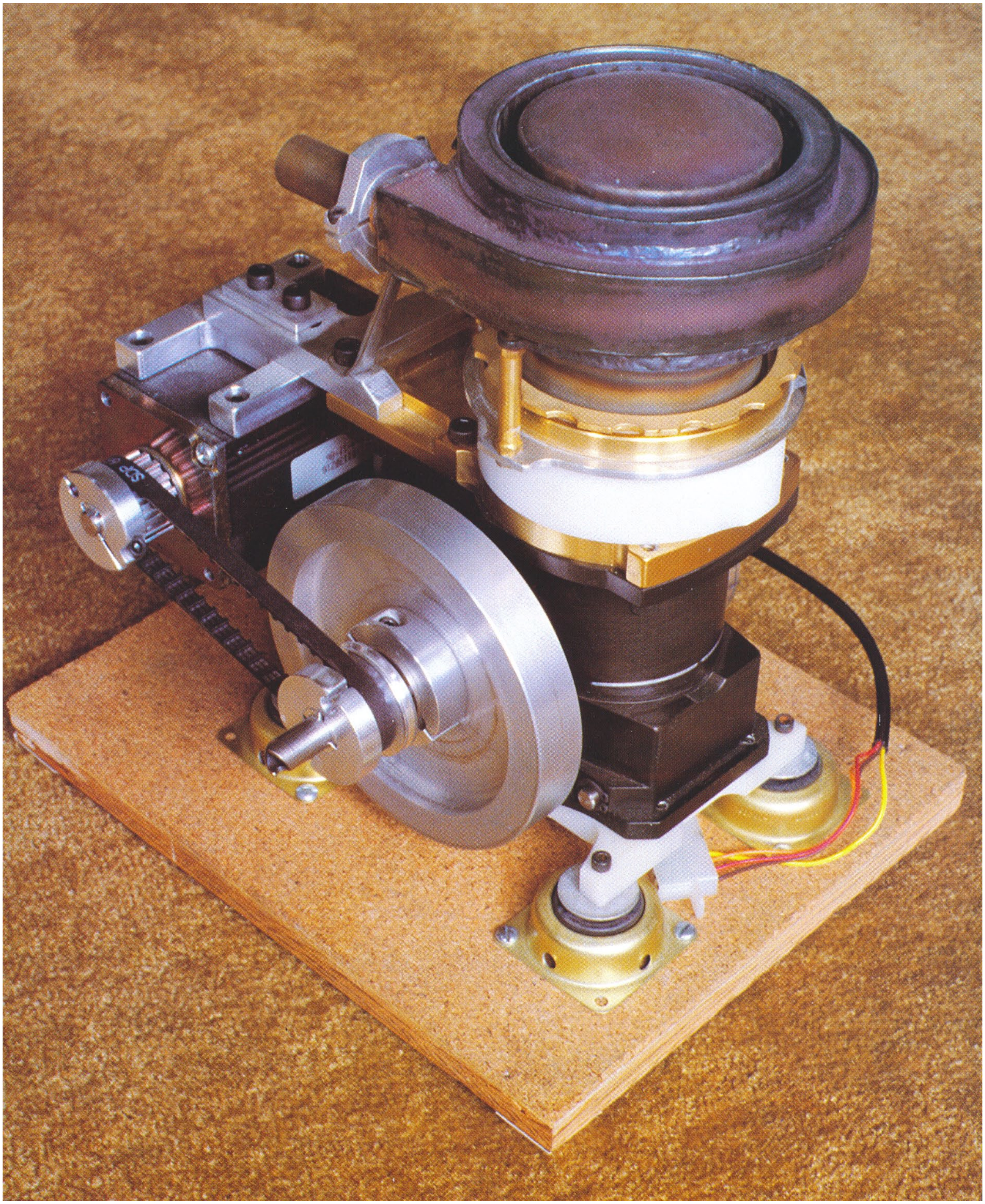
Making Stirling Engines

Andy Ross



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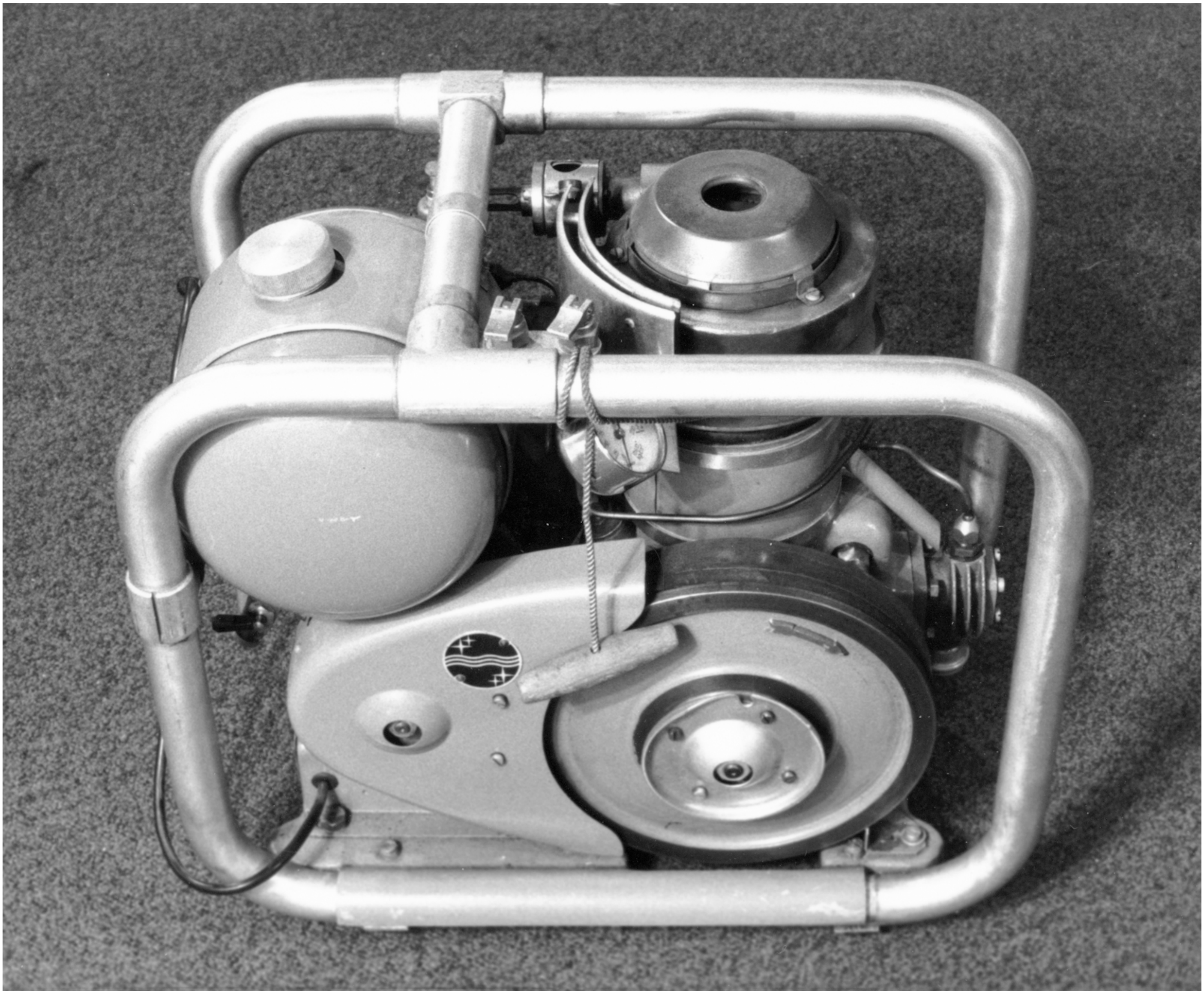
Andy Ross - January 10th, 2011

Cover photo: D-60 engine with generator

Facing page photo: 65cc rhombic

Both photos and engines by the author.

Making Stirling Engines



The Phillips MP1002CA stirling engine generator set (author's collection).

Imagine a small engine for your bicycle, canoe, or campside generator that is as quiet as a sewing machine. Its exhaust flue gases are nonpoisonous, nonpolluting and practically odorless. It starts easily, and should run without repair for many hundreds of hours, burning less than one-half liter of kerosene per hour.

Such an engine was developed 40 years ago and incorporated into a small generator set by the Philips company of Holland; it is the modern stirling air engine.

Unfortunately, only about 100 of these units were made before Philips suspended production, having concluded the 200 watt output was inadequate for commercial success in the world market at that time. Subsequent research bypassed the small air-charged stirlings, in the pursuit of larger helium and hydrogen-charged machines.

Upon first reading about the Philips air engines, I wondered why, 25 years later, such supposedly simple, reliable, and quiet engines were completely un- available and largely unknown. This puzzle so intrigued me that I decided to make a stirling air engine and find out.

What began as a hobby project quickly grew into an obsession, and I have devoted a significant portion of my time to working on stirling engines ever since. This book chronicles that work, with the aim of encouraging and assisting others interested in making small stirlings.

I assume the reader is already familiar with the basic operation of the stirling cycle. For those who are not, I recommend starting out with Jim Senft's recently-published primer, "An Introduction to Stirling Engines", which, along with other sources of additional information, is listed in the bibliography.

The Briefest of Brief Histories

The stirling engine is an externally-fired heat engine invented in 1816 by a young Scottish clergyman named Robert Stirling. With the help of his brother James, Stirling designed and built a variety of large pressurized stirling engines that were safe and fuel-efficient, and until the mid nineteenth century the stirling engine was considered a promising competitor to the developing steam engine. Certain parts of these engines operated continuously at a red heat, however, and the iron alloys of that day were incapable of such duty for extended periods of time. This limitation eventually removed the stirling from the most important categories of power generation, inhibiting further development. Throughout the balance of the nineteenth and into the early twentieth centuries, the stirling was applied only to such undemanding chores as powering household fans and water pumps, where, under the common name of "hot air engine", it earned a reputation for safety, quiet operation, and reliability.

The stirling was obsolete and nearly forgotten by 1937, when engineers at Holland's N.V. Philips Company were looking for a simple, reliable, and long-living engine to generate 10 to 20 watts of power for their radio receivers in remote regions where central station electricity was unavailable. One of the engineers found a small hot

air engine at a flea market, which proved to have a thermal efficiency so miserably below what theoretical considerations would suggest possible that further investigation became irresistible. Thus began the Philips work on stirling engines.

By 1946 Philips had made immense progress; applying heat resistant stainless steels and modern design and heat transfer knowledge to the stirling, they had increased its power per pound by a factor of 50, reduced its size per unit of power by a factor of 125, and increased its speed by a factor of 10. They also published several landmark articles on their work, announcing the birth of the modern, high speed, air-charged stirling engine. These articles are essential and fascinating reading for any serious student of the stirling, and are listed in the bibliography.

How it works

The stirling engine is based on the natural fact that the pressure of a gas in a sealed container will increase if the gas is heated, and decrease if the gas is cooled. The engine is designed so that the working gas sealed within its cylinders is first compressed, then heated to increase its pressure, then expanded to produce power, then cooled to lower its pressure, then compressed to begin the cycle anew. Since the gas is at a higher average temperature, and therefore pressure, during its expansion than during its compression, more power is produced during expansion than is reabsorbed during compression, and this net excess power is the useful output of the engine.The same gas is used over and over again, making the stirling a sealed, closed-cycle system. All that is added to the system is high temperature heat, and all that is removed from the system is low temperature (waste) heat and mechanical power.

There are three basic types of stirling engine. One type is called the "gamma" engine, wherein the heating & cooling function is performed in one cylinder by a reciprocating element called a "displacer", and the compression & expansion function is performed in a separate cylinder by a power piston.

A second type is called the "beta" engine, which is like the gamma engine except the piston and displacer are mounted concentrically within the same cylinder. The concentricity of these reciprocating elements usually requires that a drive rod from the displacer extend through the piston, which is a subtle but important mechanical disadvantage. On the other hand, the proximity of the displacer and the piston allows for a lower dead volume, and higher compression, efficiency, and power. The rhombic drive is often applied to this type of engine.

The Duplex Vacuum engine (left) was typical of small stirlings used for various domestic chores from the 1880's through the 1920's. (Model by the author, photo courtesy of John Griffin)

A third type is called the "alpha" (or "two piston", or "Rider") engine, wherein two pistons in separate cylinders cooperate to perform both the heating & cooling function and the compression & expansion function. The key to understanding the alpha engine is to realize that since the cylinders are at all times in open communication with each other, the compression & expansion cycle leads the cold piston motion by one-half the phase angle, and follows the hot piston motion by a like amount. Therefore, most of the working gas is in the hot space during the expansion stroke, and inthe cold space during the compression stroke. The V arrangement and the yoke drive (Ross linkage) are often applied to this type of engine. For larger engines, the alpha may be made double-acting, as in the Franchot, Rinia, or the Siemens engines.

Some Generalizations about Design

The three basic types of stirling described above may employ a wide assortment of possible crank drive mechanisms, or none at all, as in free piston stirling engines. The main requirements are high mechanical efficiency and simplicity, with other important considerations including good dynamic balance, the ability to operate with minimal lubrication, and compactness. But how does one choose among the numerous options? It is easy to become too absorbed in these matters. There is no one-and-only way to build a good small stirling engine. As I look back on my early work with the rhombic drive, I now realize that even my first working engine could have been developed into a very useful machine, had I continued to develop it, rather than move on to other ideas.

Superimposed upon the mechanical design is the thermodynamic design, which in a stirling engine is concerned primarily with getting the maximum amount of heat into and out of the engine through the heater and cooler, and recycling the maximum amount of heat in the regenerator, with as little temperature drop, pressure drop and dead volume as possible. These desired qualities often conflict with each other, and so judgment and prior experience are required.

Thermodynamic design also includes questions about phase angle and the motions of the pistons as imparted by the crank mechanism, or mechanical design. So we have come full circle back to questions of mechanical design.

Indeed, upon examination the stirling presents the designer with so many interrelated variables that a sort of mental paralysis can set in. How can one rationally design an engine when there is so much one doesn't know that seems essential?

In my early stirling work, I was deeply troubled by these matters. For example, I laboriously charted out hot and cold space volume variations for every 15° of crank rotation for four versions of rhombic drive geometry, for the Philips 102C bell crank engine, and for several versions of alpha engine. There were seemingly significant differences between them, and I worried that without computer analysis or expert assistance there could be no hope of designing a good stirling. Through experience I learned the following useful things:

1. Read the relevant literature, but do not become overwhelmed by it. Much of it deals with fine points of theory that are of marginal use to the engine designer, whose primary concerns are such practical problems as making a more efficient burner, improving the life of a bearing, or sealing the pistons with less friction and leakage. These sorts of challenges are what must be solved to get a stirling up and running, into the field for testing, and perhaps into some suitable niche for commerce. Only then does further refinement become useful or possible.

2. Beware of the common idea that existing gasoline or diesel engines, or oilless compressors, can be readily converted into stirlings. Plenty of people have tried this idea (including yours truly), and it usually fails. It simply entails too many compromises, as most of these machines have inadequate seals, excessive friction and unsuitable lubrication systems for use as a stirling.

3. Talk to or correspond with the authors of interesting books or articles or others who are involved in building stirling engines. Once you have read the useful literature and done some independent thinking on the subject, people in the field will be happy to talk with you and share ideas. You will learn a great deal more in this way than you will from merely reading the literature.

4. Study and restudy the design and performance data of every real stirling for which you can find such information.

5. Keep it simple, Most everyone's early designs are too complex and impractical, and most do not run. The essential starting point is a prototype that runs.

6. Keep your program focused. Select an engine size that is appropriate for your uses and stick with it, developing it as far as possible. Building prototypes of differing sizes is extremely wasteful of time, energy, and enthusiasm. It is the practical, not the theoretical, problems of scaling that will prove the more frustrating.

7. Pay great attention to mechanical details. Make sure the piston(s) seal well. The engine should have a "bouncy" feel as it is turned over compression (like that of a good model airplane engine), and the seals should be able to hold most of the compressed gas at top dead center for four or five seconds. If the compression feels "mushy", the engine will run poorly, if at all. Take care to keep friction as low as possible. Never be satisfied with binds or kinks in the mechanism. With the mechanical details done well, then one knows to look into the heat exchangers and burner for the answers to poor performance.

8. Take great pains to get the heat into and out of the working gas; you can never have too much active surface area, especially in engines charged with air.

9. Become your own machinist. It will get you quality parts on time, and encourage design simplicity. Or perhaps I should say, redesign simplicity. Countless times I have stood idle at my lathe, lazy as always, and mentally redesigned a complex part into a simpler one, before I could muster the enthusiasm to begin making it. Another advantage of doing one's own machine work is that formal drawings are unnecessary; mini-

malist sketches will serve perfectly well.

10. Be on the lookout for subtle problems that can absorb incredible amounts of power, such as heater conduction losses or crankcase pumping losses. Great patience is often required to solve these problems, and a little luck helps, too.

11. Get your prototype out in the field for tests as soon as possible. It is the best possible reality check.

Getting Started: The First Ten Years

My active interest in stirling engines began in 1971 when I discovered the Philips literature and was inspired to design an air-charged stirling of several horsepower for use on a bicycle. The project was expected to take about a year.

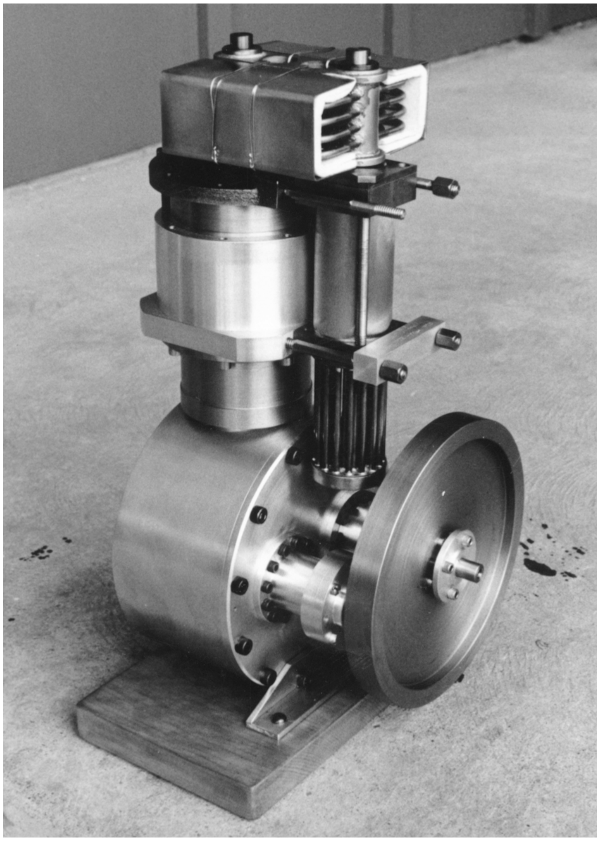
My initial design was a complex mess, featuring twin double throw cranks, scotch yokes with rollers, twin cylinders, and a novel speed control system with several valves and passages upon which I had recently obtained a patent. After nine months of work, I wisely decided to scrap it entirely, and build a simpler engine based on Philips' rhombic drive. After many more months of effort, this new engine was finally ready for its initial test run. Unfortunately, even with the heater tubes glowing bright red from the heat of a propane torch, the engine would do nothing more than turn six or seven feeble revolutions at a time, and then stop.

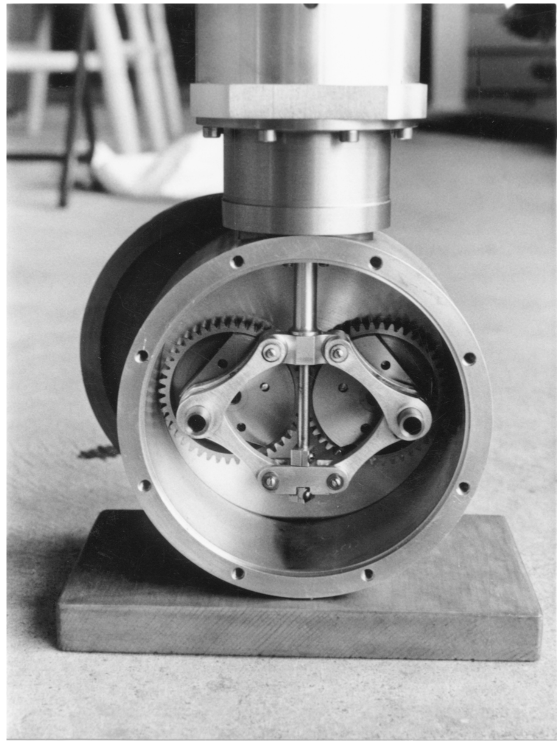
Putting this failure aside, I promptly undertook to design and build a V·2 alpha stirling based on an automobile freon compressor. This engine was to be a quick project that would be completed in one month and would raise my sinking morale. It actually took five months of spare time to complete, and it, too, showed no serious inclination to run. So it was that I spent two years of quite considerable effort in reading the stirling literature and designing, machining, and building engines, and yet was still unable to get an engine to run, let alone produce any useful power.

By this time, the "let's put one on a bike and have some fun" idea was long forgotten. I was now obsessed with the idea of the modern stirling engine, per se, and I was determined to have the satisfaction of seeing one of my engines run. To that end, I wrote to Ted Finkelstein, to obtain the benefit of his wisdom.

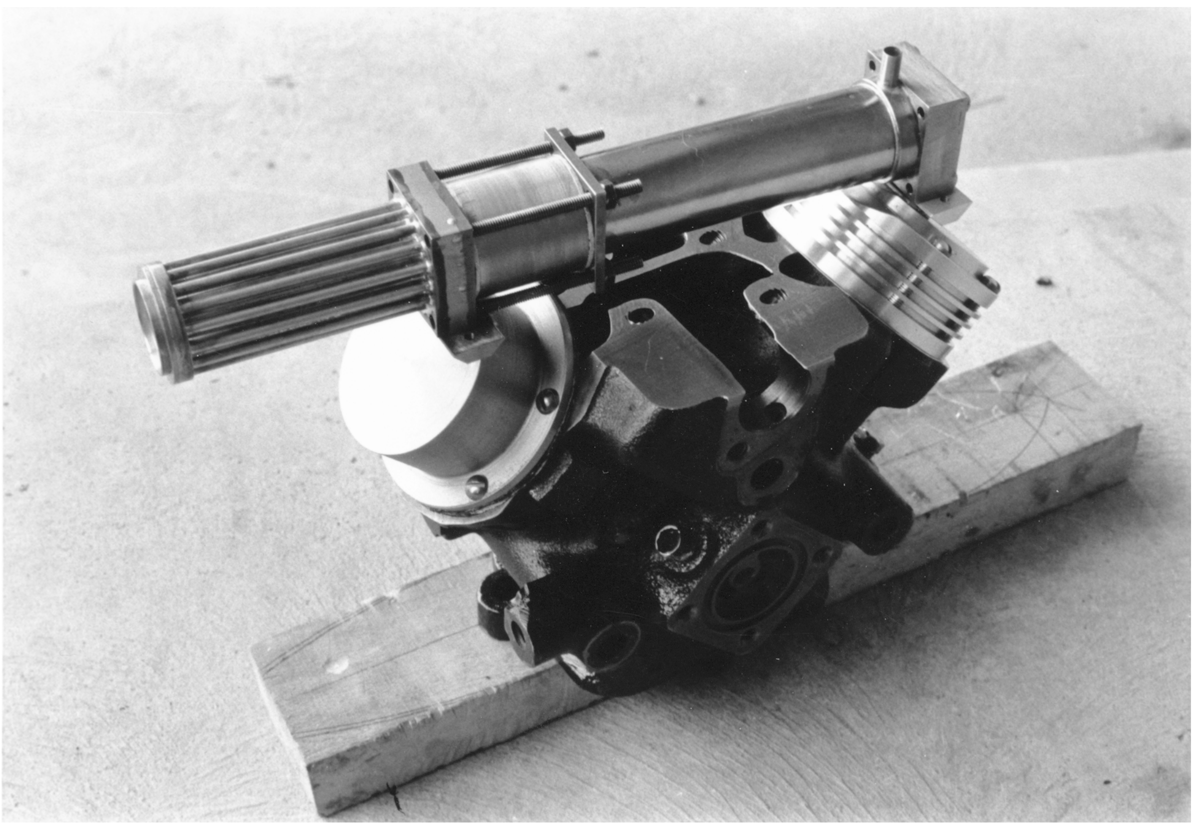
In his kind response of August 1, 1973, Dr. Finkelstein wisely suggested that I go back to the basically sound rhombic design, eliminate the complex valved speed control mechanism, and modify the heater to minimize thermal losses.

