FINAL TECHNICAL REPORT
ON
LOW PRESSURE HIGH SPEED STIRLING AIR ENGINE
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PART I. INTRODUCTION

The Stirling engine was invented by scotsman Robert Stirling in 1816. It is a piston-type heat engine in which pressure fluxuations acting on the piston are provided by alternately heating and cooling air (or another "working" gas) in the engine's cylinder. The same air or other working gas is used over and over, and the high temperature heat is supplied to the working gas from outside the cylinder. The engine may therefore run on any source of high temperature heat, including concentrated solar energy or the combustion of paper, straw, wood, coal, kerosene, or other fuels, and this constitutes one of its major advantages over most other heat engines. Additional advantages include the potential for long life, high reliability, low maintenance, high efficiency, and quiet operation.

Stirling air engines were relatively widely used 70 to 100 years ago for various domestic chores, particularly pumping water, and they earned an excellent reputation for silent and reliable operation. They were nevertheless very large and heavy for their power, and were made obsolete by electric motors and gasoline engines. [References 1 and 2].

These engines were practically forgotten by 1938, when the Philips Company of Holland decided to develop the Stirling into a modern high-speed engine. The Philips literature [References 3, 4, & 5] from this initial work is essential reading for anyone seriously interested in Stirling engines (for one actual test, see reference 16). By 1949 Philips had developed the Stirling air engine to an advanced state; but thereafter, for various reasons [Reference 2], interest in the Stirling engine wanned, and when it revived several years later with the invention of the rhombic drive [Reference 6], it was and has remained devoted almost entirely to sophisticated high pressure hydrogen and helium Stirling engines, for such intended applications as automobiles, trucks, space powerplants, etc. These high technology Stirlings are very interesting, and in some ways very promising, but they have been plagued from the start with difficulties of adequately sealing the high pressure working gas for long periods of time. [Reference 7].

Recently, with the increased public attention given to "appropriate" technology, there has been some revival

of interest in air Stirlings [References 8, 9, & 10], but by far the bulk of the interest and money in Stirling engines remains in high technology hydrogen and helium machines.

Today over 40 years after the revival of modern interest in the Stirling engine, there is still no general purpose Stirling available at a competitive price for doing useful work. There are several sources of expensive research engines, including a very interesting free piston engine [Reference 17], and several sources of desktop model engines [Reference 18], but little else. This lack of hardware has greatly inhibited the development of a broad base of Stirling engine research and development. Apart from the early Philips articles [References 3, 4, & 5] and several other important works [such as Reference 13 & 14], there is not even much practical advice in the literature intended to guide one wishing to build a Stirling engine.

The above cursory review of Stirling engine history permits the project which is the subject of this paper to be put in a proper perspective. The project was to design, construct, and test a simple low pressure Stirling air engine capable of producing 100 watts (1/8 hp.) of mechanical power (See drawing 1 and 2, attached).¹

The major purpose of the project was to demonstrate that a relatively simple, multifuel, low pressure (but high speed) Stirling air engine of useful power can be built with limited funds and resources, and can constitute appropriate technology for various applications.

The project engine can be considered to fall somewhere between the simple atmospheric engines of 70 years ago and the medium pressure (140 + psi) Philips air engines of the 1940's.

Like the antique engines, the project engine has a relatively large volume of piston displacement, a simple cylindrical (unfinned) heater, and a low pressure level; but like the Philips engines it operates at relatively high speed, employs modern materials, and is relatively light-weight.

1. These drawings were drawn full size, so as to require no dimensioning. They were reduced 33% in size (2" = 3") to more readily fit in this report. A scale (which did not reproduce very well) appears on drawing 1.

In fact, the project engine may be seen as a step toward a new line of development in Stirling engines; that is, light-weight air Stirlings of extremely large bore/stroke ratios, with plain heaters. This idea is developed further in Parts III and IV of this report, and is perhaps one of the most useful ideas to come out of this project.

