. What I have described should make good sense to your lab machinist, and he may be able to cut and try some seals as described if you give him the idea and leave him alone to work on it. (Most good machinists are like that, in my experience. Many of them consider Engineers and such as a real pain in the ass, and mostly in their experience, that is for good reason.) It is not likely that the seal will have much drag even at high pressure, because the surface area of the flexible lip is so small you cannot get much pressure force on it to lock down the surface under torque. It doesn't have to be a perfect seal, but a very good seal will do nicely.

(2.) Variable Cut Off: I know that Dr. Bruckner in particular wanted Variable cut off, and it is a good idea. There are some problems however. High Cut Off uses gas at a high rate, and that means that (a), the gas supply line to the expander heads has to be appropriately large to carry the higher mass flow without significant friction and pressure drop. It also requires (b) the ability to generate the gas at that rate in the vaporizer (boiler), or to have an auxillary high pressure storage chamber filled with max pressure. Problem with that is the auxillary storage chamber volume has to be about 10x the size of the mass of high flow gas intended to be used in order to minimize (to 10 %) the wasteful pressure drop within the auxillary chamber. Similarly, if you are going to generate the high flow rather than store it, the vaporizer (boiler) has to be oversized to the same extent as the high mass flow. If you want to double the mas flow, even for a short time, the vaporizer has to be twice as big, (all the time). The best practical alternative is to carry a propane torch to augment the vaporizer, or to use as a superheater. At any rate, for the present engine let us assume the present one half inch gas delivery lines to be unchanged, though the engine could use considerably larger lines.

The Variable Cut Off requires some attention to the variable resultant head port opening size and shape. In general, the range of variable port size can be smaller with higher pressure, and all of the variation should be controlled in such a way that any downstream area and volume is reduced compared to upstream, such that pressure drops are minimized. This leaves friction losses and the fluid dynamics gets somewhat simpler, but it is primarily a slot flow system with periodic interruptions. I do not know how to analyze that, and need some guidance. I expect this is common knowledge in aerodynamics, as slot flow in the subsonic range of our engine inlets should be well understood. Basically, I am narrowing a 0.20 inch wide slot for Cut Off, and closing the 1.25 inch long length of the same slot for Throttle. If this is a bad slot shape to use for up to 1,000 psi, let me know. Also, what mass flow can be expected with reasonably small friction losses in such a slot if it is wide open. Finally, how thin can it be made before it stalls, "wiredrawing" the old steam engine designers called it. I have three different schemes to consider for cut off control when I have some sense of these flow conditions.

(3.) 1,000 psi Engine: This depends almost entirely on the seals described in (1.) The rest of the engine can take it easily, except for the large polished aluminum caps. Note that they are fastened to the head with two capscrews. I haven't stressed it out, but I think they must resist about 3 or 4 tons of force at 1,000 psi. I do not want anybody hurt, so check that out and strengthen the caps to head connection if it is necessary. I have had it up to 800 psi before I realized that, and it didn't break, but I

didn't do it again. With good seals, the cap should not pressurize, so you could drill a hole in it (say, quarter inch dia. at the bottom so it drains) to make it safe, and also to listen for leaks in that area. Also check out the front cap, but I believe it is safe as is.

In summary, fix the seals first, enlighten me regarding fluid dynamics for 1,000 psi, and we may add a variable cut off after we have the seals satisfactory.

I will not be going to Costa Mesa after all. Good luck with Allied Signal meeting. I think we have a potential winner for deep mining, and need some research money to prove out the system working on cryogenic Air. It should be cheaper than pumping all that air and Diesel exhaust they have to contend with now, and a lot cooler.

Give my regards to all, especially Dr. Hertzberg.

Paul Trentham