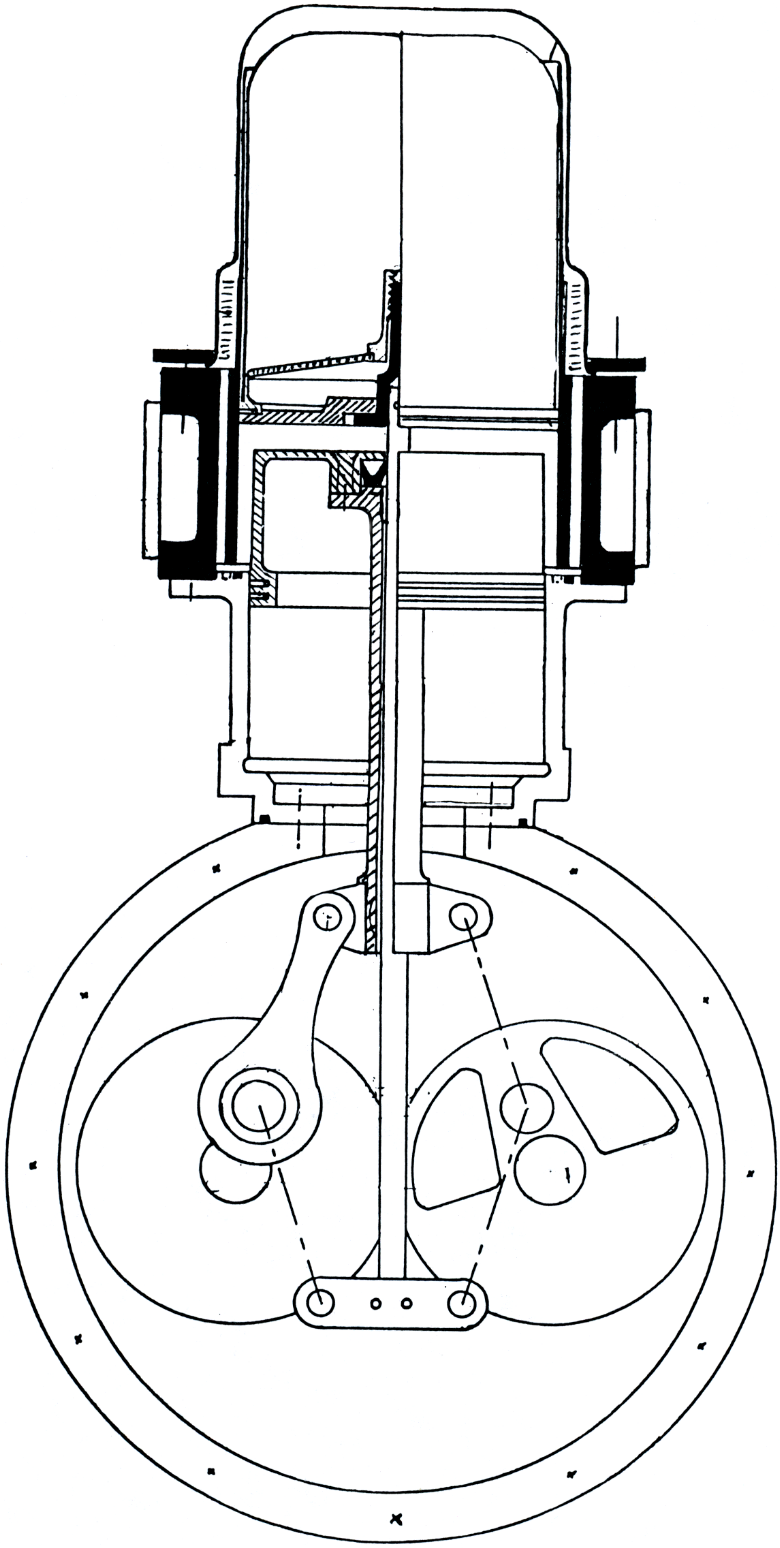
In accordance with this advice, the 65cc (cc = cm3 swept volume) rhombic was rebuilt with a simple stainless steel annular heater, which surrounded the engine's hot space and thereby greatly reduced conduction losses from that space.The new heater also eliminated the excessive internal dead volume associated with the original tubular heater. In addition, a new, thin-walled stainless insulation dome on the displacer replaced the original aluminum dome, further reducing the conduction of heat out ot





The 65cc rhombic in its original form (above & left). Below, the V-2, based on an automotive freon compressor.





The 65cc rhombic in the form in which it first ran.

the hot space. In all other respects the engine was left as it was, since mechanically it was already quite good. Its friction was low and its seals were excellent. Both the piston and the displacer used two-cycle engine racing·type piston rings, which are thin chrome plated steel rings with very low outspring. One unusual feature of the design is a displacer bore (2.280 inches, or 58 mm) larger than the piston bore (2.135 inches, or 54 mm), which eliminates the need for the conventional piston side clearance cutouts, turning what would have been dead space into displacer swept volume.

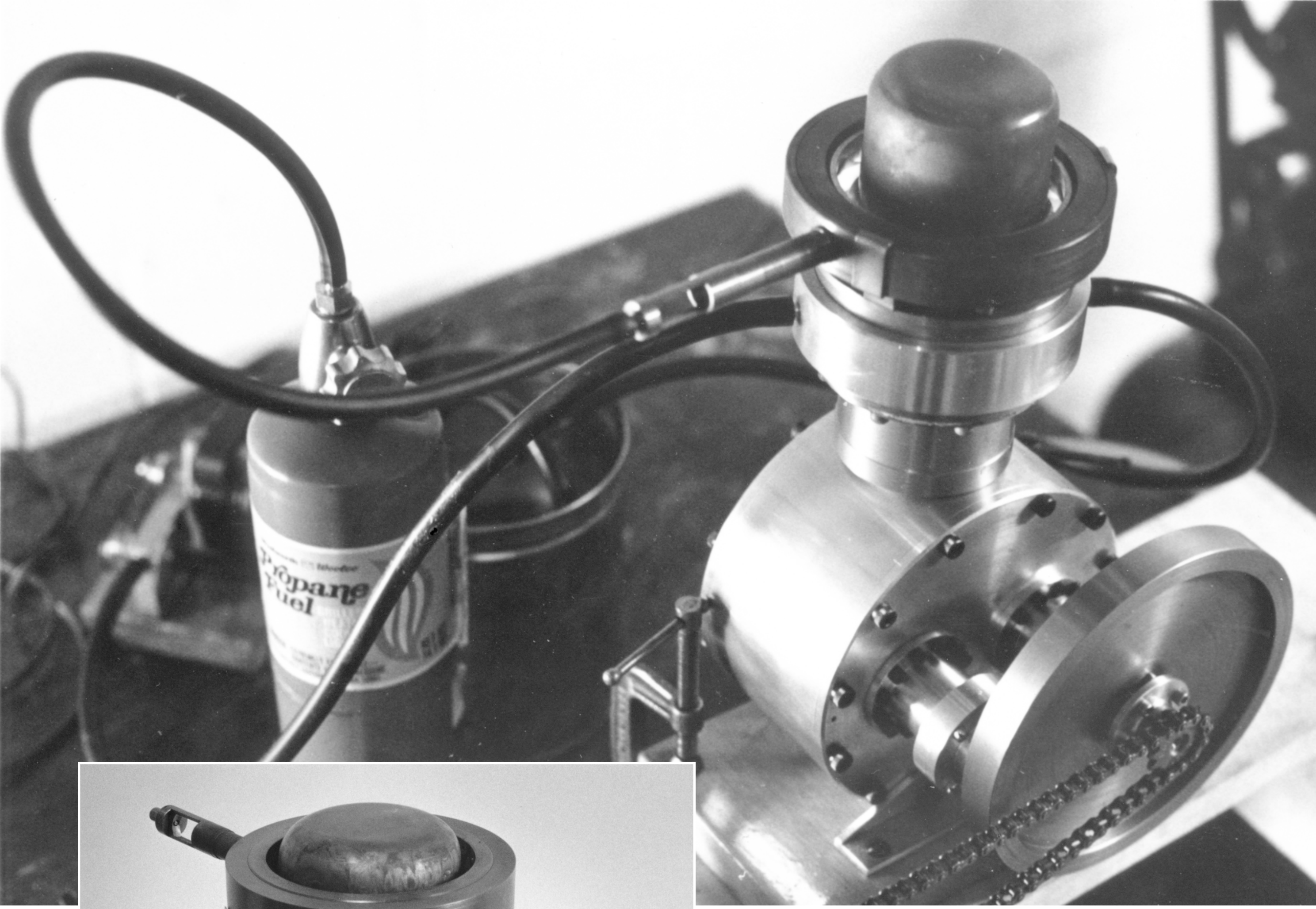
With these changes, the engine ran on its first attempt, in late January, 1974. At that time, it had no proper burner, but was merely heated by a hand held propane torch. Nor did it have any regenerator matrix. Despite these handicaps, the engine quietly turned 200 rpm, and I was quite happy.

It took alittle over a month to build an annular ring burner with a single row of jets and a rather crude prony brake. When these accessories were at last operational, I was shocked to learn that peak power was a mere 1.5 watts, @ 750 rpm, atmospheric, without any regenerator. With a 0.018 inch diameter (0.5 mm) wire regenerator power doubled to 3 watts.

Walker's book (see bibliography) suggested a good starting place for the gap between the heater wall and the displacer (or inner sleeve) was 0.015 to 0.030 inch (0.38 to 0.76 mm). The gap inthe rhombic was 0.060 inch (1.5 mm), so I added an inner sleeve to bring this gap down to 0.020 inch (0.5 mm). Performance improved to 3.9 watts, atmospheric, and 8 watts at 2 bar charge pressure. Next, I tried fine steel wool as a regenerator matrix, and power jumped to 7 watts, atmospheric, and 9 watts at 2 bar. Moreover, for the first time, the engine's free speed was higher at 2 bar (1800 rpm) than atmospheric (1500 rpm). By the end of April, 1974, the engine had produced 16.3 watts at 1265 rpm at 2.3 bar, with a propane torch assisting the burner. Even then, only a small portion of the heater head was even at a dull red heat. It was obvious that a great improvement in both speed and power would be available when a burner could be devised to keep the entire heater glowing bright red.

Of course, these power levels are absurdly low for a 65cc engine, but the fact that minor changes sometimes doubled the engine's previous performance was extremely encouraging, and served to further heighten my enthusiasm for experimental stirling work.

At this point it seemed reasonable to concentrate on improving the burner. I was aware that the annular type burner (similar to those Philips had used) would need 100% aeration for proper combustion, and that the ratios of the propane orifice cross sectional area to the mixer tube area, and of the mixer tube area to the burner jet area, were critical. What I did not realize was the magnitude of improvement available when the ratios were right. This knowledge came as I experimented with a set of interchangeable orifices I had made, each with a slightly different size of hole. I was used to rather mushy dark blue flames issuing out ofthe burner jets, which would barely turn the adjacent heater head a dim red in low light when the engine was not running. Most of the ori-



The 65cc rhombic with its first burner on an early brake (above), and in its present form (left).

fices produced just such flames.

But upon trying one of the smallest orifices, the burner immediately changed its entire personality. In the first place, it was cranky and hard to keep lit when the engine was cold (a variable mixture control later solved this problem). The jets would ignite and go out in a circular pattern around the burner. As the heater head became warm, however, the burner stabilized nicely. Instead of the mushy dark blue flames I was accustomed to, the jets were now producing hard, bright blue miniature torch points. And they were no longer silent; they produced a sort of sizzling sound. Best of all, the narrow strip of heater adjacent to them glowed bright red. At once, the answer to the burner problem seemed obvious. Simply stack four or more rows of jets into a burner, and find the right size orifice and mixer tube. I now knew how to put significant heat onto the engine's heater. Several new burners were made along these principles, and each one boosted performance. With the last burner, made in 1980, the engine produced 32 watts at 1350 rpm, atmospheric; 66 watts @1050 rpm at 2 bar; and 81.7 watts @1250 rpm at 2.7 bar inlet air pressure. The engine under the burners was relatively unchanged.

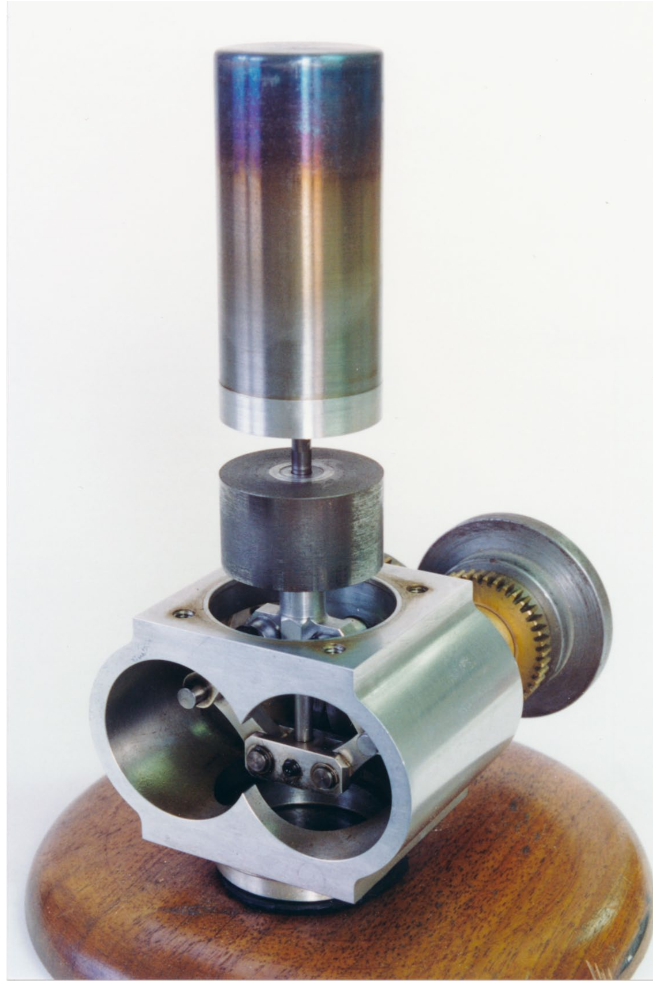
A great deal of what I learned on this engine was qualitative, rather than quantitative. For example, on various occasions the engine was running on air, and then helium was introduced into it. The speed and power would immediately increase by 50%, and the red glow of the heater head would rapidly disappear. In the darkening heater one could actually see the improved transfer of heat into the engine. Interestingly, helium has little apparent effect on later prototypes with extended surface area heaters, since they already have good heat transfer with air.

One early improvement was afinned aluminum alloy cooler, which achieved a substantially increased surface area over the original drilled cast iron cooler without any increase in dead volume. I was surprised when performance remained unaltered, but later realized that the engine was heater-limited, not coolerlimited, so the superior cooler could make no difference until the heater was improved.

Tests were conducted on various regenerator materials, including steel and stainless steel wool, woven and wrapped stainless wire, ceramic wool, and dimpled stainless foil. The stainless steel wool had numerous small particles that broke away and got into the heat exchangers. The ceramic wool broke down completely and was blown throughout the engine. The woven stainless wire and foil were the most promising, with the foil moving the peak power up to a slightly higher speed. In these and other early tests my aim was to explore as many ideas as I could in as little time as possible. I was seeking breadth of knowledge rather than depth, simply because there was so much interdependent territory to cover.

This 65cc rhombic truly was the workhorse of the first 10 years of my stirling work. It has run numerous hours on minimal lubrication without giving any trouble; and, indeed, is still doing so as a student test engine at Ohio University.

During these early years I was actively corresponding with, and meeting, just



The 11cc rhombic (above), and the 100cc rhombic (left).

about everyone I could in the field, both professional and amateur. The value of such personal contact cannot be overstated. Not only is information shared, but also morale is sustained. Stirling engine development, like any other creative work, can be lonely, frustrating, and difficult.There is no guarantee, and often little evidence, that one's efforts are not a complete waste of time. But if the small triumphs that occur and provide such satisfaction are shared with others active in the field, then all can continue their work with a better spirit.

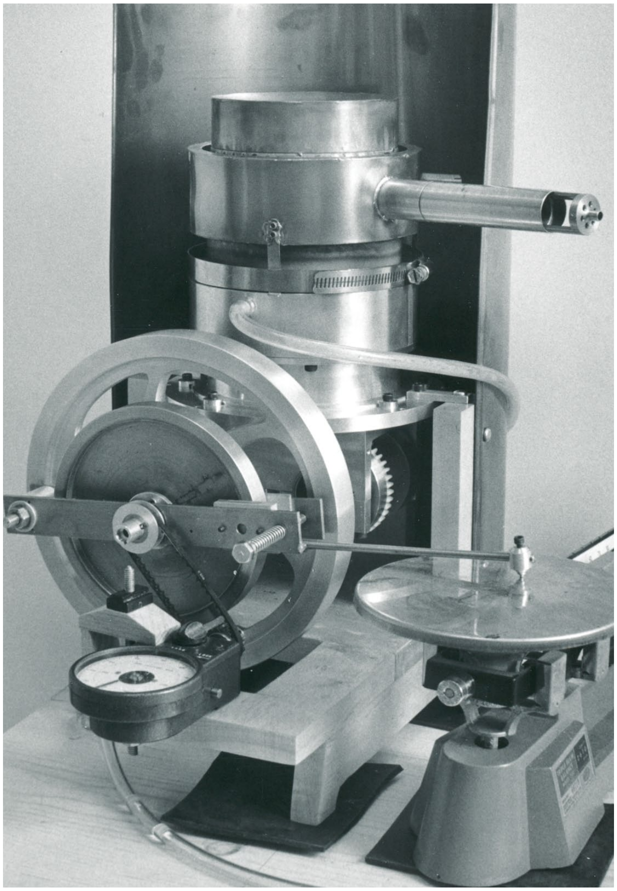
Other Rhombics

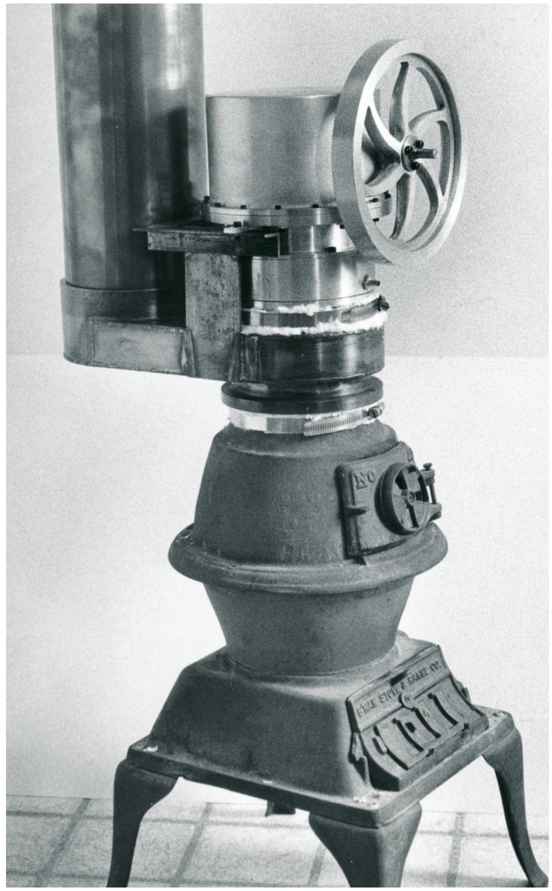
The relative success of the 65cc engine inspired a series of other rhombic designs, some actually built, others not. Among the engines actually built was a small 11cc demonstrator engine designed for an article in Model Engineer magazine. This engine employes exactly the same rhombic geometry as the 65cc engine, but scaled-down to half size. The piston is cast iron, machined to a close clearance (about 0.0006 inch, or 0.015 mm) fit in the honed steel cylinder. The displacer does not seal against the cylinder at all, but rather has 0.015 inch (0.38 mm) per side annular gap, which forms the cooler, regenerative annulus, and heater. The engine ran well from the start, producing 8.8 watts at 1980 rpm, atmospheric, and no modifications have been made to it. The entire project, including the article resulting from it, consumed only a month and a half to complete.

A second rhombic was a 100cc engine intended to be the successor to the original 65cc machine. It incorporated quiet delrin synchronizing gears, internal aluminum bronze heater tins, a separate pressurizable butter case, and clearance seals. However, the internal cross sectional area of the heat exchangers was too restricted, and the press fit between the heater wall and the internal fins produced an inadequate thermal bond, consequently initial performance was mediocre. At that time I was so very impatient to move on to such new ideas as the yoke drive that I simply abandoned this engine without any development whatsoever. Looking back on this episode, I am struck by my seemingly unlimited energy and enthusiasm, and how readily I squandered them. I would also note that the 100cc was too different from its 65cc predecessor; it was indeed a new engine in almost every respect, with all the headaches that entails. A far better approach would have been to modify the 65cc engine one step at a time, so as to learn what was an improvement and what was not.

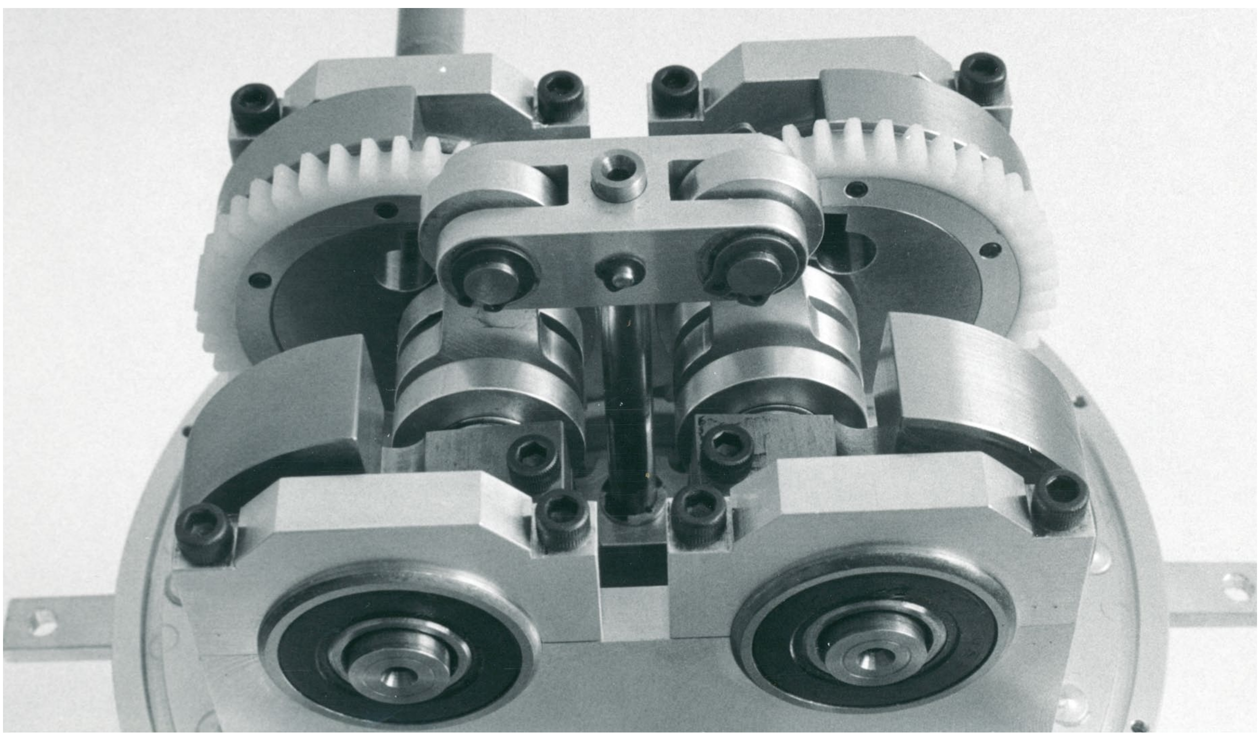
A third rhombic was a 300cc test engine built under a DOE appropriate technology grant to make a simple, low pressure, high speed hot air engine of 100 watts output. Although much larger than the 65cc rhombic upon which it was based, this engine was very much closer to that original engine in design than was the ill-fated 100cc machine described above. The DOE engine used off-the-shelf piston rings (re-machined for lower outspring and friction), a plain annular heater with inner sleeve, and a greatly larger bore (4.54 inches, 11.53 cm) than stroke (1.125 inches, 2.86 cm). It produced 112.4 watts peak power at 1150 rpm, atmospheric, and free speed was 2000 rpm. Testing under pressure was attempted, but was unsuccessful since the crankcase cover distorted un— der pressure, causing excessive shaft seal friction. By this time the grant funds had run out, and the balance of my effort on this engine was devoted to demonstration on a wood stove. This large rhombic presented few problems, other than finding the proper end gap for the rings, and the proper mixing tube and orifice diameters for the propane burner under which the power testing was conducted. There were signs that the friction could be further reduced, and the sealing improved, and I believe with more development time this engine would prove to have considerable potential. On the other hand, it was at the upper size limits of what could comfortably be made on my machine tools, so I did no more with it and eventually sold it to the University of Calgary.