In the following parts of this report it will be assumed the reader is reasonably familiar with Stirling engine operation and terminology. If more background information is desired there are a number of excellent sources [References 12, 13, and 14].

PART II. SUMMARY OF WORK DONE

The purpose of this project was to design, construct and test a simple, appropriate technology low pressure, high speed, wood-fired Stirling air engine of 100 watts output.

The initial design was a concentric piston/displacer engine of 4.54 inch (11.53 cm.) bore and 1.25 inch (3.175 cm.) stroke, with a separate crosshead to absorb connecting rod side forces, and levers to actuate the displacer. Photo 1, attached, shows the original crank mechanism. The lever arrangement would have been ultimately replaced with a simple bell-crank, but the lever arrangement allowed some change in phase angle, which seemed desirable in an experimental engine.

At a very early stage of the work, however, this crank mechanism was abandoned and a rhombic drive mechanism was designed to take its place. Stroke was shortened to 1 inch (2.54 cm.). The complete reasoning behind this decision is given in Part III, below, but the main reasons for this change were to provide a more compact design and to permit mild pressurization. Whether or not this decision was productive for the actual engine constructed, it was in any case an essential step in the evolution of the extra-compact second generation designs that grew out of this work, and that may be the most important part of it (see Parts III and IV, below).

The heater, cooler and regenerator, the piston and displacer, and the rhombic drive geometry were all based upon an 4 cubic inch displacement (65 cc) engine previously designed, built and developed by the author (Photo 2).

Details of this machine are given in Part III, below, and its development continued even while work on this project was carried on. It now develops over 80 watts of power when pressurized on air at 25 psig (2.7 bar, absolute), and it was treated as a "part engine" in the design of the larger project engine.

The project engine was ultimately completed and tested, using a propane burner for all tests as a matter of convenience. The 100 watt aim was exceeded, at atmospheric pressure, over a wide range of engine speed, as shown on Chart 1, with the maximum power being 112 watts at 1150 rpm.

A pressure can was constructed to permit pressurization, however the grant funds were running out, and the only pressurized power test attempted was unsuccessful due to seal difficulties. This was a disappointment, because numerous tests on the 4 cubic inch engine suggested power would be more than doubled with pressurization at 25 psig.

A manifold was designed and constructed to permit operation of the engine over a standard No. 40 pot bellied stove. The engine was run successfully, but at reduced speed and power, over this stove. Because grant funds had by this time run out, no development work on the stove modification was undertaken. Various ideas on this modification are set forth, however, in Part III.

The project engine started out being rather noisy in operation, but modifications discussed in Part III ultimately resulted in a very quiet engine. Various other difficulties and their solutions also appear in detail in Part III.

Total engine weight (including the propane burner) is 16 lbs. (7.3 kg). Consideration of where the weight is (See Chart 2), in light of which parts can be greatly lightened and which cannot, suggests ways to design a new generation of extremely light and compact low pressure high speed air engines (See Chart 3). These very encouraging prospects are discussed in Part IV, below, as are other conclusions and assessments of the project.

PART III. TECHNICAL REPORT

A. Design

1. Power Head Assembly.

As mentioned in Part II, above, the power-head components (heater, regenerator, cooler, piston and displacer) of the project engine were designed along the lines of a previous 4 cubic inch displacement engine. For convenience, this 4 cubic inch engine will hereafter be referred to as the "small engine". The small engine was designed over 6 years ago, and in its first test produced a mere 1.5 watts of mechanical power. Various modifications to the regenerator and (primarily) the burner raised this to 55 watts on air at 25 psig at the time the project engine was begun. Subsequent burner modifications have effectively increased the heater surface area from 7.5 to 11.3 square inches, and output is now slightly over 80 watts. Pressurization has not recently been taken over 25 psig in this machine because the plain connecting rod bearings with minimal lubrication may not take it. It is evident this engine is heater-limited, since output has remained proportional to heated surface area throughout many modifications. The power output per square inch of heater surface area has remained very close to 7.2 to 7.3 watts/sq. inch. This compares well with the Philips 200 watt engine [Reference 10], which, when tested over a wide range of temperatures, gave from 6.4 watts/sq. in. of heater, at 700°C, to 10.5 watts/sq. in. at 900°C. These rates are very much lower, it should be mentioned, than those common in high pressure hydrogen and helium Stirlings; the GPU engine, for example, produces 40 watts for each square inch of active heater area.