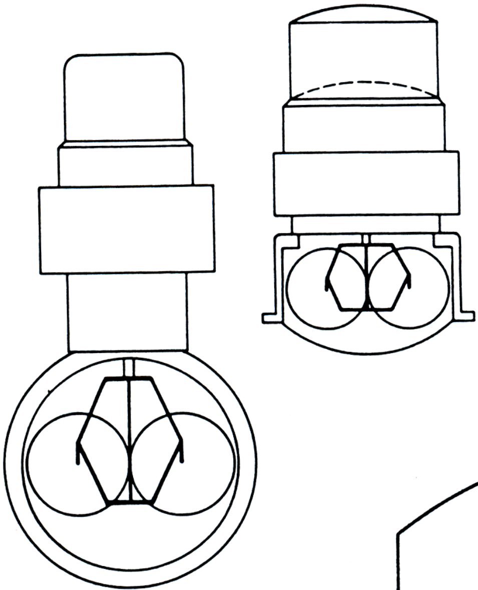
During this DOE work, it occurred to me that the rhombic drive lent itself to use in a low pressure pancake-shape engine. If one greatly increases the bore relative to the stroke (6:1 to 8:1 ratios), and uses the cylinder head, rather than the cylinder side, for the heater, then a very compact engine with ample heater surface area is possible. Several new versions of both the 65cc and the 11cc engines were designed along these lines, and overall dimensions were significantly reduced. A 1 10cc version of the 11cc engine was begun, featuring a 4 inch (10.2 cm) bore with the same 0.56 inch (1.4 cm) stroke. Overall height would be a mere 5 inches (12.7 cm), which is actually less than that of the 1 1cc engine upon which it is based. Even with an unfinned heater, there is sufficient surface area to produce 100 watts output, charged with air at atmospheric pressure. Although never completed, I still believe this design represents an excellent way to make a simple, compact, high speed, low pressure stove-top air engine.





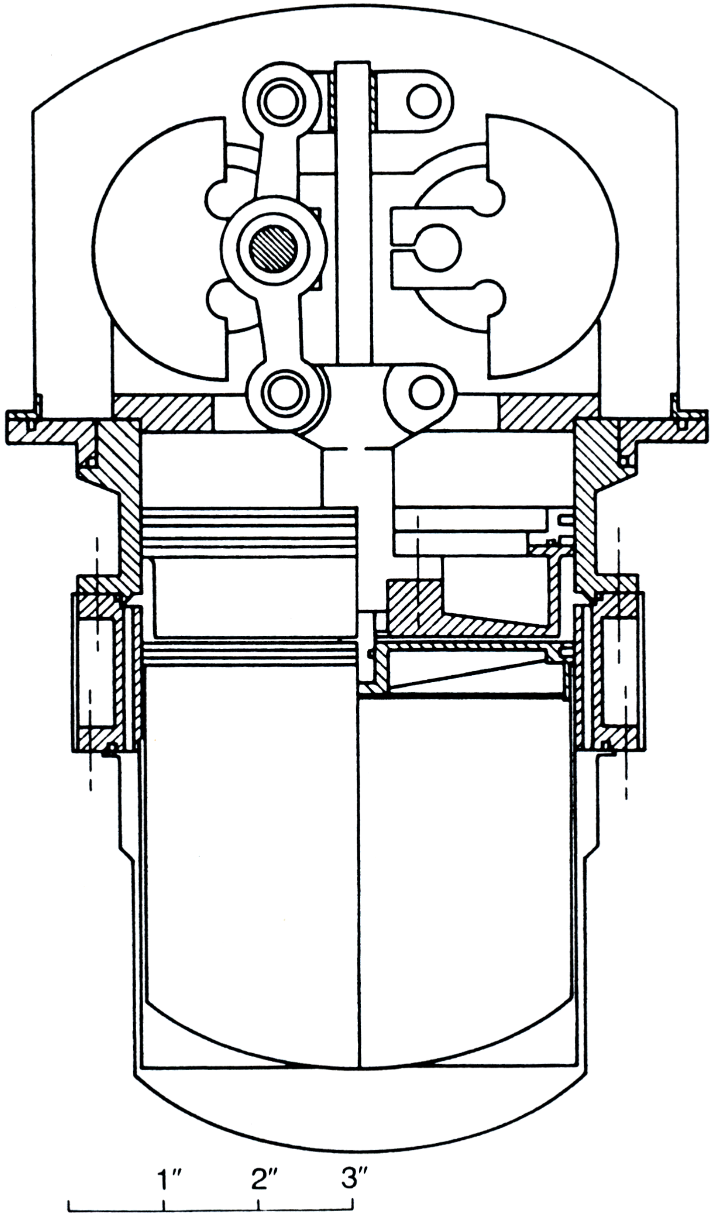
The 11cc rhombic (above), and the 100cc rhombic (left).





On the left is the 65cc rhombic, with its bore/stroke ratio of 2.125 to 1. On the right is an engine of the same swept volume, but with a bore/stroke ratio of 6 to 1. The dotted line shows the further height reduction possible if the top, rather than the side, of the cylinder cap is made the "heater".

Below is a sectional view of the 300cc rhombic.



Dead Ends and New Beginnings

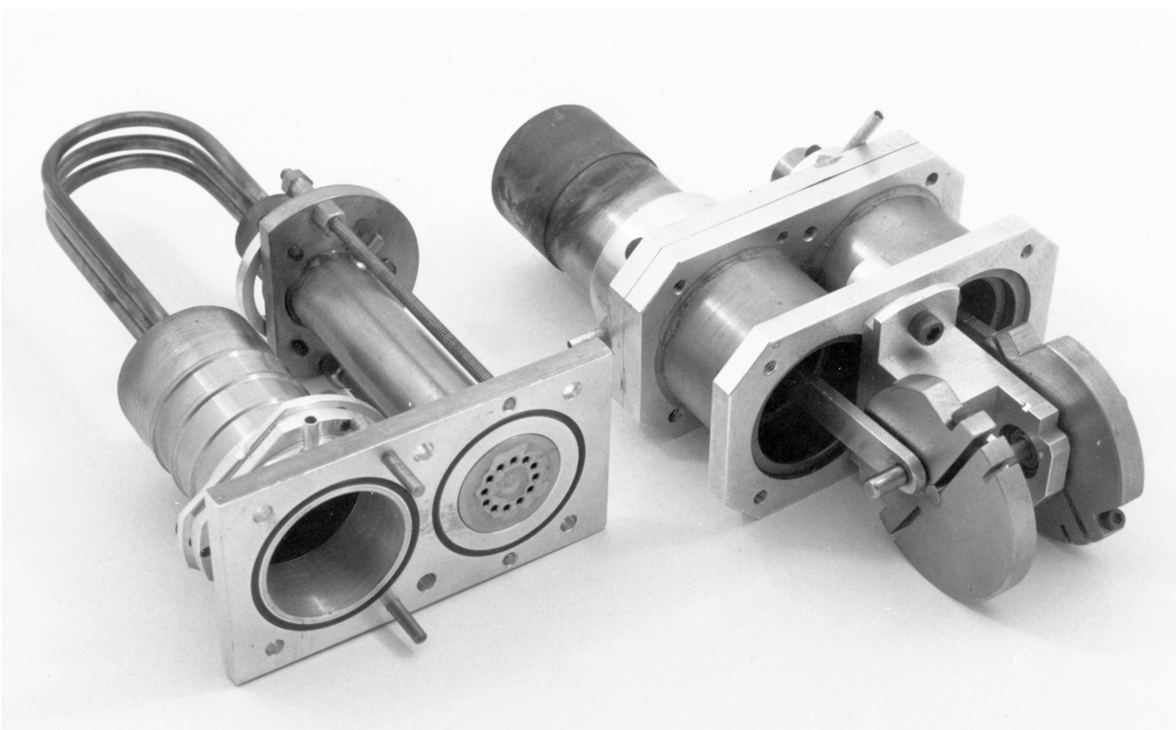
Why didn't I simply stay with the 65cc rhombic engine and develop it further? I certainly understood that it had a great deal of unrealized potential, even as I moved away from it. An extended surface area heater, additional regenerator volume, increased working pressures, anti-friction bearings on the connecting rods, and other more or less obvious modifications would all have substantially improved its performance. But there was too much I still did not know about other types of stirling to let me comfortably settle on one design for development. At this point, I had become more interested in exploring new ideas than in developing a practical engine.

The first attempt to see if a simpler approach might work as well as the rhombic drive resulted, in the Spring of 1975, in a 38cc V-2 gamma type engine, which incorporated the existing displacer dome, burner, heater, and regenerator of the 65cc rhombic. This new engine was quite easy to make, and it had excellent dynamic balance. Once afew initial bugs were worked out, the most serious of which was a leaky crankcase casting that wasted considerable power pumping air, the V-2's output and speed were (with elevated pressure) encouraging enough to spur the design of a largerV-2 gamma engine. Fortunately, before too much effort was wasted in this enterprise, comparative thermal efficiency tests were conducted which showed the V-2 to be less than one third as efficient as the 65cc rhombic. Fuel in to shaft power out, the rhombic showed an efficiency ofjust under 5%, whereas the V-2 showed just over 1%. Excluding stack losses and heater head radiation losses, the rhombic showed 13.5% thermal efficiency on air, and 16.7% on helium; whereas the V-2 showed only 4.5% on air, and 6.1% on helium. I suspect the low compression ratio inherent in the gamma type engine effectively magnified the deficiencies of the regenerator, and was the main cause of these poor thermal efficiencies. In any event, my enthusiasm for the gamma type engine faded rapidly with this knowledge.

A second and more successful attempt at simplicity was a 15cc alpha engine completed in November 1976. It featured simple annular heat exchangers like those used inthe 11cc rhombic, and very close-fitting cast iron clearance pistons running unlubricated in honed steel cylinders. Other than the care required in machining the piston-to-cylinder fits, the engine was extremely easy to make. With the conventional alpha phase angle of 90° between the pistons' motion, compression seemed so high that I seriously doubted whether the crank discs which served as flywheels would have sufficient inertia to sustain operation. What a delightful surprise to start this engine and have it run faster and faster until it reached 3600 rpm, far faster than any stirling I had built up to that time. Like the 65cc rhombic, this little alpha engine became a testbed for various modifications, such as a tubular heat exchanger system, a variable dead space speed controller, and a new yoke drive mechanism.

One interesting set of tests involved changing the phase angle in increments from 60° to nearly 180°. The engine's performance changed dramatically with phase angle. At narrower angles the engine's compression ratio became extremely high, it became

The 38cc V-2 (above), and the 15cc alpha (below).



harder to start, it required a higher hot end temperature to run at all, but when it was hot enough to run it did so with great power and speed. As the phase angle increased, the engine became more docile, easier to start, more of a low temperature engine, with lower compression and power. Although all of these differences could have been anticipated by theory alone, to experience them first hand in a real engine was most satisfying.

Another interesting test was a power comparison between the small rhombic and the alpha that Jim Senft and I conducted in Athens, Ohio, in May 1980. These engines had similar expansion space volumes, and I expected similar outputs using the same burner. But the alpha produced only 6.5 watts, or 75% of the power of the rhombic. Initially, I attributed this difference to some inherent superiority of the rhombic drive. Only later did I realize that the alpha heater was in fact somewhat shorter, and it provided only 75% of the internal surface area of the rhombic.

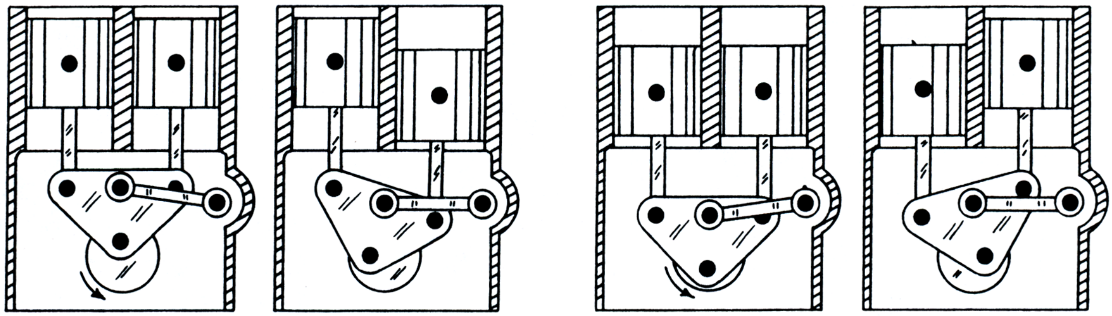
The Yoke Drive

The success of the small alpha produced a burst of activity. By December of 1976, I had devised the yoke drive mechanism (now generally referred to in the literature as the "Ross linkage") and a method to dynamically balance it (US Patent 4,138,897). The 15cc alpha engine was immediately modified to incorporate the yoke drive, and it performed as well as ever, but not noticeably better, as I had hoped it would. By January of 1977 I had begun a 50cc yoke drive engine that would employ the existing insulation dome, heater, regenerator, and burner of the 65cc rhombic. After the discouraging activities with the gamma engine, I needed some promising new path to follow, and the yoke drive seemed to be just that.

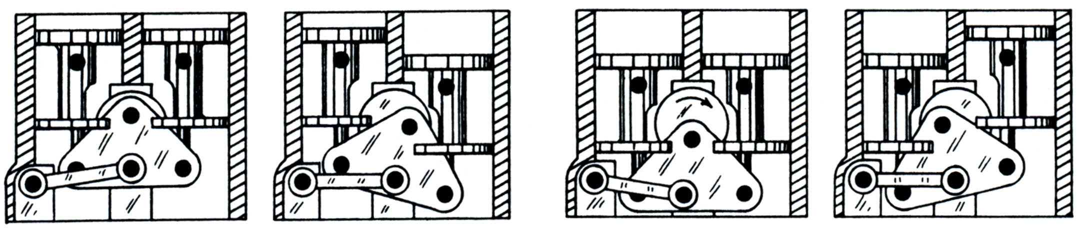
The yoke drive consists of a triangular yoke mounted on a single crankpin, and guided by a rocking lever. The combination of the circular motion of the crankpin and the arc of the rocking lever produces nearly linear motion at the extended arms of the yoke, with a phase between the motion very suitable for an alpha type stirling engine. The three major advantages of this drive mechanism are: 1) very low piston side loads, permitting long life and low friction with oil-less operation, 2) closely spaced parallel cylinders, which are easily connected with compact heat exchangers, and 3) relatively small size and low weight for a given swept volume. The use of a single counter—rotating balance shaft will put the engine in complete primary balance, or, the engine can be partially balanced without the extra shaft if some vibration can be tolerated.

During the construction of the 50cc yoke drive engine, I was sure that I had finally found a way to make a simple stirling that would perform well. When it was finally far enough along for an initial test, I wasted no time. The engine was fired up, and when the heater was red I flipped the flywheel. The engine ran, but rather slowly. It built up speed, but again rather slowly. After what seemed like 5 minutes, but was more likely only several minutes at most, the engine still did not seem to be performing well at all.

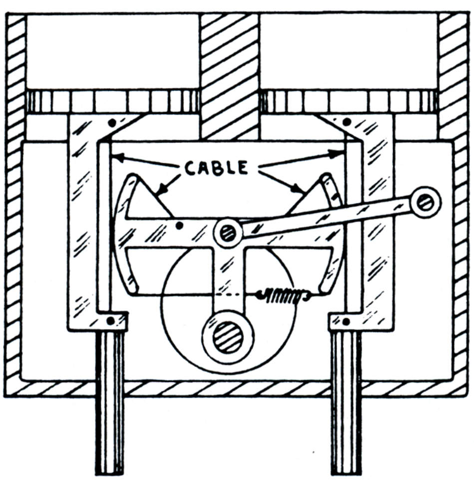
Variations of the Yoke Drive or Ross Linkage



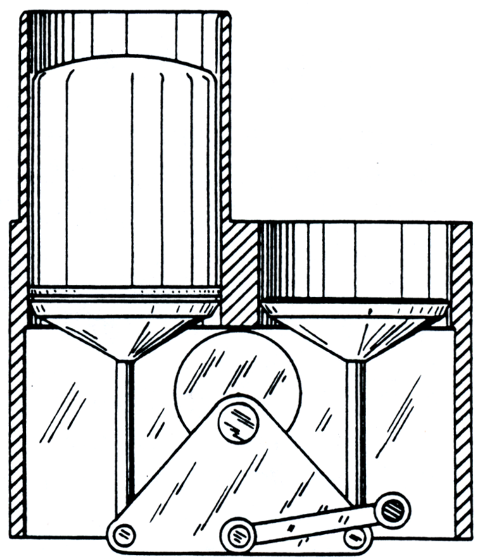
The original version of the Yoke Drive.



The compact Inverted Yoke Drive.

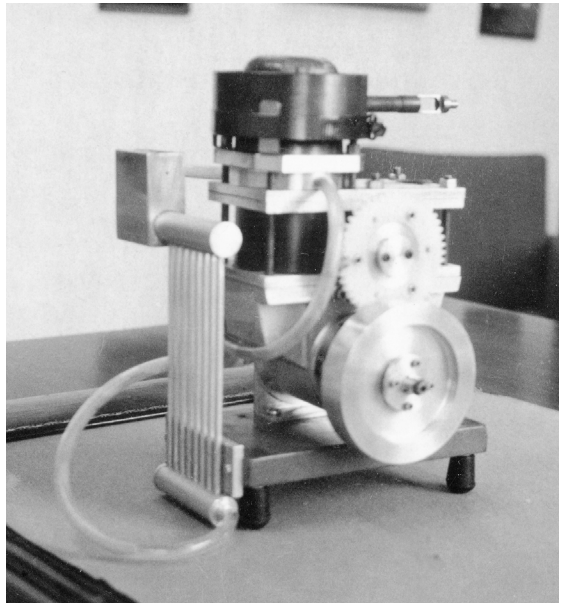


The Cable-Driven Yoke Drive.



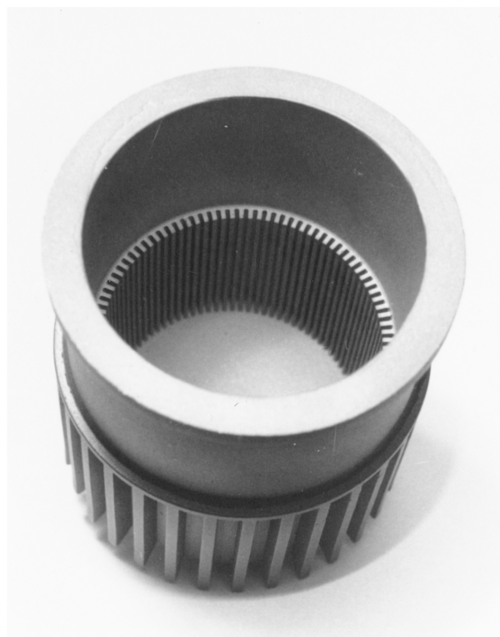
The Rocking Piston Yoke Drive.

The 15cc alpha with yoke drive,
shown with the 11cc rhombic.



The 50cc yoke drive engine.

Wax die for cast heater head.



Type 316 ss cast heater head.

In disgust and frustration, I shut it down and put it on the shelf.

Diversions

A period of extended disillusionment followed this brief initial run of the 50cc yoke drive engine. My stirling work continued, however, and considerable time was spent thinking of ways to create extended surface area in heaters. Eventually, I decided to attempt an investment cast, externally and internally finned, stainless steel heater head. After overcoming the usual unforeseen difficulties, several successful multipart aluminum dies were made to produce the wax patterns necessary for the casting process. To my dismay, the internal fins of the patterns, being 0.020 inch (.5 mm) wide, 0.060 inch (1.5 mm) deep and 0.020 inch (.5 mm) apart, proved to be uncastable by the very firm that had previously assured me they would be "no problem". These parts were eventually successfully and consistently cast by another firm using vacuum investment and a newly developed ceramic. Indicative of my sagging morale at the time, however, this successful work was never followed up by actually testing one of these elegant heaters on an engine.

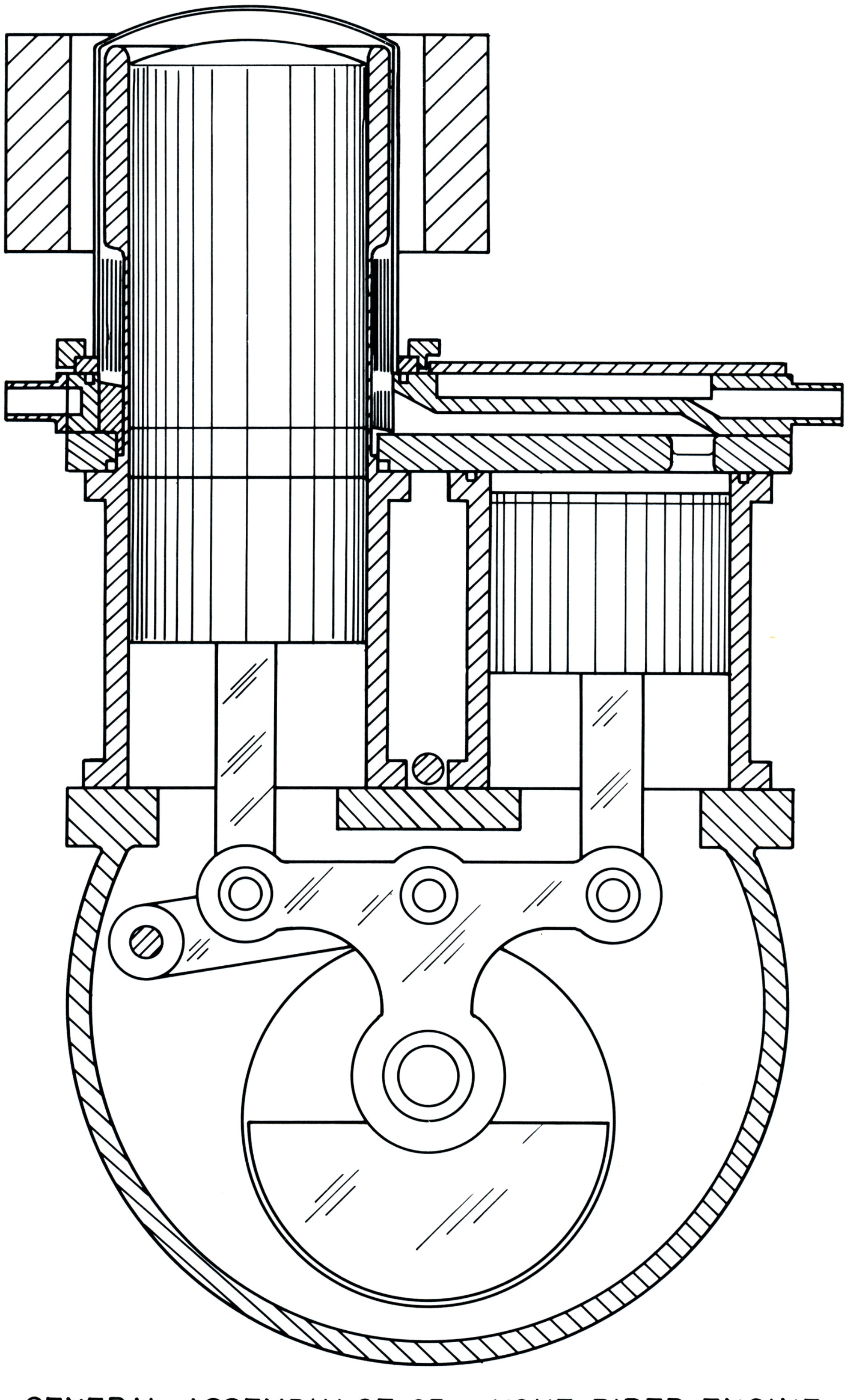
Another project undertaken during this period was a machine to dynamically test gas flow losses through heat exchangers. This machine was painstakingly designed and constructed, and then, for lack of interest, never used and eventually scrapped.

Renaissance of the Yoke Drive

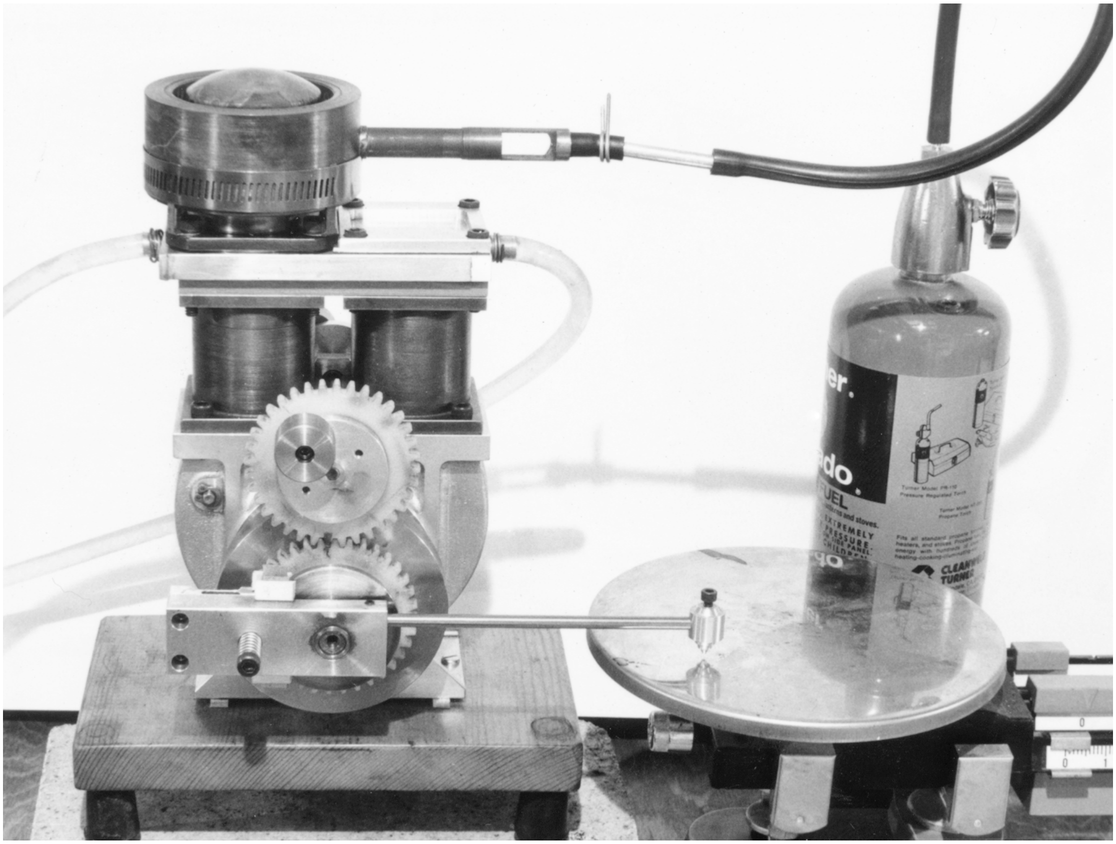
In September of 1980, Professor Dennis Chaddock of Quorn, England, stopped by Columbus to see my stirling engines. While demonstrating the 15cc alpha engine for him, I noticed that it seemed to take a longer time to come up to speed than the rhombic engines. I knew at once I'd better retest the 50cc yoke drive alpha, which had now sat on the shelf for over three years. Given a chance to properly warm up, the 50cc alpha showed very promising performance, with a free speed of 2000 rpm. I quickly built a balance shaft for the engine, and thereby confirmed that the patented balance scheme worked. My enthusiasm for stirling work was restored.

It occurred to me that a general purpose stirling engine could be designed and usefully sold as a kit in an effort to encourage more people to get involved with stirling engine development. The 50cc engine was obsolete in various ways, so a new engine was designed from scratch, incorporating everything I had learned about stirlings over the years.

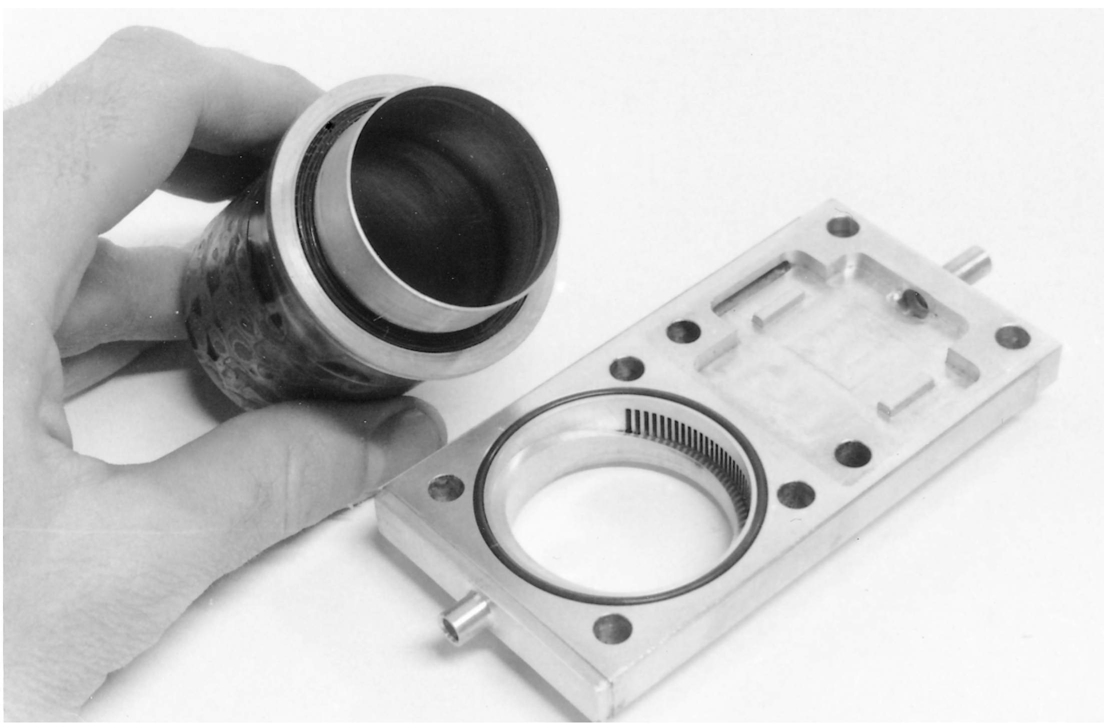
The resulting engine was a 35cc alpha yoke drive engine that was without doubt the finest stirling engine I had designed.The heater and the hot pistons insulation dome were stainless steel deep drawn cups, available commercially as cases for electronic devices. The heater was of the simple annular gap type. The regenerator was wound of stainless steel foil, 0.0015 inch (0.04 mm) thick, that had been dimpled with a star wheel

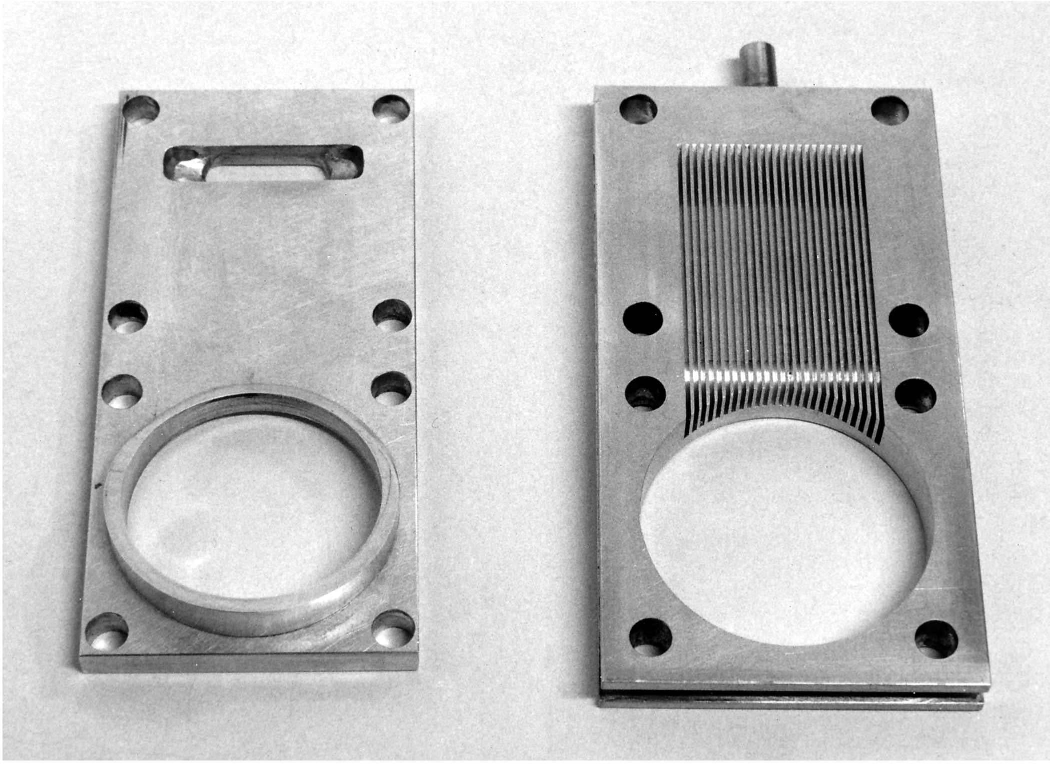


GENERAL ASSEMBLY OF 35cc YOKE RIDER ENGINE

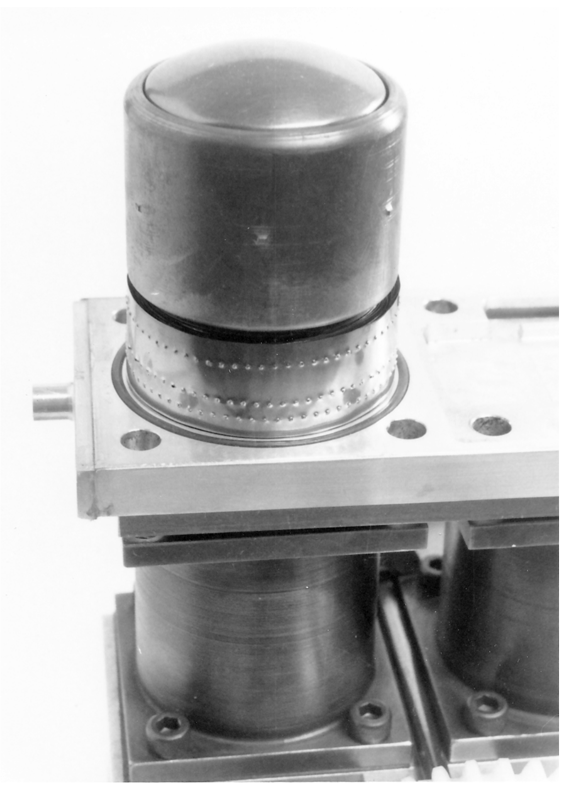


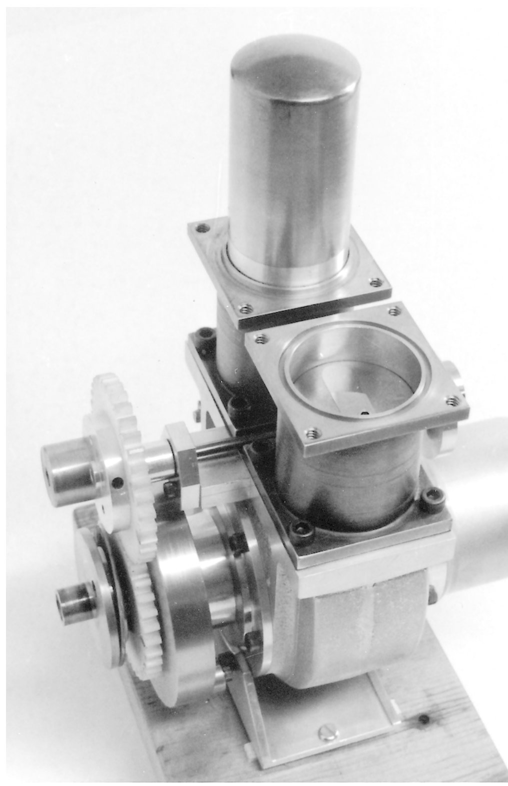
The 35cc engine (above), and its heat exchangers (below); and apart (opposite).

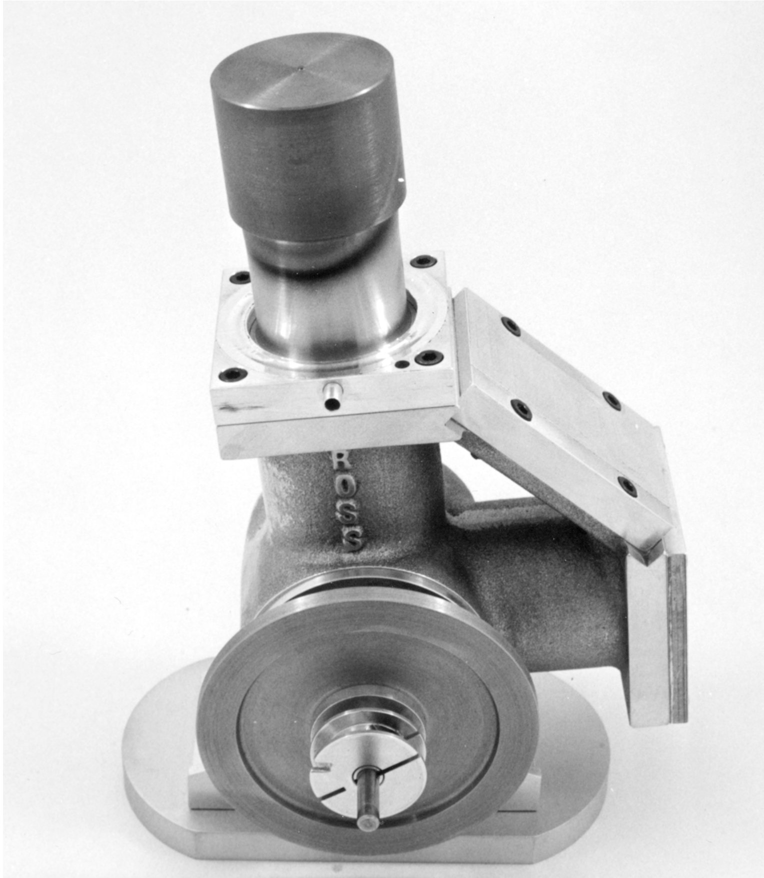




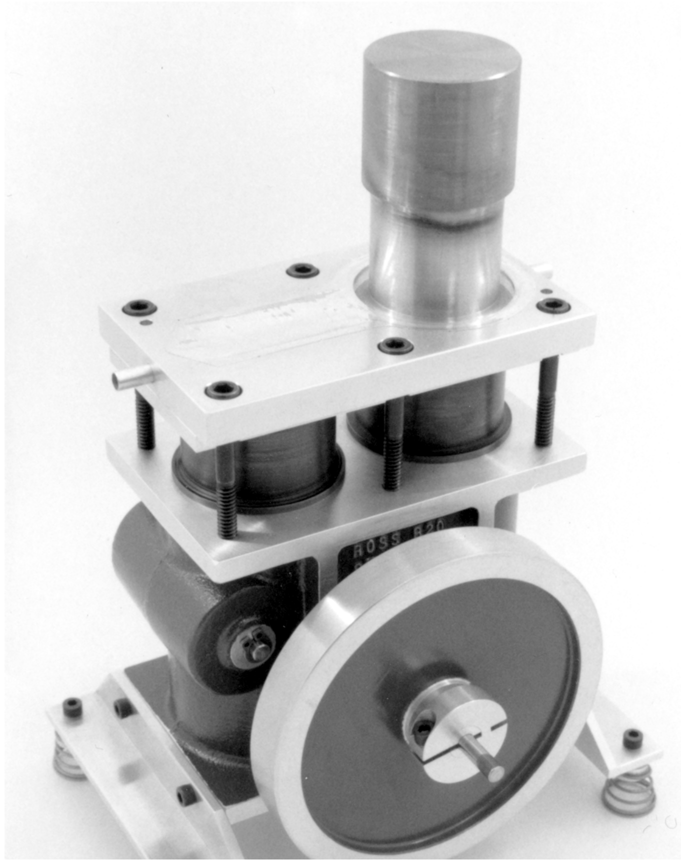
The two part cooler (above); the inner sleeve and foil regenerator (below, left); and the engine less heat exchangers (below, right).



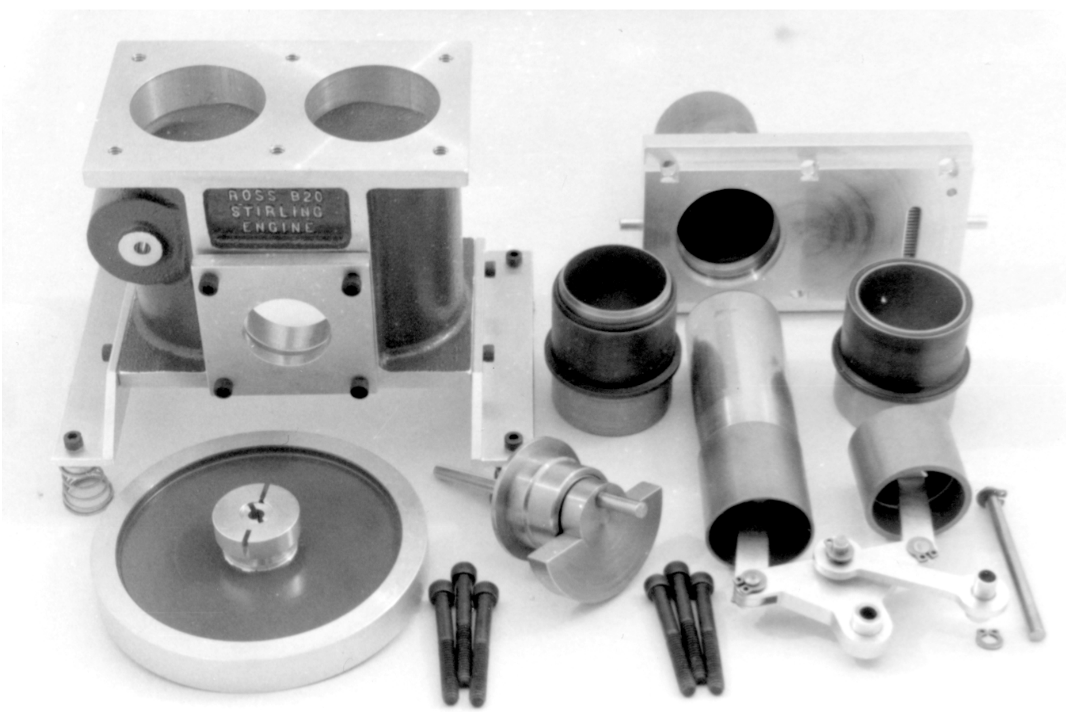




The V-15 engine, together (above), and apart (below).



The B-20 was designed to replace the V-15 kit, which had proven difficult for some home shop machinists.



The B-20, as incorporated into a genset by General Pneumatics Corp. (courtesy General Pneumatics Corp.).

to give a regenerator fill factor of about 10%. The cooler consisted of water-cooled slots cut into the cylinder head, connecting the compression space to the plenum beneath the regenerator. The pistons were of the clearance type, made of thin-walled cast iron, running in honed steel cylinders.

Performance was very good from the start. On the first power test the engine produced 21 watts at 2250 rpm, atmospheric pressure. After the snifters were added to the crankcase and the workspace, peak power atmospheric increased to 28 watts. Brief tests at 0.3 atm. showed 40.2 watts. Maximum free speed at this time was 3500 rpm. The cold piston subsequently seized, and the cylinders were honed out a bit more. This time clearance was sufficient to permit a smear of light oil to be used as lubrication without excessive drag. Free speed moved up to 4200 rpm, and power increased to 35.3 watts at 2200 rpm, atmospheric.

On tear-down, further signs of piston rubbing appeared, so additional cylinder metal was honed away. Free speed jumped to 4700 rpm, and peak power went to 44.1 watts at 2750 rpm, atmospheric. These results were extremely gratifying. This engine was substantially smaller, lighter, faster, simpler and more powerful (at a given pressure) than the 65cc rhombic. It was indeed a turning point in my work.

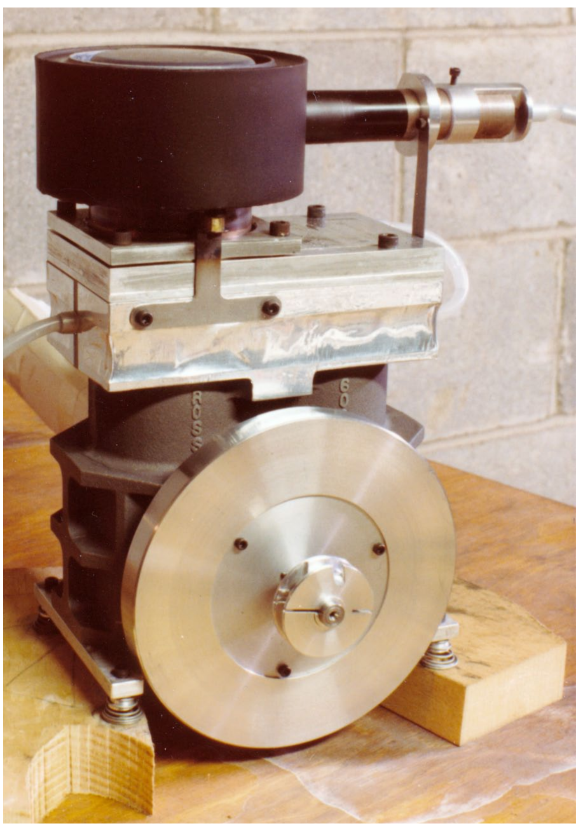
I undertook my first field test with any stirling, by incorporating the engine in an outboard rig made from copper tubing, a suitable synchro drive belt, and a Sears plastic trolling-motor propeller. This device was mounted on a 17 foot canoe, and tested on the nearby Scioto river. As expected with a mere 40+ watts of power, performance was mild, but nevertheless encouraging. After 25 minutes of cruising, a portion of an epoxied-on water jacket fell off, stopping the flow of cooling water and allowing one ofthe pistons to seize.The field test was both great fun and instructive. The water jacket that had so easily come loose in the jostling of the field test had given no problem in hours of prior bench testing. I was also much more willing to push my engine when it was the means to some end in the field, rather than the focus of pampered attention on the test stand.

Putting this engine in kit form took much longer than anticipated. About 50 kits were sold, but it soon became clear that most first-time stirling engine builders needed something much simpler. For this purpose, a V version of the old 15cc alpha engine was developed. This engine, called the V-15, was popular, and it makes a very quiet and impressive demonstrator engine. Some builders were still having problems machining the proper piston-cylinder fits, however, so it was replaced with a 20cc yoke drive engine, the B-20, which had removable cylinders that could be more easily refinished if necessary.