The small engine employs chrome-plated steel, low tension, 2 cycle racing engine piston rings of exceptionally low drag. These rings are only .025" thick, and are a very important part of this engine's respectable performance. The project engine was designed for similar rings, with the thought that suitable rings could be readily ordered from speciality ring makers. When it came time to obtain the rings, various ring makers were not interested, and the author finally had to re-machine conventional cast iron rings. They seal fairly well, and their tension has been considerably reduced by reducing their inner diameter, but their drag is more than seems necessary. Future engines will be designed around suitable low tension rings that are already available.

Complete specifications of both the small engine and the project engine are given in Chart 4. The similarities between the two engines will be evident from studying this chart.

2. Crankshaft Mechanism

The original crank and slider crankshaft mechanism was practically complete before this project officially began (see original proposal), and it is what one might expect to see on a simple appropriate technology engine. There can be no question the switch to a rhombic absorbed grant funds that could otherwise have gone toward additional development of the stove, etc.

In designing an appropriate technology Stirling, one faces innumerable alternatives. One possible choice, and perhaps a sound one, would be to copy a successful antique, such as the 5" Ericsson [Reference 15], and simply use (1) aluminum alloy in place of cast iron for the cylinder, frame, etc. to save weight, (2) pressed stainless hot caps and domes, in place of cast iron to save weight and heat conduction loss, and (3) roller element (needle & ball) bearings in place of plain bearings to save friction. These steps would no doubt double the power and halve the weight.

A second approach would add to the changes of the first approach a sealing displacer and a regenerator.

A third approach would aim at a somewhat smaller, higher speed engine. This approach was the initial aim in this project.

A fourth approach, ultimately chosen here, would retain a plain (unfinned) hot cap, but in all other respects would be thoroughly modern, and as light and compact as possible. Even a plain (unfinned) hot cap will usually permit increased power with mild pressurization, and it would seem worth while in most cases to take advantage of this fact. An interesting variation of this approach would use an extra large heater (hot cap), with a stuffer can inside, and relatively small reciprocating components, with moderate pressurization. This combination allows extended heater surface area without the expense of fins.

It is easy to see that one could continue this reasoning, and the fifth or sixth approach would be a medium pressure finned heater Philips air engine, and the seventh or eighth approach would be a high pressure, high technology

helium engine. Yet in these later hypothetical approaches, the heat exchangers (heater/burner, primarily) would begin to dominate the total size of the engine, and whereas piston volume would continue to get smaller, engine size and weight might not.

In any event, having finally chosen the fourth approach, the rhombic drive has much to commend it. First of all, total engine height can be much lower than with the inherently tall crank/crosshead system. Philips used an oil-filled crankcase in their single cylinder air engines which permitted the piston to be its own crosshead, as in internal combustion engine practice. This would be impractical on an inverted engine; and, in any event, to avoid oil contamination of the regenerator as well as any possibility of oil ignition, I prefer to maintain a dry crankcase. A rhombic drive with needle bearings in the connecting rods, ball or needle bearings on the crankshafts, and delrin gears, eliminates the need for an oil-filled crankcase. A film of oil on the cylinders seems adequate, as does a small amount of non-migrating grease on the needle bearings. The small engine has run many hours with no other lubrication, and the steel piston cylinder, as well as the hard anodized displacer cylinder, show no sign of wear or other distress. The piston and displacer also show no sign of destructive wear.