The primary purpose behind all this kit activity was to interest other people in experimental stirling work, and thereby speed up the process of small stirling development. A few purchasers did try various modifications, but most were happy if their engines merely ran, and they had no interest in testing or improving performance. Eventually it became obvious that the unmachined engine kits absorbed a great deal of my time without serving their intended purpose, and so, reluctantly, they were discontinued. The idea of introducing a pre-machined kit for a power-producing engine remained appealing to me, however.

Meanwhile, stirling enthusiast and machine shop owner John Mazur of New York suggested simplifying the 35cc design by combining the crankcase and cylinders into one unit. I redesigned the engine along these lines, and John kindly made eight unit blocks from bar stock on his numerically controlled milling machines. The modified engine was more compact and considerably simpler to make and assemble than the original 35cc.

This engine was intended to become a pre-finished version of the 35cc engine, but, after John’s untimely death, I decided to up-size the engine to 60cc to be assured of



The compact Unit Block engine (right), shown with the original 35cc (above).

The first of the 60cc yoke drive engines, the B-60 (left).

getting at least 100 watts output with a simple unfinned heater.

The resulting engine, the B-60, was based on a cast aluminum unit block, which was hard coat anodized after final machining to give the cylinders a good wear surface. The water jacket on the block was formed by applying aluminum tape to cover relieved water passageways. There was provision in the block casting for the balance shaft, but none was made, as experience showed the engine could be more easily mounted on springs for satisfactory testing. The pistons were aluminum alloy, coated with a baked on teflon resin paint called "Xylan".

This engine seemed moderately successful, after a few initial bugs were sorted out. It produced 57.5 watts at 2700 rpm, atmospheric, and its free speed was just over 3500 rpm. Power tests under pressure were not completed, however, because the type 304 stainless steel heater began to scale badly after three or four hours of operation. A second heater developed the same problem. This scale, subsequently analyzed and found to be mostly iron oxide, would migrate to the cold cylinder, score the Xylan coat on the piston, and bring things to a gummy halt.

I had used 304 stainless heaters on other engines (such as the 35cc) for much longer periods of time with no such problems. Perhaps these heaters were being overheated by the powerful burner, or perhaps the material was substandard 304. This problem by itself was not so difficult, but it triggered a major loss of morale. Why bother with these troublesome engines? I had already solved a great many problems during this program, but there seemed to be no end to unexpected new ones.

Adding to the mental chaos of this time were a number of interesting new ideas. After thinking over several cable-drive mechanisms of Jim Senft and William Beale, it occurred to me that the use of cable-driven pistons in a yoke drive engine would eliminate four bearings and their noise, lubrication, weight and expense. Further thought revealed that several new cable arrangements could also replace the rocking lever and its bearings.

Substantial additional reductions in engine height could come from using disc pistons with tail rods guided from below, as shown on the schematic drawing of the cable-drive system, above, but such pistons would require an excellent line (not clearance) seal. Mick Collins had demonstrated just such a seal in his 5cc competition stirling. These were extremely thin-edged (about 0.010 inch, or 0.25 mm) pressure-actuating cup seals made of Rulon, a brand of filled teflon. I promptly made and tested a few examples, and they proved to seal beautifully with very low friction. These new ideas and tests served to restore my interest in stirling engine work.

I was well into making a guided-piston, cup-sealed version of the B-60 engine, when another idea occurred to me that was extremely appealing. If the yoke were inverted (as it had in tact been in the original 15cc yoke engine), then the cylinders and pistons could be partially cut away so they could be moved down into the drive mechanism, and thereby occupy the same space as the crankshaft and yoke (US Patent 4,532,819). The height of the cylinders would thus be enclosed within the height of yoke mechanism, not added to it as in the previous yoke designs. Moreover, the crankshaft would penetrate the new shorter block more or less in its center, rather than near the bottom as before, so the flywheel, too, would be contained within the height limits of the cylinders. Although the cylinders would be partially cut away, they would remain adequate to guide self-aligning pistons, without tail guides. An exceptionally compact and lightweight engine would result.

Several problems were also immediately apparent. Any balance shaft on an inverted yoke engine would now be below the cylinder block, and thereby add back some of the unwanted height. The cut away areas would make the cylinders difficult or impossible to hone. Counterbalance masses mounted on the crankshaft would have to be hung outside of the cylinders in order to clear them.

The potential problem that worried me the most, however, had to do with the geometry of the yoke drive. Like the conventional crank and slider mechanism, the yoke drive has a dwell at one end of its stroke and a snap at the other, caused by the yoke's varying angularity. By inverting the yoke, relative to the pistons, the dwell is moved from bottom dead center to top dead center. In fact, the piston phasing is slightly different throughout the cycle. My initial investigation into this difference lead me to believe that engine power with this new arrangement might be 10% lower at any given pressure level. Only later did I realize that the inverted yoke phasing looked at least as good as the 90° V-2 phasing, and this realization largely dispelled my concern. Subsequent test results reveal no decrease in performance from inverting the yoke.

Soon enough, other aspects of the inverted yoke design began falling into place. The stroke-multiplication effect of the yoke mechanism means the crankthrow diameter needs to be only 71% ofthe actual piston stroke, making possible a strong, one-piece stepped crankshaft, supported by bearings at both ends, which is nevertheless small enough to fit within the main needle bearing in the yoke. Counterbalance mass may readily be hung outboard of the main bearings of the rigid crankshaft. Assembly and disassembly could be extremely simple and rapid. The spool-like cutaway pistons are very lightweight, so the balance shaft can be permanently omitted. The triangular braces for the yoke arms are now stressed in tension, rather than in compression, permitting a lighter yoke design.The cylinders can be left intact, honed, hard anodized, finish honed, and only then cut away as necessary. One by one, the problems began to disappear, and additional advantages emerged. The new engine was named the model C-6O, and its overall size would be similar to that of the original 35cc engine.

At this point, my enthusiasm for this new approach was so high that the C-60 was designed and machined in the matter of a few months. The cylinder block was cut from 6061 aluminum alloy bar stock, and hard anodized for wear resistance. The cooler, cylinder head, and regenerator (as well as the first burner) are from the B-60 engine. The heater is identical to that of the B-60, except for being made of type 310 stainless, for higher scaling resistance.

The pistons are made from aluminum alloy bar stock, with thin strips of etched

Rulon LD epoxied onto the wear surfaces.The Rulon is then machined to final size, and grooved axially so its high rate of thermal expansion will not cause it to buckle circumferentially as the piston heats up. Diametrical clearances on the pistons of about 0.003 inch (0.08 mm) have proven adequate. Piston sealing is provided by thin-edged cup seals also machined from Rulon LD.

Originally both pistons were similar, and employed separate connecting rods. Subsequently a rocking type piston, which is a piston and connecting rod combined into one piece, was installed in the cold cylinder. This modification resulted in a piston that is easier to make, lighter in weight (40 grams vs 80 grams), and quieter in operation. It has even contributed a few watts to power output, probably due to reduced friction.

The yoke and rocking lever are also machined from aluminum alloy bar, with drawn cup needle bearings pressed in. The crankpin bearing in the yoke was initially a full complement needle bearing, and it was axially located on the crankshaft with a shoulder and a retaining ring; however, this arrangement resulted in fretting of the bearing against the retaining ring after several hours of operation. Apparently the needles were skewing, due to their short length relative to the crankpin diameter (ratio = 1 to 2), and this skewing repeatedly drove the bearing against the retaining ring.The substitution of a longer bearing (bearing length to crankpin diameter ratio = 1 to 1.25) with caged needles solved the problem. The yoke now floats on the crankpin, with its axial location determined solely by the rocking lever, and the shoulder and retaining ring have been eliminated.

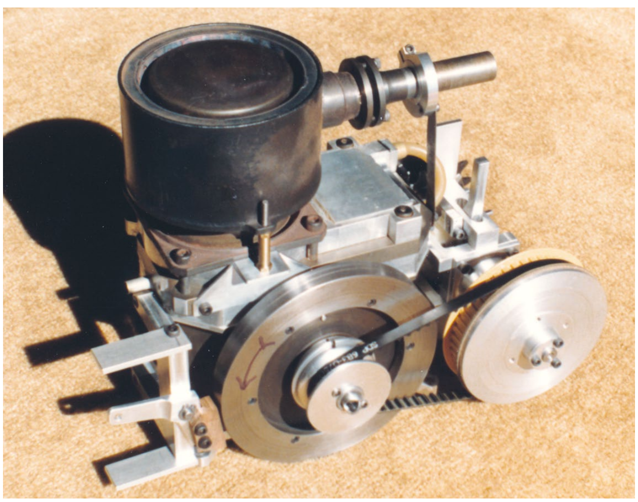
With the new bearing installation, cupped grease catchers were also added to the ends of the main yoke bearing to catch the small bits of grease that were being thrown form the bearing onto the cylinders, thus solving another early problem.

The crankshaft is machined from low carbon steel, case hardened to Rc 60, and finish ground. Its axial location is maintained by a ball bearing slipped onto the rear of the crank, and located between a shoulder and a clamped-on balance bob weight. The front main bearing is another needle bearing. The crankcase seal is a simple Rulon lip seal, held by a retaining ring in the front bearing case.

The C-60 ran well from the start. It produces a steady and reliable 100 watts at two atmospheres pressurization on air. Maximum recorded free speed is 4002 rpm. I have put 21 hours of operating time on the engine, and Sunpower, Inc., has put another 50 hours on it.

On one occasion the engine failed to run properly after having been apart for inspection. Free speed was down, and power was off at least 25%. The engine was again taken apart, and after considerable scrutiny the only anomaly I could find was that the foil regenerator was wrapped the opposite way around the inner sleeve.

This regenerator is made of stainless foil 1 inch wide and 0.001 inch (.025 mm) thick. It is dimpled with a seamstress's tracing wheel to create about 0.009 inch (.229 mm) spacing between wraps. I had previously wrapped it with the dimples facing the



Four illustrations of the C-60, showing, (upper left) the piston assembly with the new rocking compression piston; (upper right) the block with the original pistons and crankshaft; (lower left) the engine with a clutch and reduction gear set, ready for mounting in a bicycle; and (lower right) the heat exchangers, which are the same as used on the B-6O.

inside, but on this occasion I had wrapped it with the dimples facing outward. On this particular foil the dimpling process seems to have caused more distortion than usual, and, when wrapped with the dimples outward, the foil showed a slight waviness, which no doubt caused nonuniform flow. When the engine was rebuilt with the foil wrapped the other way, full performance was restored. I had exclusively used similar foil regenerators for years before this instance, and yet had not noticed such a problem.

With a nice little 100 watt engine, it was time to conduct another field test, this time on an old ten speed bicycle. A clutch and reduction gear drive was made to connect the engine to the crankset via a suitable freewheel sprocket. In this way, five of the bicycle's extant speeds could be used. Engine speed control was a primitive spring-loaded flywheel brake controlled by a motorcycle twistgrip on the handlebar. Engine cooling was provided by an engine driven water pump and an onboard aluminum radiator. Unfortunately, there was no provision for engine pressurization, so power was limited to about 50 watts.

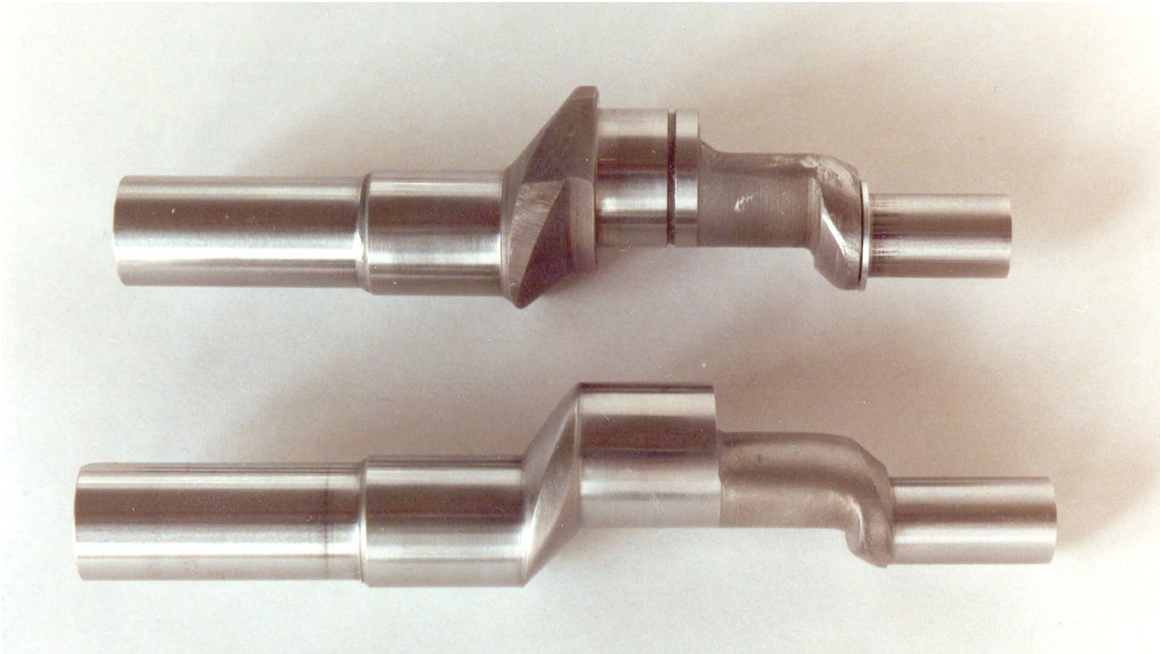
On October 19, 1986, what may have been the world's first stirling powered bicycle was ridden for about 5 miles. With the limited power, the performance was modest. As in the previous field test, I noticed how much more willing I was to push the engine hard when it was outside doing something useful, than when it was on the test stand. Also apparent was the importance of small details, such as the quality ofthe water pump, the tubing connections, the burner control, etc.. It was one thing to develop a good stirling for test purposes, and quite another to develop one for everyday hard work.

As always, I had many new areas I wanted to explore. Unusual speed control devices and wick-fed kerosene catalytic burners were two among many others. But what I actually did was more sensible, and that was to further develop the heat exchangers of the C·60.

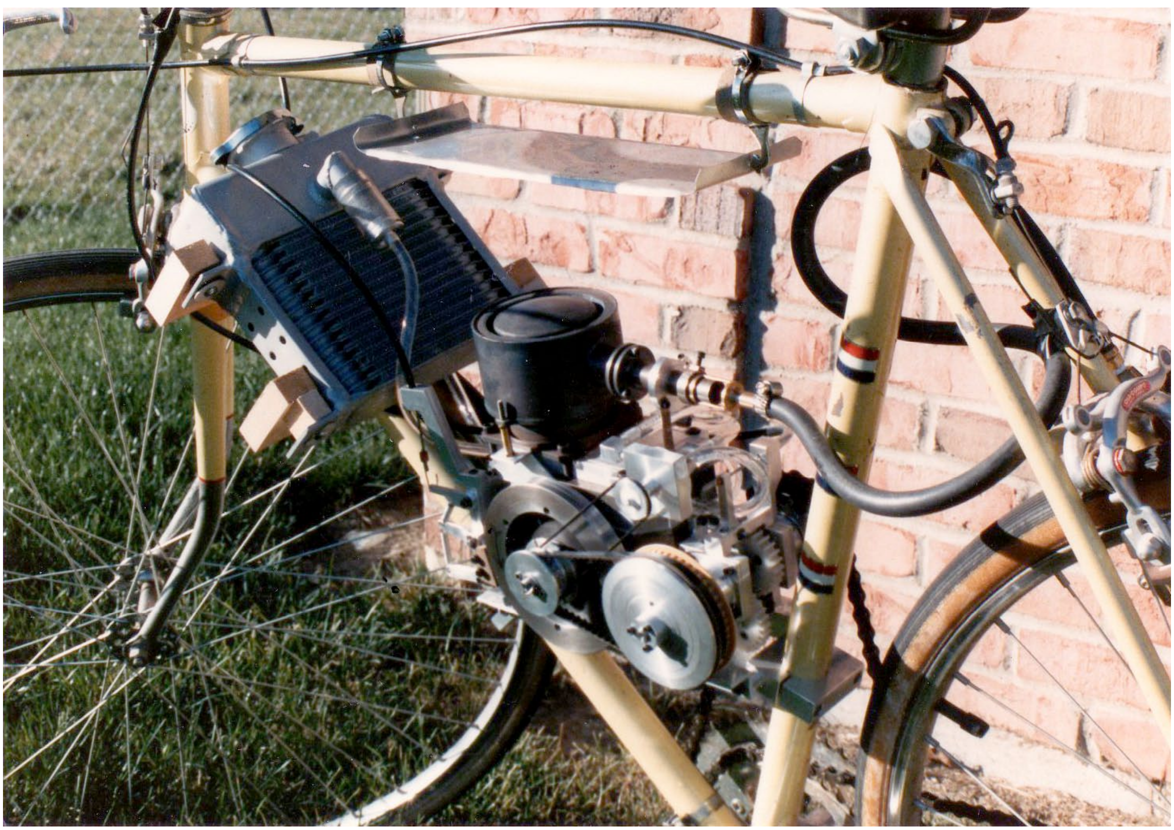
It was apparent, and no surprise, that the C-60 was running out of power by 2.3 atmospheres pressure when charged with air. It was also likely that the limitation was in the heater, since it had somewhat less surface area than the cooler. But the cooler was also limited, by its very design; there is only so much surface area one can fit into a flat cylinder head connecting two closely spaced parallel cylinders. It would be pointless to make a superiorfinned heater for the engine only to have performance now be cooler-limited. The plenum located between the cooler and the regenerator of the C-60 (and the B-60, B-20, and 35 cc engines before it) was also undesirable. This volume was always filled with gas at the wrong temperature for what was happening in the engine at any given time. During expansion, for example, it was filled with cooler gas than during compression. Obviously, such a plenum, if it could not be eliminated entirely, should at least be moved to the other end of the cooler.

These considerations lead to the next version of the 60cc engine, the model D-60, and this engine was indeed sketched out before the C-60 was even finished.

The major design differences in the D-60 engine are an internally finned heater



The original shouldered crankshaft is shown above the modified crank that solved the fretting problem (above); the C-60 mounted in a bicycle for testing (below).



and an annular cooler.

The internally finned heater is actually an intermediate design, since a heater finned on both the inside and the outside will probably ultimately be necessary. Nevertheless, it was of interest to explore whether the C-60's apparent heater limitations were on the outside (flame to heater head) or the inside (heater head to working gas).

My belief was that the inside surface area was the limiting factor, so corrugated fins were formed from nickel 200 and furnace brazed to the inside wall of the type 310 stainless steel heater can.

Before the actual heater assembly was brazed, several flat test assemblies were prepared and brazed with both silver-based and nickel-based fillers. The silver filler made nice large fillets, but it also partially blocked a few fin passages.The nickel filler was very clean and neat, but formed little or no fillet, leaving some doubt about the adequacy of its thermal contact. Nevertheless, the nickel filler was used for the actual heater, with satisfactory results, although one portion (under 10%) ofthe fins is unattached to the heater can.

The resulting heater is slightly shorter in length than that of the C-60, so its outside surface area is only about 80% that of the C-60. The internal finning, however, gives an inside surface area that is 4.8 times larger, and a dead volume that is over 3 times larger, than in the C-60.

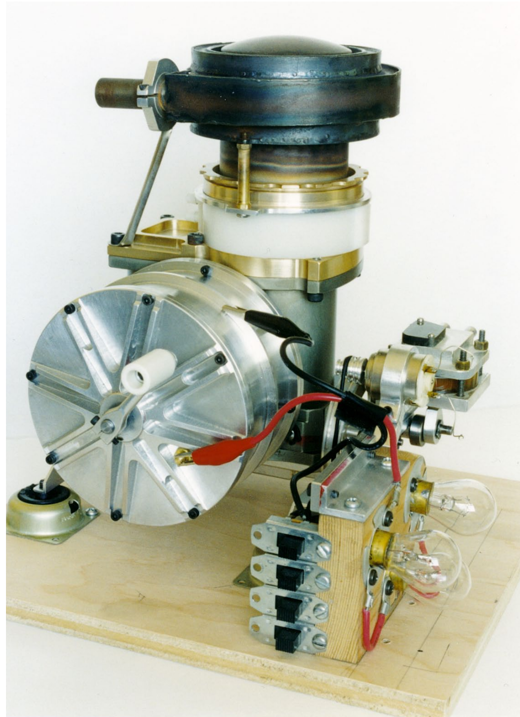
The annular cooler permits a great deal more surface area than the flat cylinder head coolers ofthe previous prototypes, but it does tend to make the engine taller, since now the cooler is positioned vertically instead of horizontally. Mechanically this change offers certain advantages; for example, the cylinders may be located closer to each other, and much less cutaway clearance is needed for the yoke. In constructing the D-60, unlike the C-60, no portion of the block needed further relieving after final honing.

The D-60's cooler has 160 internal fins to provide 1.38 times more surface area than the C-60 cooler, but this is still only half the area of the D-60's heater, and is probably less than is desirable, since the uncooled compression cylinder runs somewhat hot at 175°F (80°C).

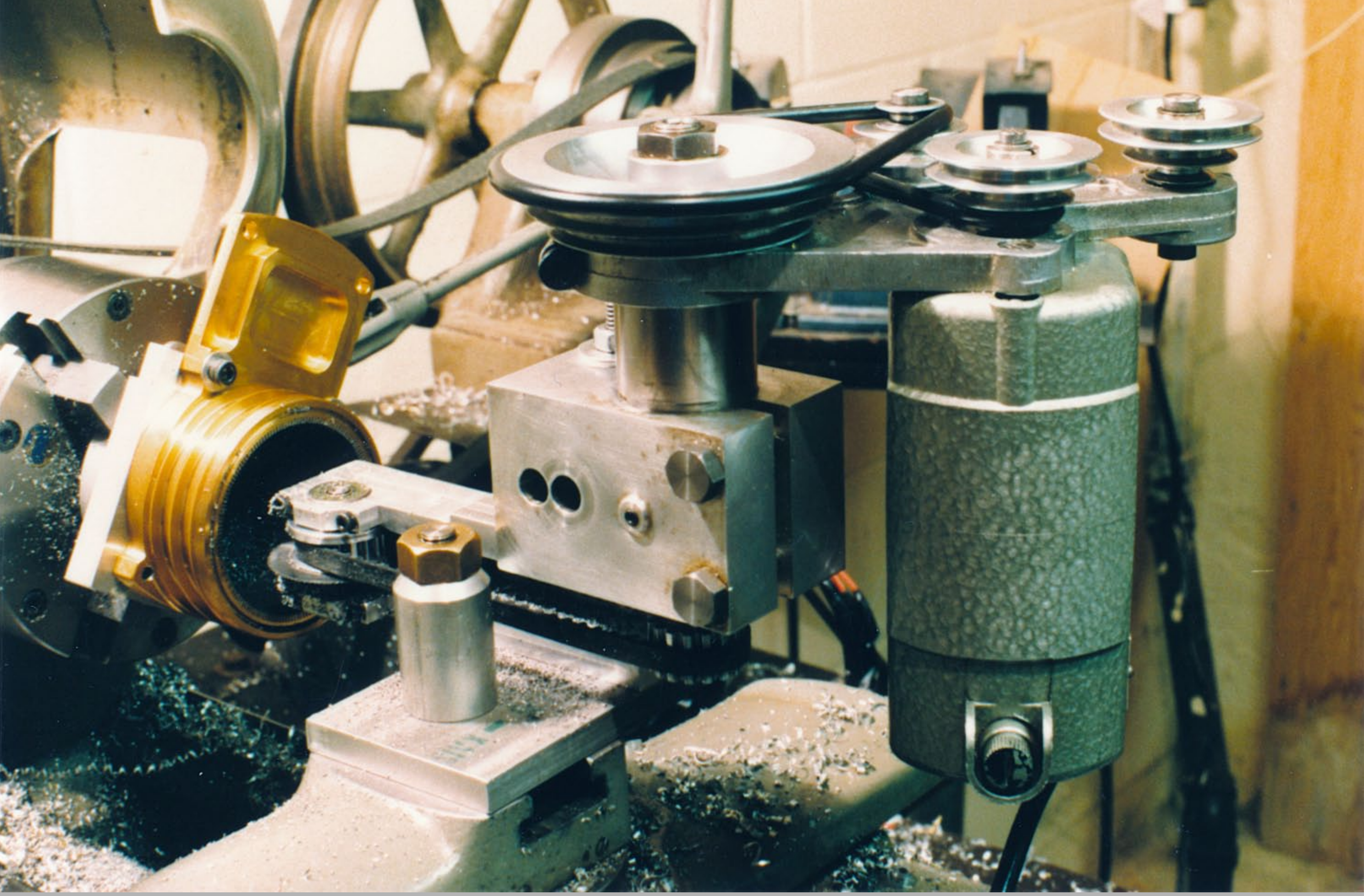
These fins are machined internally into the cooler wall in order to assure the best possible thermal bond. A tool-post mounted internal fin cutting machine was made expressly for this job, by mounting a small slitting saw on an arbor in an arm, and driving it through a miniature synchro belt. This setup was sufficiently rigid to machine the aluminum alloy cooler, but it would not have been suitable for machining heater fins out of stainless steel or nickel

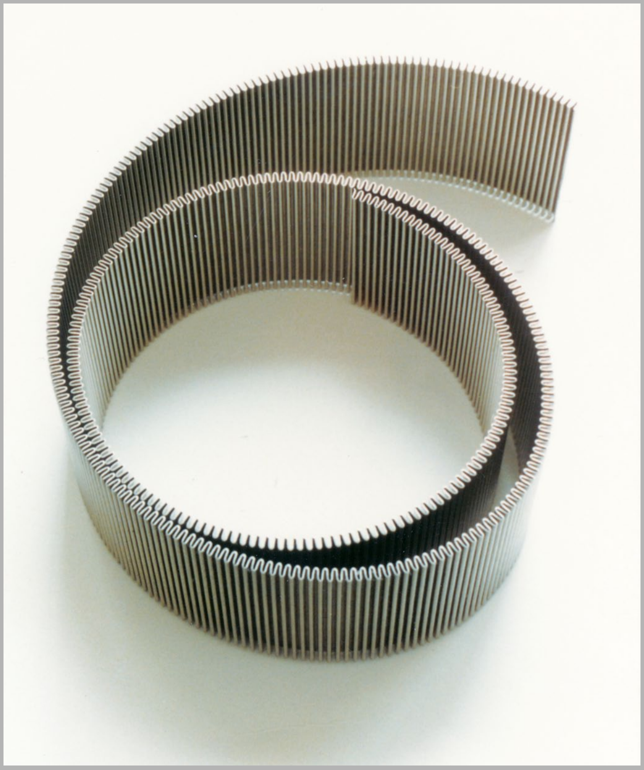
In other details the D-60 engine is the same or very similar to the C-60, with the exception that considerable effort was made to keep its total weight low. The C-60 weighs 3.4 Kg (7.6 pounds) with burner and flywheel, while the D-60 weighs 2.2 Kg (4.75 pounds), also with burner and flywheel, Further significant weight reduction is possible.

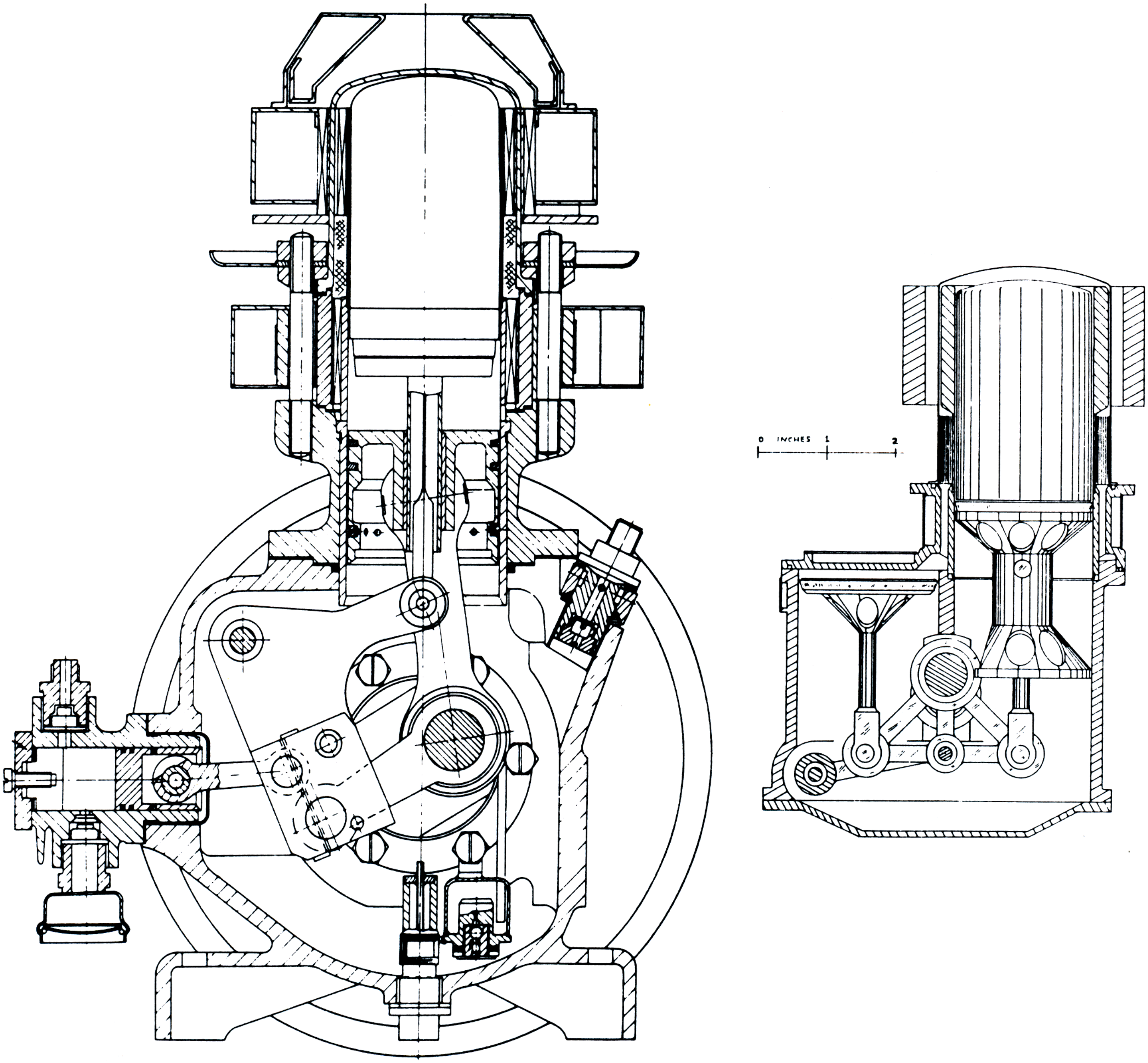
The D-60 is a wonderful engine. Whereas the C-60 is essentially a 100 watt engine,



The original D-60 (above left) and the subsequent version with alternator and bulbs (above right). The D-60 cooler, crankshaft, rocking lever, and yoke (below). Opposite: The machine devised to cut the internal fins of the cooler (top), the D-60's piston assembly (bottom left), and the internal fins for the heater (lower right).







The Philips MP1002CA air engine of about 63cc swept volume (left) is shown on a common scale with the D-60 (right). (drawing of Philips engine courtesy of Professor Allan J. Organ).

at 2 bar pressurization, the D-60 is a 200 watt engine at 3 bar pressurization. Even before its heater is at a visible red heat, the D-60 clearly outperforms the C-60 at its best. At similar temperatures and pressures the D60 is considerably superior, producing, for example, 1.5 times the power, at 1.3 times the speed, of the C-60, at 2 bar pressurization. The limitations that are beginning to show at 3 bar are probably related more to the limited surface on the outside of the heater and cooler, than to any internal limitations.

Although no outdoor field tests have been conducted with the D-60, it was mounted on the same outboard rig used to test the 35cc, and run in the shop's basin, where it could be pressurized. Nothing very scientific was learned from this amusing exercise, but 200 watts of power does move a lot of water around a small basin in a hurry.

The completion and testing ofthe D-60 represented a definite high point in the program. Follow·up work concentrated on making a version of the engine suitable for limited production and sale to other interested parties. Before getting into the history of that enterprise, it would be a good time to describe some totally unrelated efforts to make small engines.

Model airplane fever

Model aircraft engines have always appealed to me, and when Flob McConaghy demonstrated the world's first model aircraft stirling in radio controlled flight, I knew I had to try my hand at a model aircraft stirling.

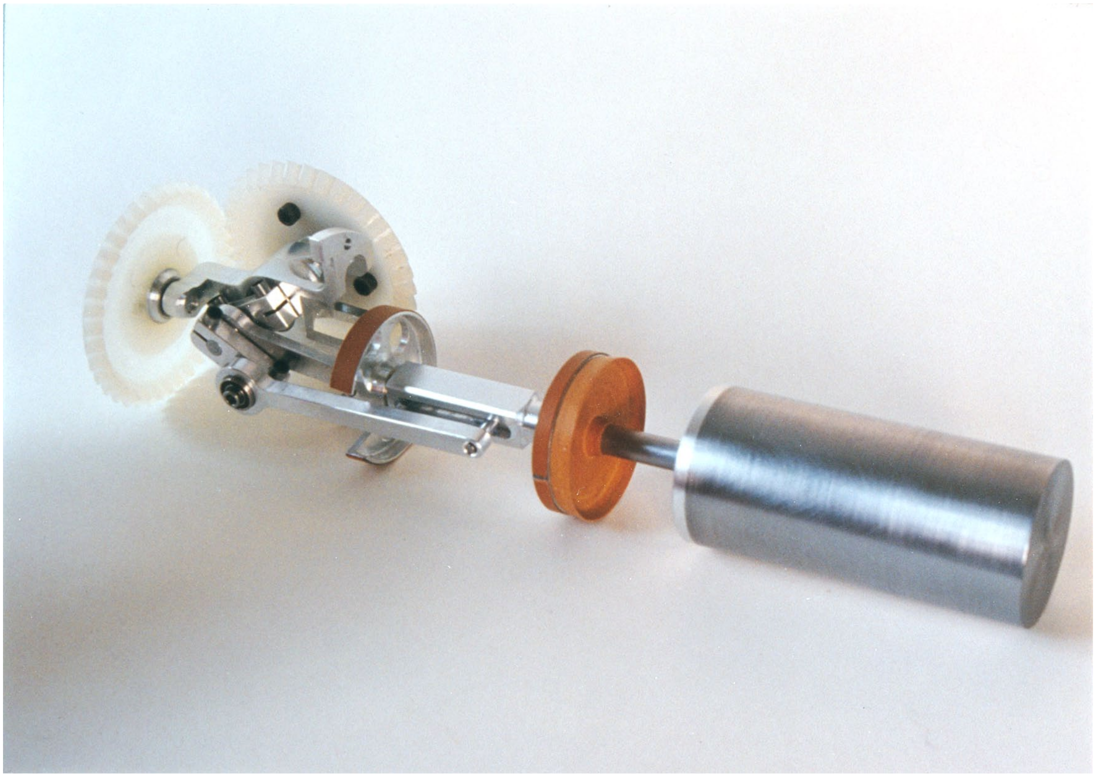
Rob had used (and still favors) pressurization, but I decided to stay atmospheric, for simplicity. The key would be to make each part as absolutely lightweight as possible.

A first effort was a one inch bore alpha engine based on a wobble plate drive mechanism. The engine had an inner sleeve and a foil regenerator, Ftulon cup seals, and water cooling. Although it ran adequately, it was grossly overweight, and its water cooling made it impractical.

A second effort, conceived and completed in three weeks time, was much more promising. It was a simple beta engine, with Ftulon cup seals on the piston and displacer shaft, an annular regenerator, a cantilevered built-up crank, and plastic miter gears making the prop shaft concentric to the long cylinder. Less prop and burner, the engine weighed 80 grams, and it produced 90 grams of static thrust. Great pains were taken in keeping wall thicknesses low, and as I recall the wall thickness of the regenerative portion of the hot cap is at most 0.008 inch (0.2 mm).

The prop used is a 12-6, made of maple for use on much more powerful gas engines. Obviously a lightweight custom prop of balsa would be in order before flight testing.

One remaining challenge is to devise a suitable flight burner that is not going to set farmer Smith's barn on fire in the event of a crash. A butane burner with an inertial gas shut-off valve is one possibility. Another is to use no burner at all, but merely a heat



The lightweight model airplane engine is a beta design.

storage canister, filled with aluminum made molten with a ground-based propane torch, then covered with insulation prior to flight.

An "improved" version of this engine was subsequently made, incorporating higher compression (piston to displacer strokes = 1 to 1, rather than 1 to 1.25), a shorter, lighter hot cap (mistake #2), and a simpler, stronger crankshaft frame (the only true improvement). This engine weighed 10 grams less than its predecessor, but its performance was substantially lower.

These projects were diversions from my primary aim of making a practical fractional horsepower stirling, but they were fun and great morale boosters. There is something transfixing about watching a little stirling, its hot cap glowing red with heat, steadily and quietly turning the big prop to a blur, pushing a stout breeze.

The D-90 Engine

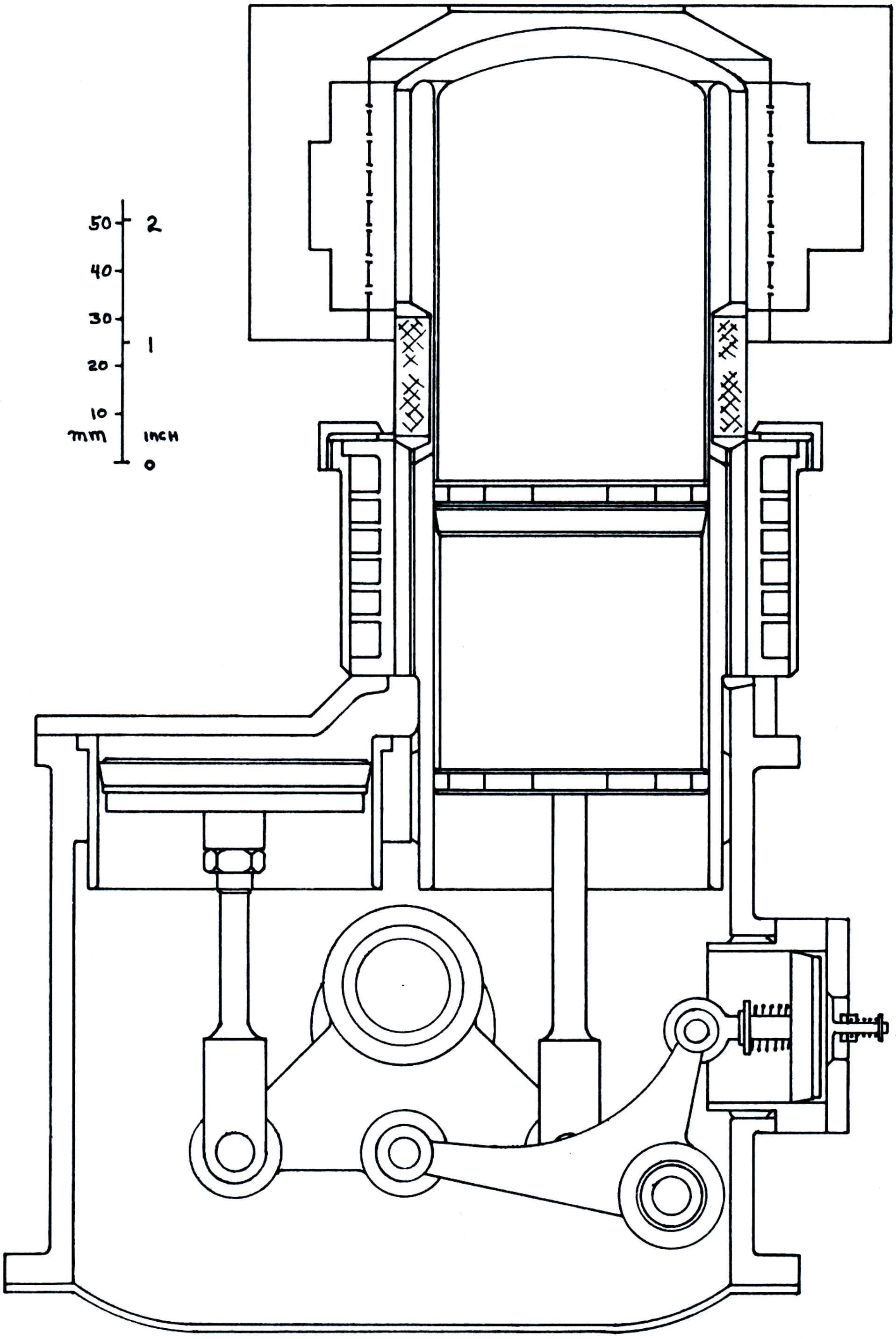
The excellent performance of the D-60 engine convinced me to proceed with the next step, which was to redesign the engine for limited production. I decided that any production engine would have a cast block, rather than one carved from bar stock, to decrease the time necessary to machine it. The expense of the pattern for such a casting suggested that due care should be exercised to select a swept volume for this new engine that would satisfy all my long term aims. After considerable indecision, I settled on 90 cubic centimeters swept volume, which offered the possibility of becoming a 500 watt air-charged engine, weighing under 5 kg, with a charge pressure of only 5 bar absolute.

The overall design of the D-90 is quite similar to that of the D-60, and its construction presented no major challenges. The engine ran on the first try, as expected, and it was extremely quiet as a result of the pains I'd taken to reduce the clearances in the needle bearings by grinding custom oversized shafts for each bearing.

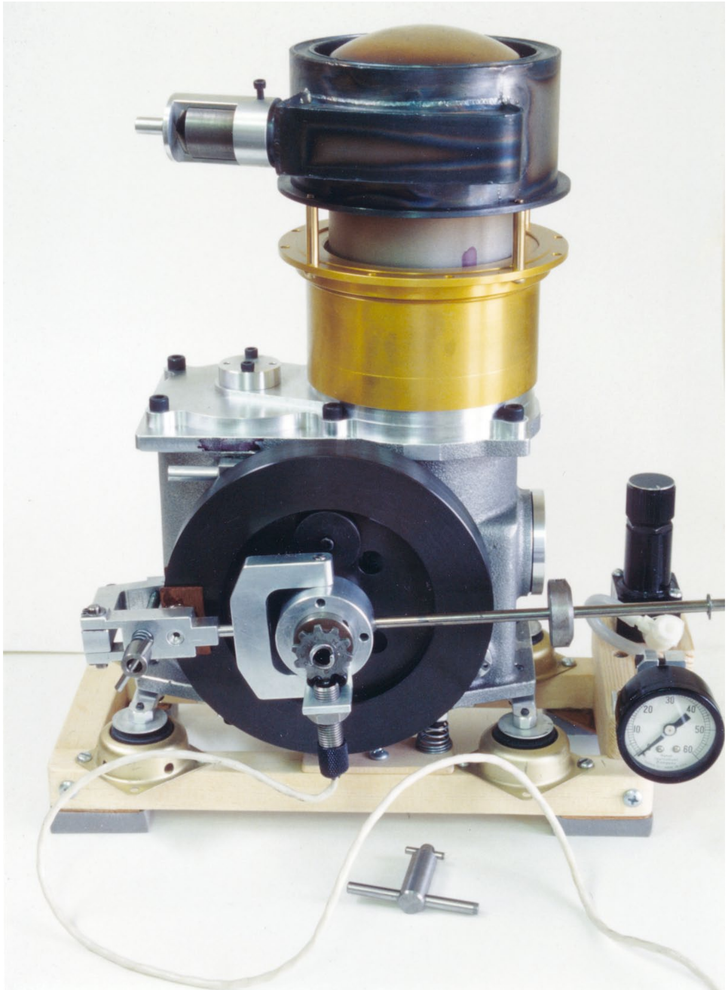
The power and speed on the initial runs on the brake, however, were extremely disappointing. The engine was expected to produce a peak power of about 100 watts for each atmosphere of pressurization, at a speed of about 3300 rpm. In fact, the engine produced only 48 watts at 2880 rpm at one bar, and 77 watts at 2724 rpm at 1.7 bar pressure.

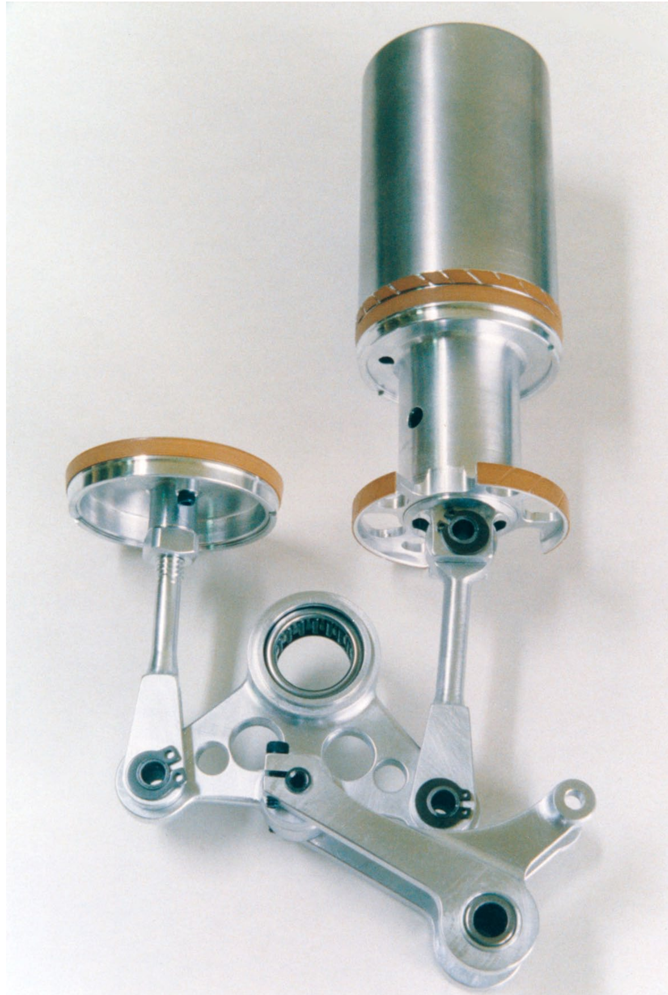
Subsequent inspection revealed that the dome of the hot piston was heat discolored only to a pale yellow, not the dark brown that would be expected, indicating that the working gas was probably not getting above 275° C (550°F). There obviously was a problem with the heater.