Can a rhombic drive be simple? Most investigators would say no, but I would say, if overhung cranks are used with the crank discs doubling as sole counterweights and gears, the answer can be yes. When one counts the parts (each one different) in a conventional bell-crank design including a crosshead, then the overhung rhombic doesn't look so bad. It will be noted, of course, that the project engine has cranks supported at both ends, and this becomes quite complex. This design was chosen because it allowed the simple application of a concentric pressure can, and because it was mechanically stout and conservative, not because it would be the best way to build an appropriate technology Stirling.

What about weight? The rhombic system, with its twin cranks and need for complete counterbalancing, does become heavy. I now believe the answer for this problem, with low pressure engines, is a move toward extreme (i.e., by internal combustion engine standards) bore/stroke ratios (see Part IV, below). Going to very short strokes, and large bores, while maintaining a given crank disc (or gear) size, permits the required balance weight to become much lighter, not just because of the shorter throw but also

because of the larger relative size of the crank disc vis a vis the throw. Bearing loads caused by pressure (as opposed to those caused by inertia, which become relatively minor) increase, of course, but here the twin crankpins become an advantage. Overhung cranks also permit the easy use and installation of one-piece connecting rods with needle bearings pressed in them.

The extremely large bore/stroke ratio engine designs (assume a ratio of 6:1, for example) lend themselves to providing a great deal of heat exchanger surface area without resorting to the complication of fins. (See Part IV, below). It may be objected that the large bore design increases conduction losses. In the modified small engine (Chart 3), for example, calculations suggest conduction losses down the displacer and regenerator wall would be about 1.5 times those of the existing small engine. Shuttle heat transfer, on the other hand, would be about 3.2 times less in the short-stroke modified engine (using formula in Reference 13, p. 82). In light of the various possible ways to reduce conduction losses, and the shuttle heat transfer advantage of the modified design, I do not think this objection need be decisive. Preliminary calculations also indicate bearing loads will not be troublesome (See also Reference 13 pp. 91, 92). The bore may "look" excessive for the bearings, but if one mentally "bores" out a high pressure Stirling, e.g., the GPU engine, to maintain the same gas pressure loads on the bearings at 30 psi mean pressure, one ends up with a bore over 12 times the stroke!

The rhombic geometry used in both the small engine and the project engine is relatively conservative; it is self-supporting, since the crankpins do not cross over the yoke pin centerlines, and is generally similar to the geometry in the GM GPU engine.

B. Construction.

1. Displacer Dome and Hot Cap

Both of these items were hydroformed out of 321 stainless steel. The displacer dome is only .010 inch thick and weighs a mere 102 grams. It was formed on an existing die, in the interest of economy, hence the unusual bore size of 4.54 inches. I regretted this economy move when it came to finding ready-made piston rings!

The displacer dome has only one heat shield, located at the ring end of the dome. It should no doubt have more.

The dome itself is epoxied to the lower, aluminum alloy, body of the displacer, which carries the ring. This epoxy, of the common hardware store variety, has held up well in this and other engines.

2. Displacer and Piston.

Both of these parts are aluminum alloy. This piston was initially fitted with an aluminum clearance seal instead of rings. The engine was never run with this seal, as it seemed to require too perfect an alignment, and the ring problems were soon sorted-out. The total reciprocating masses with each of these parts are about 350 grams. This weight could no doubt be reduced by about one third. The displacer shaft seal is a lip seal machined of Rulon, with a suitable o-ring providing the tension. This type of seal has worked well in the past, and seems to be behaving well in the project engine.

3. Connecting Rods and Yokes.

These parts are all aluminum alloy. The rods were drilled, bored and reamed on a face-plate fixture to assure that they all have the same center distance between the pressed in needle bearings. Yokes were also drilled, bored and reamed on a fixture. Future designs will probably use a pivoted piston yoke to assure equal distribution of bearing loads between crankpins.