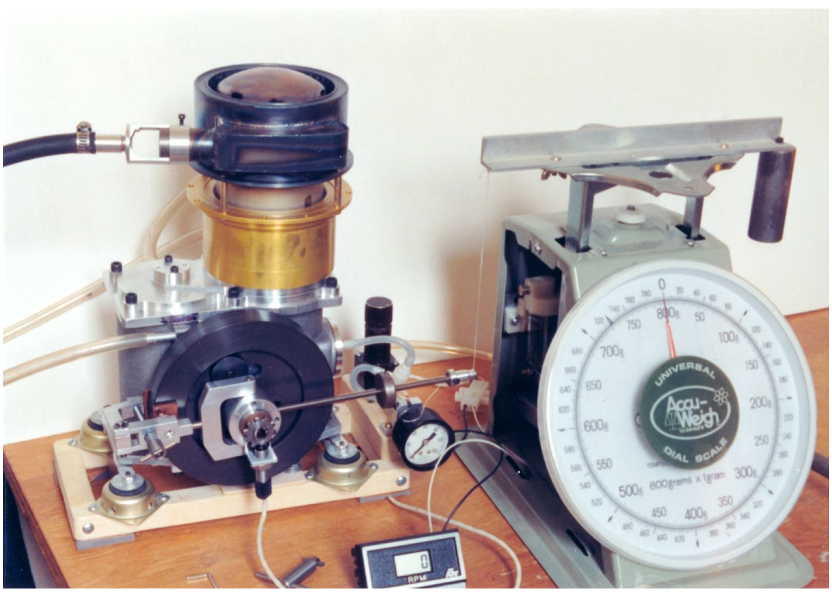
The problem involved the method of brazing the fins to the inside wall of the heater can. The fins are corrugated out of nickel 0.015 inch (0.38 mm) thick, and are furnace brazed to the type 310 stainless steel heater can. In the heater ofthe D-60 engine, similar (but 33% thinner) fins were held against the wall of the heater can for brazing by an inner plug made of stainless steel. This plug was coated with stop-off material to

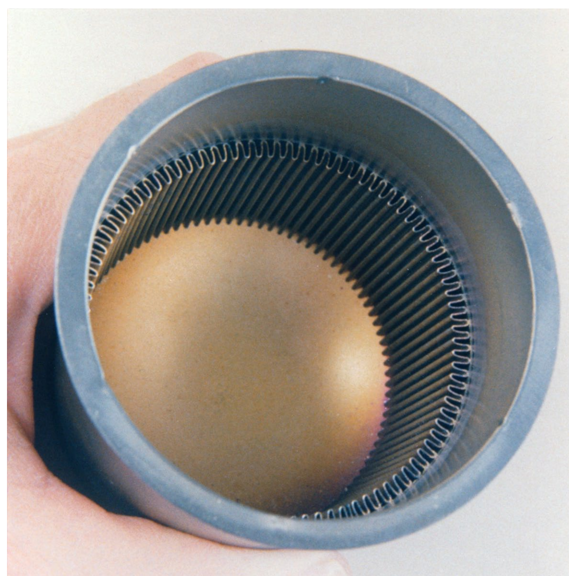


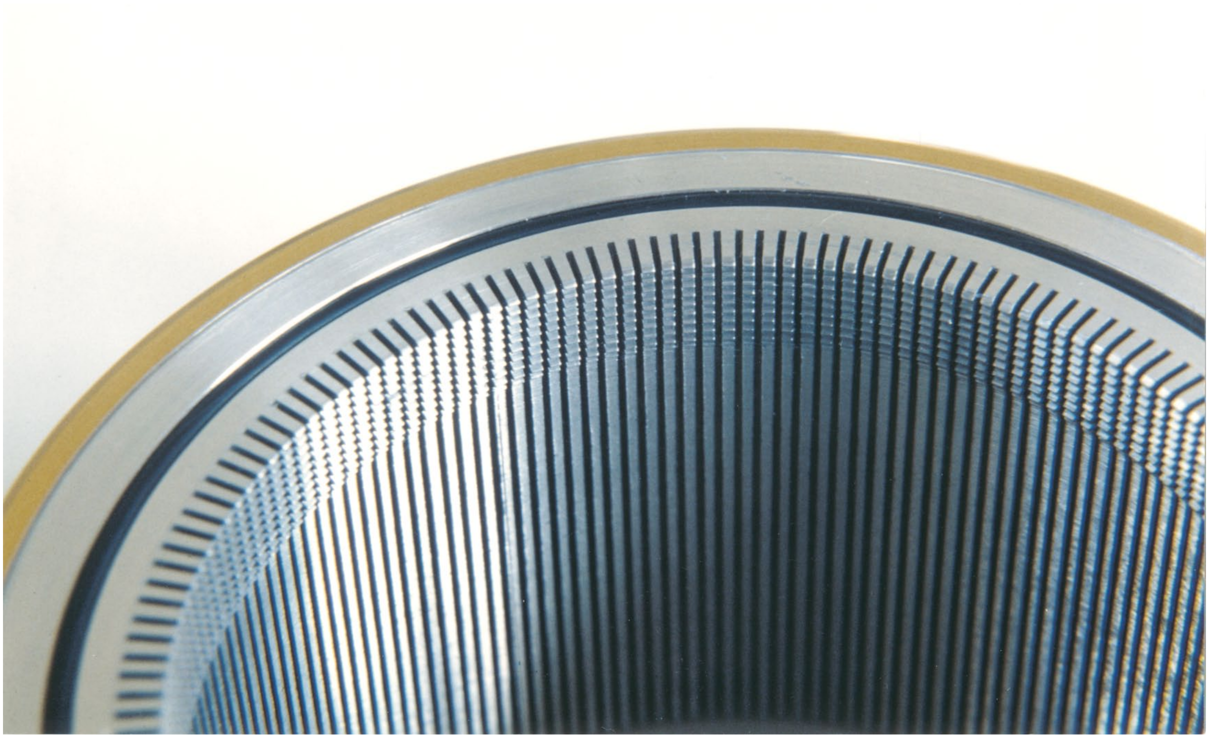
The D-90 engine (above and on the following three pages).

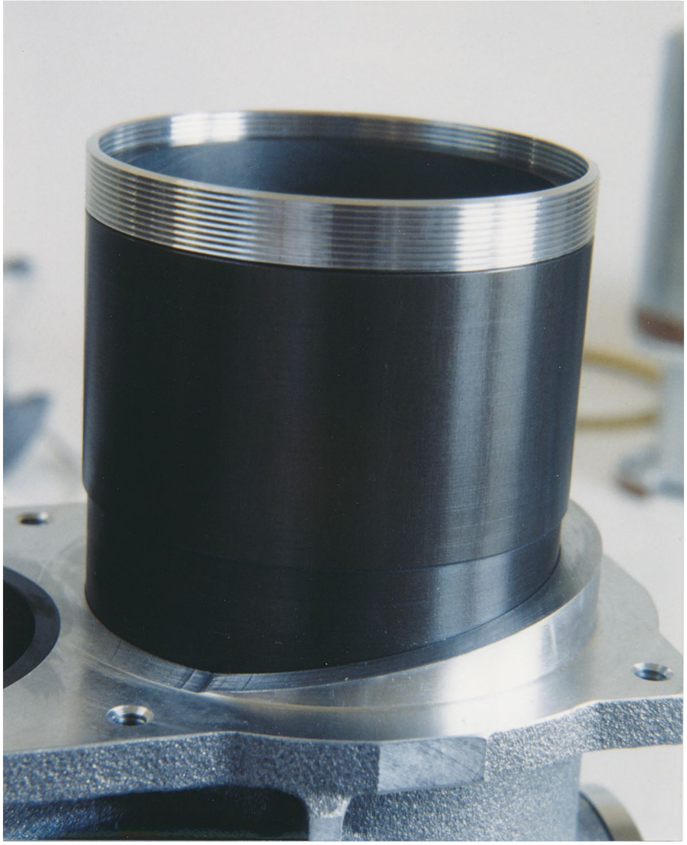


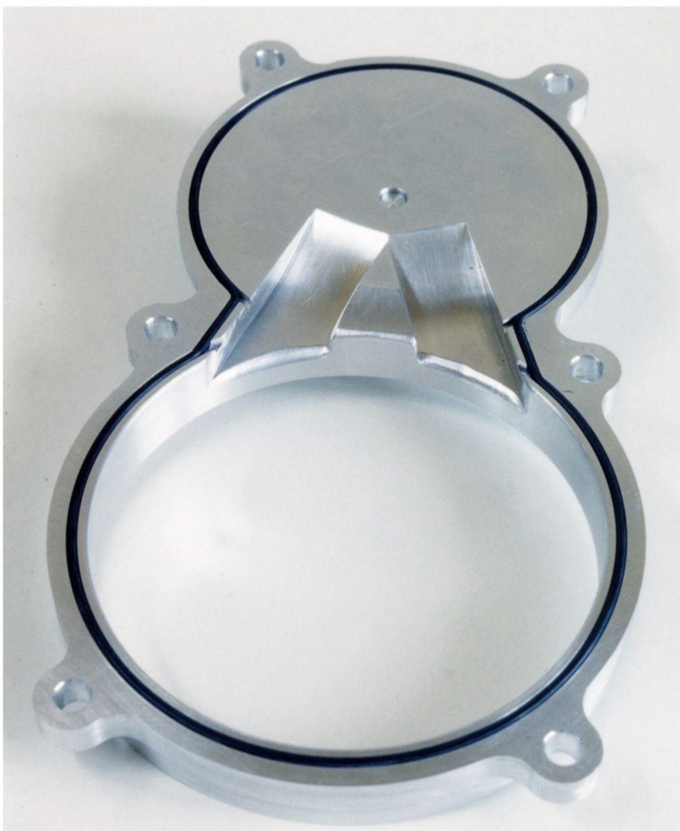


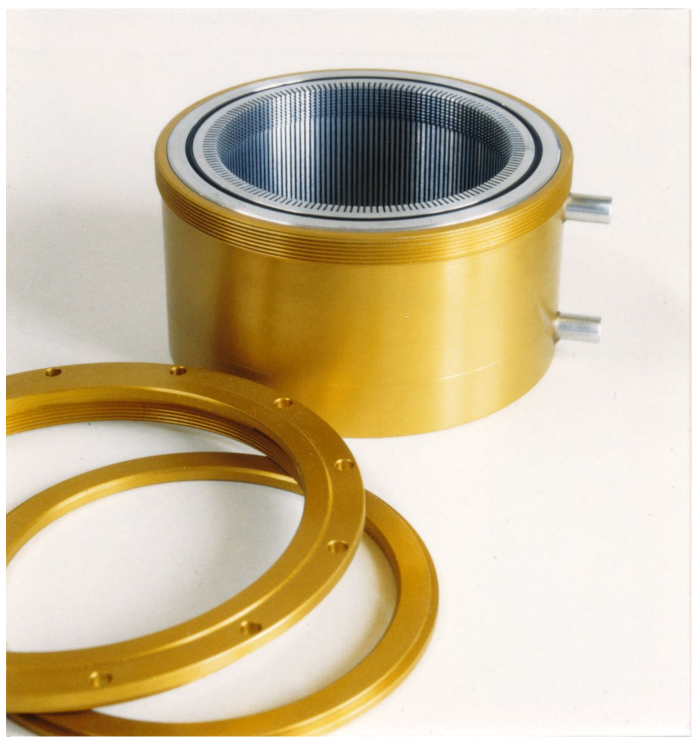

UNIVERSAL
Accu-Weigh
DIAL SCALE
800grams x 1gram
RPM











prevent it from being brazed to the fins, but there remained the risk that some of the stop-off would be scraped off during assembly, leaving the plug permanently attached to the fins.

With the thicker, stronger fins of the D-90, it seemed possible that the fin material could be fit tightly inside the heater can, fixturing itself during brazing, and dispensing with the plug. Unfortunately, this procedure did not work. Apparently gravity and the softening of the nickel fins at brazing temperature combined to allow the fins to ride up slightly on the internal radius at the closed end of the heater can. Consequently, the filler metal attached the fins to the can only at either end; their midsections stood away from the can wall, forming long, thin triangular gaps. Initial visual inspection did not reveal the flaw, since the visible end of the fins were nicely filleted with filler metal. Only after the discouraging initial test run of the engine was a proper visual inspection made, with a magnifying glass and a small flashlight to illuminate the fins from the closed end of the heater can. Then, the obvious triangles of light leaking from fin to fin revealed the cause of the poor performance.

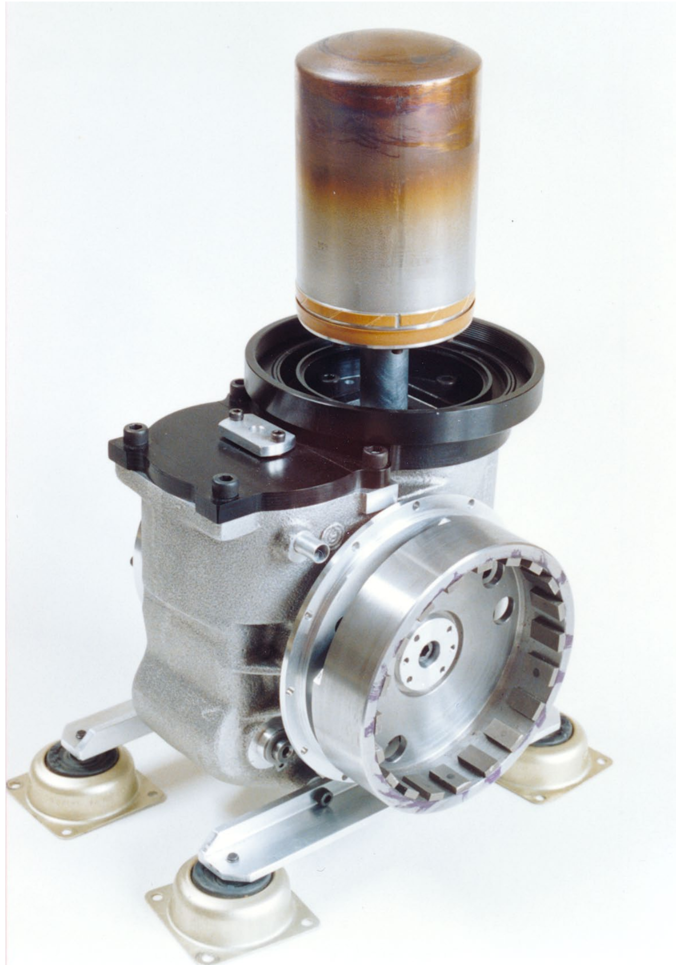
A new heater assembly was promptly made, and the performance improved to a satisfactory level. Power tests were not conducted above 2.7 atm for the lack of an adequate test cell.

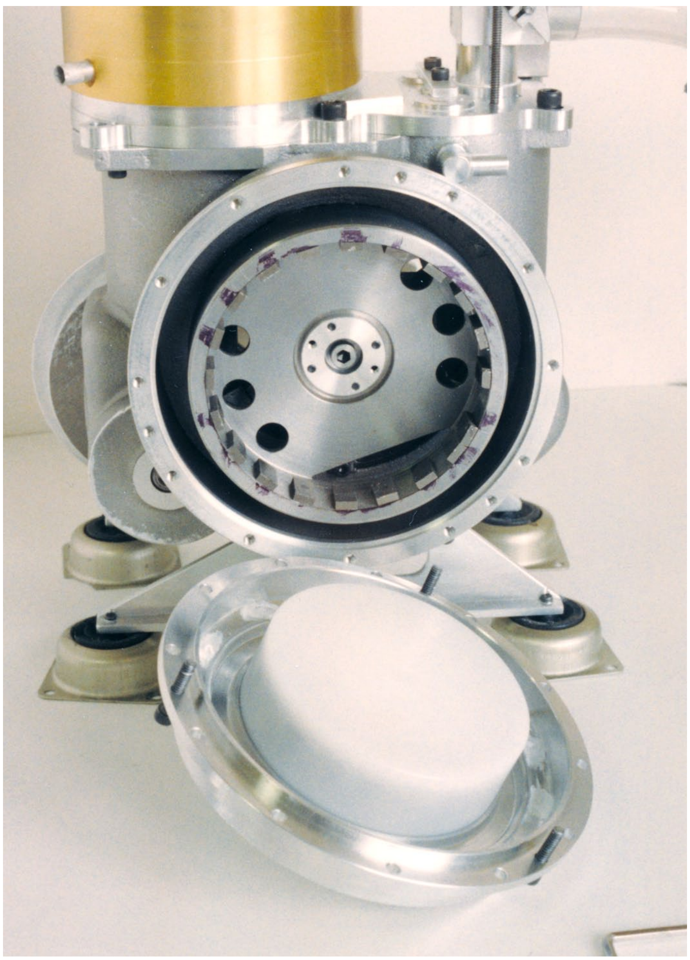
Originally, I had intended to construct two D-90s concurrently; one for me and one for Briggs & Stratton, for some work they hoped to pursue with John Hoke on catalytic combustion. Many duplicate parts had accumulated on my bench, but the work was going so slowly that I decided to proceed with just one engine. No sooner was it running right than I had to deliver it to its new owners under my prior agreement. Fortunately, it would eventually return home.

In the meantime, there were other ideas I wanted to pursue, such as the rocker hot piston and the magnetic shaft drive.

For some time William Beale and I had realized that a yoke drive mechanism where the rocking lever length was made close to the length of the opposite yoke arm would produce a motion with that yoke arm that was nearly linear (US Patent 4,738,105). By attaching the hot piston, with its extended insulation dome to this yoke arm, one could eliminate the upper wrist pin and bearing (which hardly oscillates 2°, and is tough duty for a needle bearing), lighten the hot piston assembly considerably, and provide superior guidance for the piston, all at once. The challenges would be to provide proper lateral guidance for the piston tail rod, and to provide some means of initial adjustment to center the slight oscillations of the insulation dome. My solution was to put the entire hot cylinder (which could now be quite short) in the cylinder head, then properly locate the head and tix its position with dowel pins. This method had the additional advantage of permitting an unusually large upper rib to strengthen the one piece pressurized crankcase casting.

Magnetic drives, on the other hand, were not new. They had been used in centrifugal pumps for some time, and with the availability of super magnets they seemed to be





The E-70 engine (above) used the rocking expansion piston and the magnetic shaft drive ideas. Its expansion cylinder did not extend beyond the cooler (upper left), which allowed very close cylinder spacing. The magnetic drive was later adapted to the D-90 engine.

a good way to get shaft power out of a sealed high speed stirling engine.

The D-90 engine block did not lend itself to incorporating either of these ideas, so I designed a 70cc engine, using the 2.250 inch (57.2 mm) bore of the D-90, with the 0.285 inch (7.2 mm) crankthrow and 2.250 inch (57.2 mm) cylinder spacing of the D-60. This engine was named the E-70, and it was intended to become the production engine that had proved so elusive.

The E-70 was relatively easy to make since it was simply a blend of the two preceding engines. It runs quietly, and apparently well, but some still unsolved problem prevents it from performing as it should. At atmospheric, for example, it produces a mere 49 watts, whereas it should be producing about 70 watts. Its free speed is 4690 rpm, which is 400 rpm short of the D-90 and over 600 rpm short of the D-60. All kinds of minor modifications to the regenerator, heater, pistons, seals, etc., have been tested without improvement in performance. This engine seals well, has no excessive dead volume, appears to be reaching high internal temperatures, and has no apparent friction problems, and yet something is still quite wrong with it.

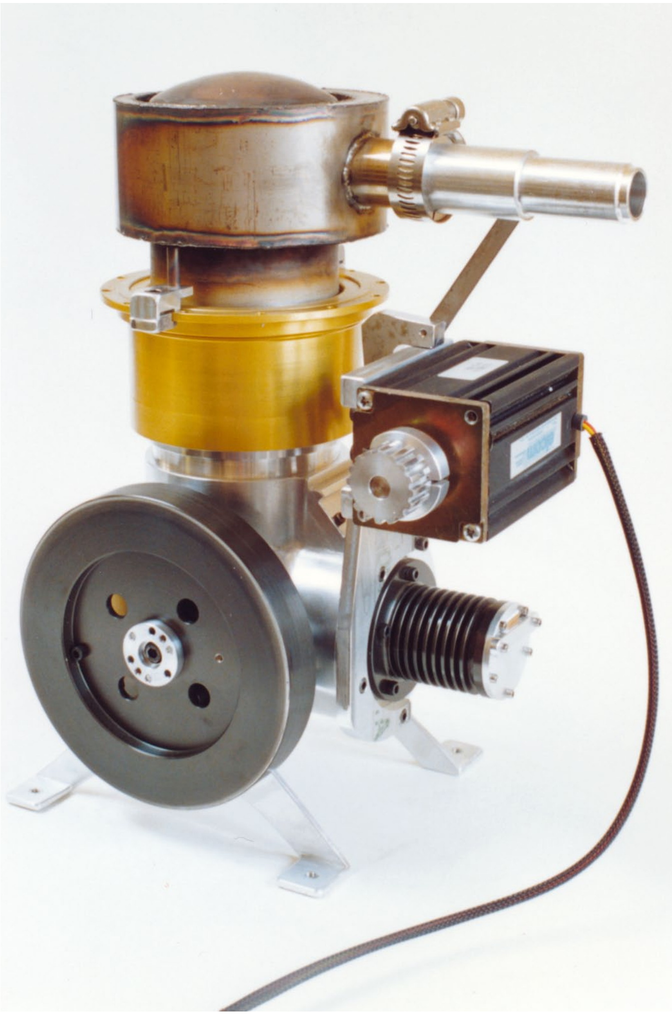
I managed to reacquire the D-90 about the same time I learned that my brazer had, at one stroke, ruined two modified heaters for the E-70 by mistakenly brazing the short fins into the long can, and the long fins into the short can. These events convinced me to put the enigmatic E-70 on the shelf for awhile, and refocus my attention on the reliable and powerful D-90, and several variants thereof.

The V arrangement for the alpha engine has long seemed to me (and many others) an ideal form for small stirlings. It is simple, robust, and easy to balance. The disadvantages are the side loadings on the pistons, which cause friction and wear problems in oil-less machines, and the relatively long distance between the cylinder heads that must be connected by the heat exchangers, which leads to excessive dead volume. Long connecting rods would reduce the side loading, but increase the distance between the cylinder heads.

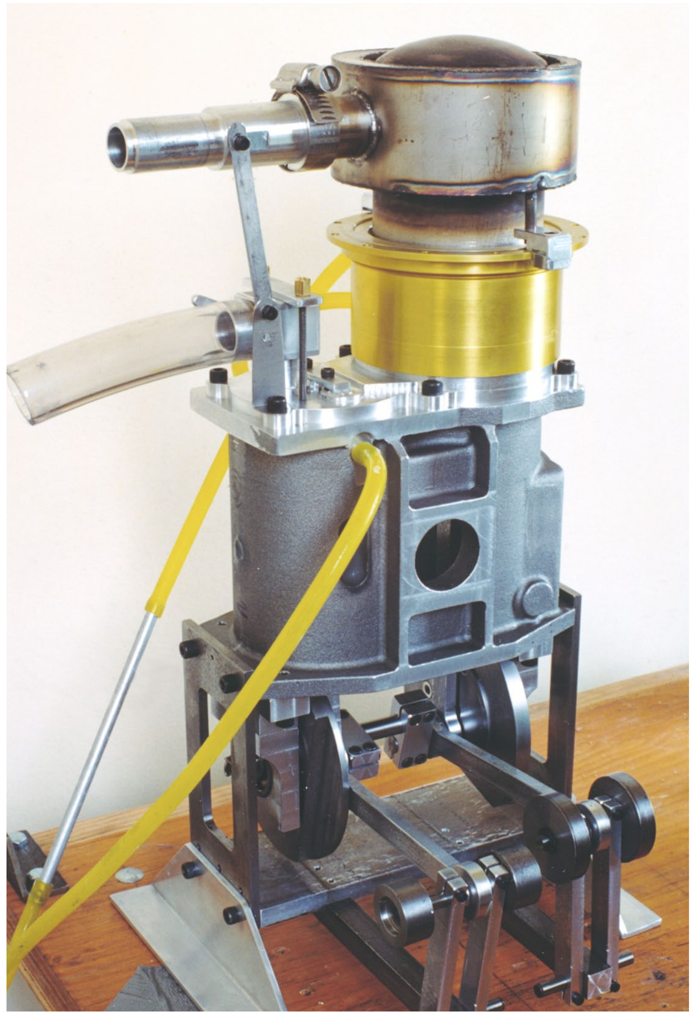
Two different approaches to an oil-less V alpha had been simmering in my mind, and the return of the D-90 spurred me to try both in metal, based on the burner, heat exchangers, and hot piston of the D-90.

The first approach was a conventional V alpha with an unconventional stepped piston (US Patent 5,103,643). The idea was to combine the low dead volume of annular heat exchangers and short connecting ducts, with the low side loading and excellent balance provided by long connecting rods. This engine was named the V-90.

The other approach was to make a double 90cc engine, using two D-90 power heads mounted 90° apart from each other above a common crankshaft. In this arrangement conventional pistons with connecting rods of any desired length could be used, since each power head was a complete and separate engine, and no heat exchangers needed to cross the valley of the V. This engine was named the Double V-90. For simplicity, the prototype was made with only one power head (the only one I had), and the



The V-90 engine.



The Double V-90 engine.

connecting rods for the other power head merely drove dummy bob weights to allow proper balancing.

Both engines ran without noticeable vibration. Their power and speed, however, were very disappointing.

The V-90 produced 78 watts at 3120 rpm, at 1.3 atm., whereas the D·90 produced 123 watts at the same speed and pressure. Free speed for the V-90 was 4000 rpm, over 1000 rpm below that of the D-90. On each succeeding tear-down there were ever more teflon flakes on the stepped compression piston's small wear band. Eventually, particles of hard coat anodizing from the small extension cylinder were being transferred to this wear band. Despite numerous theories and modifications, these problems were never solved.

The Double V-90 proved even weaker. Its free speed never exceeded 3000 rpm, indicating it had no power to spare at a speed where the D-90 would produce over 90 watts of excess power, atmospheric. This lackluster performance was very puzzling at the time. Only recently have I discovered that serious fretting had occured beside the crank-pin bearings of both connecting rods, which most likely would account for all the missing power.

These experiences with the V arrangement were helpful in re-convincing me that the yoke drive was truly worthy of my full attention. The D-90 was reassembled, and further testing proceeded with it.

Considerable thought was now given to speed control means. The first idea tried was a variable poppet valve interrupter gear. This mechanism allows one to variably open the work space to the buffer, starting at the low pressure portion of the cycle. In this way, one can delay the onset of the compression stroke, and thereby change the effective swept volume, power, and speed of the engine. The mechanism required a cam or eccentric driven at crankshaft speed, and a variable fulcrum rocker to actuate the poppet valve, so it was not simple. It was effective, but the nature ofthe alpha engine's piston phasing is such that a great deal of the bottom of the cycle must be opened up to the buffer before any noticeable speed control occurs. But as one continues to open up more of the cycle, the opposite effect begins to be seen, and minute differences in control input make for great differences in speed.

I then tried a needle leak valve. This was very simple, but unstable in operation. If the valve was adjusted to provide, say, 2000 rpm free speed, then any slight load on the engine would slow it down and allow more leakage per cycle, which would further slow the engine allowing yet more leakage, etc., and engine speed would rapidly decay to a stall. To be satisfactory, such a device would require some sort of feedback means, and thereby loose its sole virtue of simplicity. An attempt to couple this valve with a fixed dead volume was unsuccessful.

Another control means tested involved variably cutting off the high pressure portion of the cycle with a spring-loaded check valve. This approach was simple and effective, but inefficient. An attempt to couple this valve with a fixed dead volume was also unsuccessful.

Various dead volumes without valves were made and tested. These proved very satisfactory and highly stable. As the dead volume was increased the speed and power dropped, but torque remained strong. The engine was quite resistant to stalling even at very low idle speeds. A three valve manifold was made to variably connect three dead volumes in proper sequence to provide eight steps of control.

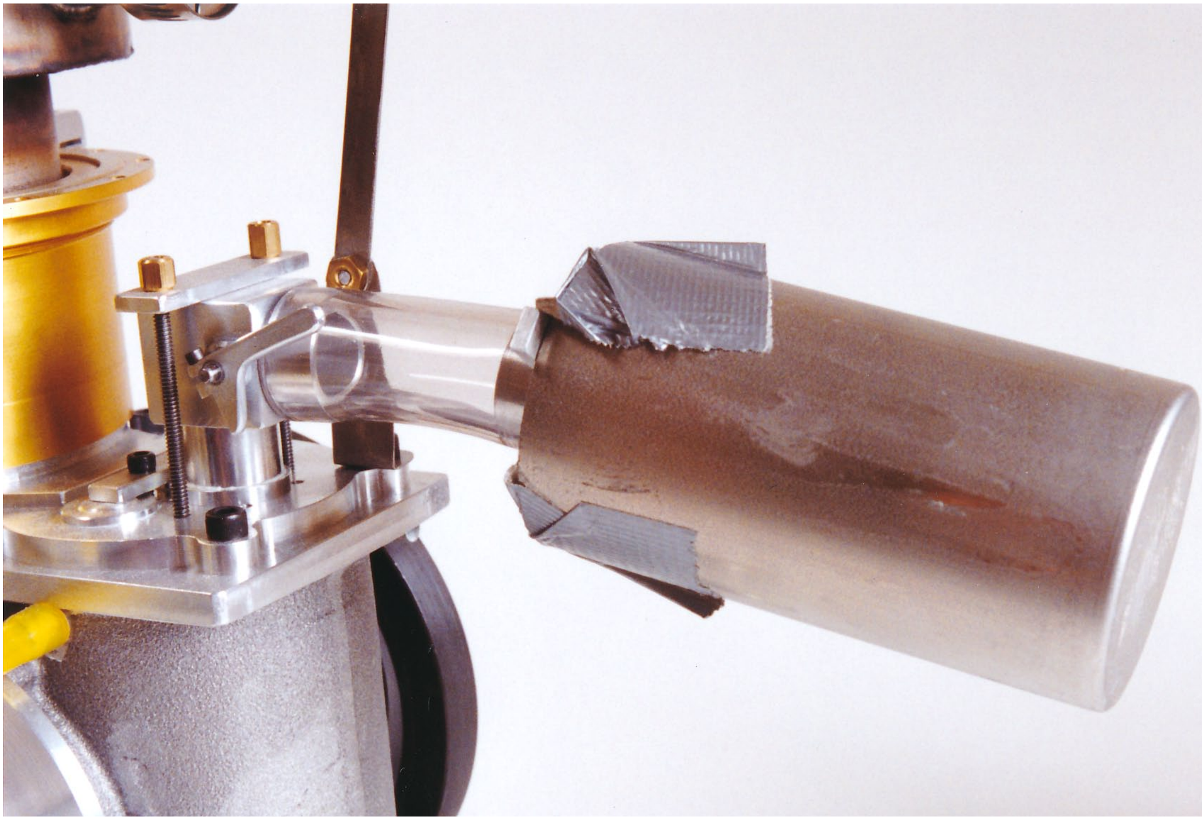
A simpler approach involved a single large dead volume connected to the engine by a spring-loaded, hand-actuated poppet valve. This system allowed a surprising degree of control by merely varying the pressure on the valve, and by fully opening the valve a reliable idle was immediately available. Closing the valve would rapidly restore full power.

Several other promising speed control devices were tried, and I am confident that developing a simple, useful control will not be difficult.This work was great fun, because it is easy to come up with ideas to try, and a few hours of machine work is usually all that stands between the idea and its trial.

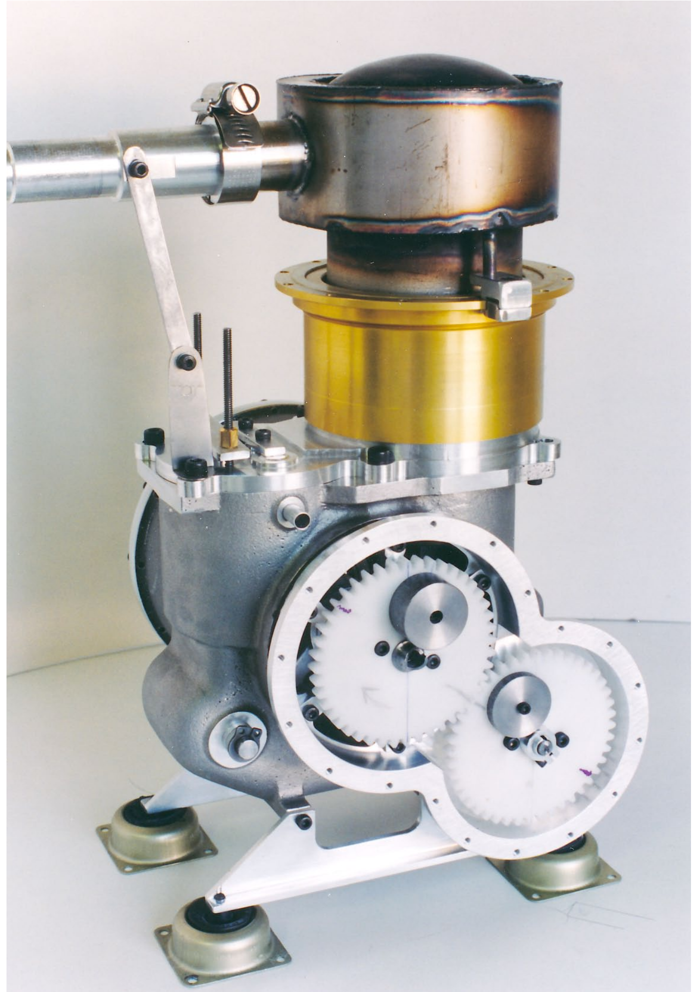
Another loose end was dynamic balance. With the preferred inverted yoke drive, the standard balance shaft (US Patent 4,138,897) necessary for complete primary balance is located directly below the crankshaft, adding substantially to overall engine height. This balance scheme also requires piston masses to be equal, but the hot piston in an alpha would normally outweigh the cold piston by a factor of 2 to 3. Adding mass to a lightweight piston naturally goes against the grain of any mechanician. It intuitively seemed that some sort of offset of the balance shaft toward the heavier hot piston could solve both of these problems, but a solution eluded me. Gary Wood finally found a means to achieve complete primary balance with pistons of different masses (US Patent 5,146,749). I promptly made a test rig for this idea, and it seemed to work, but I wanted to test it on a real engine at higher speeds before making a new crankcase incorporating it into the D-90. For this purpose, an upgraded version of the B-20 was made, incorporating the new balance scheme, an inverted yoke, and Rulon J cup seals. The dynamic balance proved to be excellent, and so a new crankcase for the D-90 was made that incorporates the balance shaft and also the magnetic shaft drive system originally made for the E-70 engine. This shaft drive system can readily be replaced with an alternator, if desired. Starting is accomplished by an o-ring sealed key incorporated into the engine, which can engage the crankshaft and turn it over compression.

Test runs showed the balance shaft doing a fine job, but the magnetic drive was absorbing about 50 watts of power. This loss was the result of hysteresis within the stainless steel pressure barrier used between the magnets. After a new pressure barrier was made from Delrin plastic, the magnetic drive losses diminished to insignificance.

In its current form, the D-90 is being periodically field tested in both an outboard rig and a mountain bike, which brings the story of my stirling work more or less up to the present time. Future plans include additional field and life testing, as well as inves-



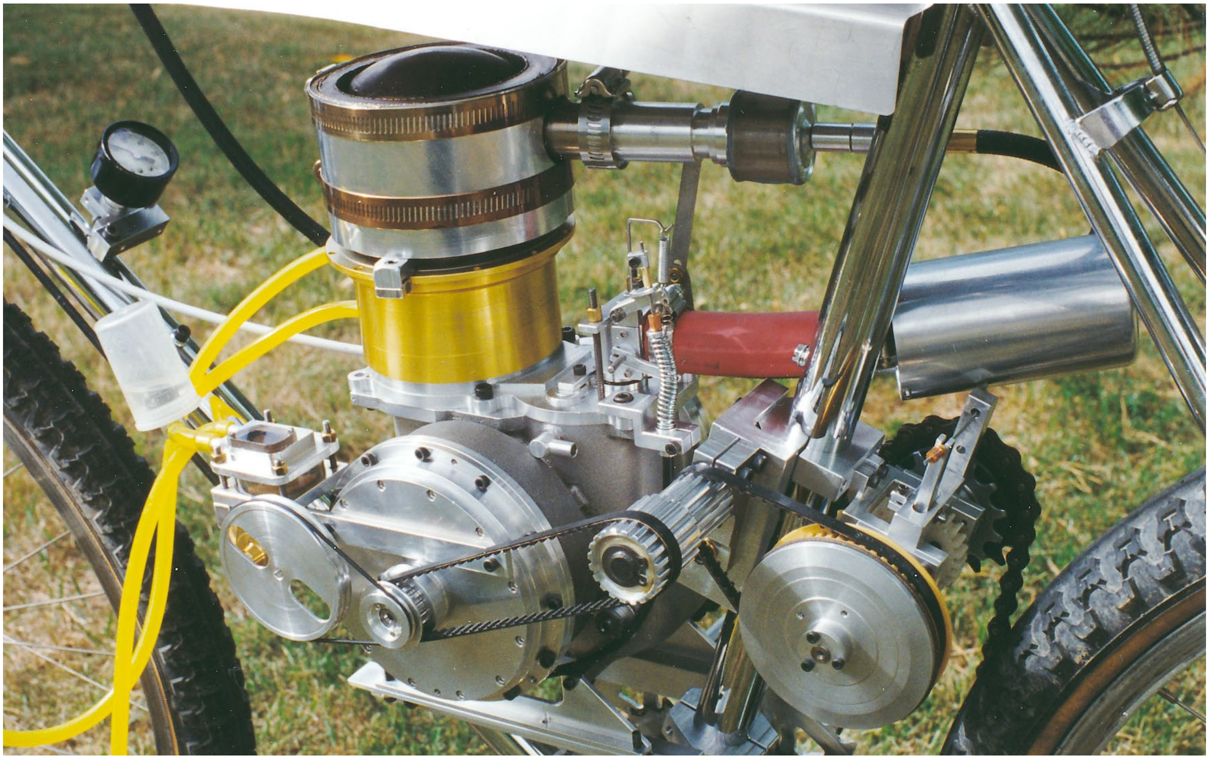
The poppet valved dead volume speed controller (below), and mounted on the D-90 engine (above).



The balanced B-20 (above left).

The balanced D-90 (above right).

The D-90 on a mountain bike (left).



Close-up of the D-90 on the bike (above).

The D-90 mounted on an outboard rig, for further testing (left).

tigation of a liquid fuel recuperative burner, air cooling, and increased pressurization. Then, perhaps, I can finally pursue my elusive aim of getting the engine into some kind of limited production, for sale to the many people searching for a small stirling for use in their various projects.

TABLE 1

ENGINE:	Philips 102C	Ross 65 cc	Ross 35 cc	Ross C-60	Ross D-60	Ross D-90
GENERAL SPECS:						
Type	Beta	Beta	Alpha	Alpha	Alpha	Alpha
Crank mechinism	Bell-crank	Rhombic	Yoke	Inv. yoke	Inv. yoke	Inv. yoke
Crankthrow (dia)	~1.094 in ~27.8 mm	1.000 in 25.4 mm	0.596 in 15.1 mm	0.570 in 14.5 mm	0.570 in 14.5 mm	0.670 in 17.0 mm
Bore:						
Exp or pwr cyl	~2.156 in ~54.8 mm	2.125 in 54.0 mm	1.520 in 38.6 mm	2.025 in 51.4 mm	2.025 in 51.4 mm	2.280 in 57.9 mm
Comp or displ cyl	same	2.280 in 57.9 mm	same	same	same	same
Stroke:						
Exp or pwr piston	~1.094 in ~27.8 mm	1.125 in 28.6 mm	0.843 in 21.4 mm	0.806 in 20.5 mm	0.806 in 20.5 mm	0.947 in 24.1 mm
Comp or displ pstn	~1.044 in ~26.5 mm	same	same	same	same	same
Net swept vol.	62.3 cm^3	65.4 cm^3	35.4 cm^3	60 cm^3	60 cm^3	89.6 cm^3
Max. hot vol.	62.3 cm^3	75 cm^3	25.1 cm^3	42.5 cm^3	42.5 cm^3	63 cm^3
Working gas	air	air	air	air	air	air
Mean buffer press. (atm)	12 to 15	2.7	1	2.3	3	2.7
Max pwr (watts)	450-688	81	44	104	200	230
Speed at max. pwr (hz)	25	26.7	45.8	41.7	55	55
Max temp (°C)	650-800	~650	~650	~700	~650	~650
Weight	~17.3 Kg			3.4 Kg	2.2 Kg	
HEATER: (Inside)						
Type	annular fins	annular plain	annular plain	annular plain	annular fins	annular fins
Heating	flame	flame	flame	flame	flame	flame
Material	al. bronze	304 ss	304 ss	310 ss	nickel	nickel
Number of slots	180	1	1	1	224	197
Slot width	.0118 in 0.3 mm	.020 in 0.51 mm	.016 in 0.41 mm	.022 in 0.56 mm	.0245 in 0.62 mm	.030 in 0.76 mm
Slot depth	.0984 in 2.5 mm	n/a	n/a	n/a	.090 in 2.29 mm	.125 in 3.18 mm
Slot length	1.48 in 37.6 mm	1.5 in 38.1 mm	1.25 in 31.8 mm	1.875 in 47.6 mm	1.5 in 38.1 mm	1.75 in 44.5 mm
Length / width	125	75	78	85	61	58
Fin aspect ratio	2.9-1	n/a	n/a	n/a	9-1	8.3-1
Cross sect. area	.209 in^2 1.35 cm^2	.148 in^2 .955 cm^2	.09 in^2 .58 cm^2	.169 in^2 1.09 cm^2	.469 in^2 3.03 cm^2	.739 in^2 4.77 cm^2

Surface area	58.6 in²	11.1 in²	7.1 in²	14.5 in²	68.7 in²	98.7 in²
	378 cm²	71.6 cm²	45.8 cm²	93.5 cm²	443 cm²	637 cm²
Dead Volume	.309 in³	.222 in³	.113 in³	.316 in³	.704 in³	1.293 in³
	5.06 cm³	3.64 cm³	1.85 cm³	5.18 cm³	11.5 cm³	21.2 cm³
(Pressure wall)						
Material	ss	ss	ss	ss	ss	ss
Heat trnsfr area	12.6 in²	11.1 in²	7.1 in²	14.5 in²	11.7 in²	15.9 in²
	81.3 cm²	71.6 cm²	45.8 cm²	93.5 cm²	75.5 cm²	102.6 cm²
(Outside)						
Type	fins	plain	plain	plain	plain	plain
Surface area	58 in²	11.1 in²	7.1 in²	14.5 in²	11.7 in²	15.9 in²
	374 cm²	71.6 cm²	45.8 cm²	93.5 cm²	75.5 cm²	102.6 cm²
Material	al. bronze	ss	ss	ss	ss	ss
REGENERATOR						
Type	annular	annular	annular	annular	annular	annular
Material	ss wire	ss foil	ss foil	ss foil	ss foil	ss foil
Mtrl thickness		.0015 in	.0015 in	.001 in	.001 in	.001 in
		.038 mm	.038 mm	.025 mm	.025 mm	.025 mm
Height	1.25 in	.625 in	.625 in	1 in	1 in	1 in
	31.8 mm	15.9 mm	15.9 mm	25.4 mm	25.4 mm	25.4 mm
Cross sect. area	1.42 in²	1.21 in²	.662 in²	1.43 in²	1.43 in²	2.26 in²
	9.16 cm²	7.81 cm²	4.27 cm²	9.23 cm²	9.23 cm²	14.6 cm²
Total volume	~1.6 in²	.91 in²	.414 in²	1.43 in²	1.43 in²	2.26 in²
	~10.3 cm²	5.87 cm²	2.67 cm²	9.23 cm²	9.23 cm²	14.6 cm²
Fill factor	~25 %	~11%	~11%	~11%	~11%	~11%
Dead volume	1.25 in³	.76 in³	.368 in³	1.27 in³	1.27 in³	2.01 in³
	20.5 cm³	12.5 cm³	6.0 cm³	20.8 cm³	20.8 cm³	32.9 cm³
COOLER:						
(Inside)						
Type	annular	annular	flat plate	flat plate	annular	annular
	fins	fins	fins	fins	fins	fins
Cooling	air	water	water	water	water	water
Material	copper	al alloy	al alloy	al alloy	al alloy	al alloy
Number of slots	180	120	25	33	160	192
Slot width	.0118 in	.020 in	.028 in	.028 in	.016 in	.020 in
	0.3 mm	0.51 mm	0.71 mm	0.71 mm	0.41 mm	0.51 mm
Slot depth	.0984 in	.063 in	.120 in	.185 in	.080 in	.100 in
	2.5 mm	1.6 mm	3.0 mm	4.7 mm	2.0 mm	2.54 mm
Slot length	1.48 in	1.5 in	1.75 in	1.96 in	1.094 in	1.938 in
	37.6 mm	38.1 mm	44.5 mm	49.8 mm	27.8 mm	49.2 mm
Length / width	125	75	62.5	70	68.4	97
Fin aspect ratio	2.9-1				2.7-1	4.3-1
Cross sect. area	.209 in²	.150 in²	.084 in²	.171 in²	.205 in²	.384 in²
	1.35 cm²	.968 cm²	.542 cm²	1.1 cm²	1.32 cm²	2.48 cm²
Surface area	58.6 in²	29.7 in²	11.7 in²	25.7 in²	30,8 in²	81.9 in²
	378 cm²	192 cm²	75.5 cm²	166 cm²	199 cm²	528 cm²
Dead Volume	.309 in³	.225 in³	.147 in³	.335 in³	.224 in³	.744 in³
	5.06 cm³	3.69 cm³	2.41 cm³	5.49 cm³	3.67 cm³	12.2 cm³
(Pressure wall)						
Material		al alloy	al alloy	al alloy	al alloy	al alloy
Heat trnsfr area	12.6 in²					
	81.3 cm²					

crankcase inlet pres.	C-60 speed hz	C-60 power watts	D-60 speed hz	D-60 power watts	D-90 speed hz	D-90 power watts
1.0 atm.	38.7	54.2				
1.3 atm.	46.4	81.2	54	102.6	51.4	128.5
1.7 atm.	42.9	94.4	52.9	133.3	52.8	155.8
2.0 atm.	41.7	104.3	54.9	159.2	54.3	184.6
2.3 atm.	42.2	105.5	53.8	173.2	53.4	208.3
2.7 atm.			54.4	190.4	54.8	230
3.0 atm.			55	200.8		

TABLE 3

Dead Volume Experiments
D-90 Engine
(engine's own dead volume=~148cc)

Added Volume	**Free Speed (hz) @ Approx Heater Temperature** ~550°C	~600°C	~650°C
60cc	58	66	69
290cc	30	32	36
503cc	18.1	18.5	19.4
1025cc	~5	—	~10

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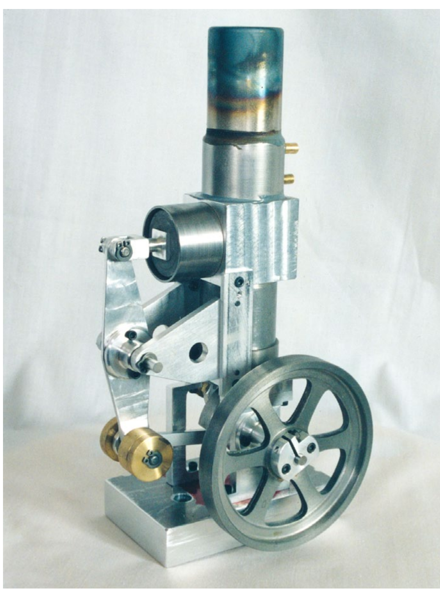
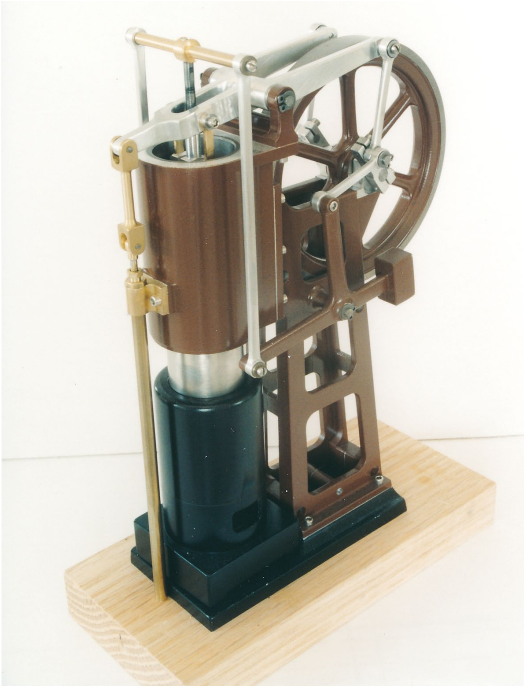


This much-modified engine was the first of the “Rocker-V” type alpha machines. As the name implies, the engine is balanced like a 90° V-twin, and employs a rocking lever to connect the compression piston to the single crankpin.v



A recently completed model of the Denney improved Ericsson (left) made by the author and his son Bryce. What began as a father-son project was blatently taken over by Dad when it started looking good. The engine has a one inch bore, and it runs nicely from the heat of a short candle concealed within the firebox. No special provision for cooling has proven necessary.

A stirling engine (or compressed air) driven model of a Swiss railcar (below), made by the author and described in the March 2002 **ModelTec** magazine.

The author (center) with Harald Berg and their interpreter Hilde, aboard Berg's wood-fired stirling-powered boat near Askim, Norway, one summer day in 1984.(photo courtesy of Sigmund Kydland).