4. Crankshafts.

Cranks are made of steel, in three parts, and clamped together. Crank pins (and wrist pins) are commercially available hardened and ground "dowel pins". These seem to work well with needle bearings, and they are inexpensive. Crank discs were machined between centers, then mounted on a fixture to bore the holes for crank pins. Maintaining alignment in assembly and disassembly is burdensome, and I would not use this arrangement again. The main crank is .001" inch out of true, and this has been a continuing source of frustration. I would favor one-piece overhung cranks in the future.

5. Displacer Cylinder and Power Cylinder.

These parts are of aluminum alloy, and the inner bores of both are hard anodized, which makes a very tough wear surface. Honing this surface proved very difficult with conventional stones. I am informed diamond laced stones will make a very easy job of it, however. Hard anodizing

causes a build up of the cylinder wall (each side) of about .0005" inch or so, so this must be taken into account. Don't expect closely fitting parts to still fit after anodizing. I prefer to have flanges, etc., masked during the process.

The cooler passages were drilled into the displacer cylinder while on the lathe. This type of cooler is similar to the small engine's original cooler, although the present cooler on that engine is a finned type of much greater surface area, and less dead volume. Unfortunately, no tests have yet been conducted to test present cooler effectiveness.

6. Regenerator Matrix.

Present matrix is a commercially available woven strip of .004" stainless steel wire. Stainless foil of .001" thick was obtained, but not tested (as the funds ran out). Similar foil in the small engine has shown the promise of shifting the power curve toward higher speeds and power. Complete tests have yet to be conducted.

7. Propane Burner.

This part was fabricated and welded together of .020" thick stainless steel. It has eight rows of jets, with 44 1/16" dia. jets per row. Fine mesh stainless screen is the anti light-back device. Mixer tube diameter is .934 inch, and the propane orifice diameter is .018 inch. This burner was very troublesome at first, being hard to light and producing an overly rich mixture. A series of different size orifices were then made and tested, and its performance became satisfactory for testing, though it is still not by any means a well-developed burner. It is interesting to note that parts of the burner eventually run at red heat, with no flashback problems.

8. Wood Stove Modification.

As it became clear the grant funds were running out, the best way to assure running the engine on wood seemed to be to make a simple manifold modification which would bolt over a standard pot-bellied stove. This proved very easy to do, but no effort was made to prevent heat loss to the stove castings before the gases reached the engine, consequently maximum speed on the stove was 1150 rpm, rather than 1950 rpm as was the case on the propane burner. There was no development undertaken on this component. I would expect a great improvement if only the stove part

were insulated and the grate moved much closer to the engine heater. Moreover, the heater of the engine should no doubt be on the bottom of the hot cap, rather than its sides, to make use of the radiant heat transfer from the luminous flames.

9. Miscellaneous Other Components

Self locking retaining rings were used on wrist pins with no problems. A reed (check) valve was added to the piston, which consisted of a two cylce gasoline engine inlet reed valve. It has worked very well. The delrin gears show no sign of wear, although conceivably this could be because the rigid yokes do not require them to carry any load. They have practically no backlash. Other general comments on building a small rhombic (model) engine are in Reference 19.

The grant proposal mentioned the possibility of using rolling diaphragm seals on the piston. Prior to the grant I had conducted limited but successful tests using toy balloons as rolling seals. Subsequently, I obtained seals made of balloon rubber on dies I supplied, but these seals were not tested for lack of time. Because this type of rubber is attacked by oil, and because of the great difficulties with such seals reported in the literature [e.g. Reference 7], I decided not to pursue them further on this project. It is worth noting, however, that the rolling seals developed by Philips and GM operated with about a five atmosphere pressure differential, the balance of the pressure being supported by an oil column, and that regulation of the oil column apparently gave rise to many of the difficulties encountered. This suggests that such seals may be worth investigating for unsupported use on a low pressure air, helium, or hydrogen Stirling.

C. Testing.

The project engine ran the first time, but it was somewhat noisy, with bearing knock being the apparent cause. A reed valve was added to the piston, making the forces on the piston one way only, and noise was greatly reduced. Power was also improved. The delrin gears seem to make very little noise. When the pressure can was added (even without pressure) the engine became quieter still, so that it now is very quiet indeed.

Early tests indicated the working gas was not getting very hot, as the displacer dome was not heat-discolored. An insulated cap was added to the hot cap, to slow the heat leak there, and different burner orifices were tried

in the burner. With these changes it became clear the working gas was at last getting well heated, since the displacer dome was blue from the heat, as was the top half of the regenerator, and all of the inner sleeve.

Later tests indicated the piston ring gap was insufficient, as there seemed to be a tendency for the engine to sieze or slow down just as it began to run well. This gap was increased on all rings to .020 inch, and this problem disappeared.

The displacer shaft showed score marks after several tests, and it was later determined that the screws mounting the gears had become loose. These were tightened and showed no signs of loosening again. However, a brass collar was added to the piston above the displacer shaft seal to act as a bearing on the shaft, just in case. This collar shows no signs of excessive wear.

During the process of sorting out various bugs in the engine and burner, the power tests indicated improvement in power from 70 to 112 watts. The power shown in Chart 1 is the best obtained to date, however, it is still apparent there are problems not yet resolved. For example ring friction seems high, and sealing is not what it should be. Whether the rings or the displacer shaft seal is to blame, I do not yet know. There is also some indication the spacers on the crankpins are too wide and may be causing some extra friction.

I mention these things not by way of excuses, since the engine has made its intended power in any event, but to emphasize that any new engine requires a lengthy development period before one can hope to realize its potential. It is apparent this engine has a great deal more potential than has yet been realized.

After the relatively successful atmospheric pressure tests, a pressure can and seal were prepared for tests at elevated pressures. Unfortunately, the grant funds had nearly run out, and the only test conducted proved unsuccessful as seal alignment problems plagued the test. There was simply no time to sort out the various potential problems and reconduct the test. The process might easily take several weeks.

Attention was directed instead to completing a wood stove modification with the remaining funds. This was done, and the engine ran on wood, then charcoal, but power was not tested. It should be noted, however, that the engine

running on the stove was extremely quiet and trouble-free. The 6 inch diameter six foot tall stack seemed to draw the flue gases through the manifold quite well. Some creosote formed in the stack, but the experiment was too limited to really even see what the problems, if any, might be.

It will be noted no efficiency tests were conducted. Neither the propane burner nor the stove were sufficiently perfected to make such tests significant. Efficiency tests were previously conducted with the small engine showing 4% (power out/fuel in) and 14% (power out/heat in), but these also suggest there is immense room for development.

PART IV. CONCLUSIONS

The project engine cannot by any means be considered a developed engine. It is a starting point only. The bulk of the grant money went into the construction of the engine, leaving very little for its testing and development. The design decision to use a rhombic drive mechanism is partly responsible for this situation, yet I think the results of the project fully justify this design modification.

I believe the most important result is the evidence, provided not just by the project engine but by the small engine as well, that the high speed low pressure Stirling engine has a significant and largely undeveloped potential to become a useful engine for small power applications. A crucial part of this evidence is the idea, summarized in Chart 3, that combining an extremely large bore/stroke ratio (on the order of 6:1) with the overhung crank rhombic drive provides a excellent way to make an exceptionally compact high speed low pressure Stirling engine.

In the original proposal for this project it was suggested that the project engine be compared with two antique Stirling engines. This has been done in Chart 6, based on information in Reference 15. It seems apparent that a small high speed engine has immense advantages in terms of weight and size per unit of power over the antique slow speed designs. But the antique engines are arguably straw men in this comparison; the questions remain, does the project engine, as a low pressure high speed design, have the potential to be a useful machine in today's world, and if so, how?

I believe the answer is, yes, it does, in at least several different applications.

One application is as a true appropriate technology engine, designed especially for solid fuel operation. I visualize such a machine as similar to the project engine but with the following modifications:

1. A larger bore, shorter stroke, to decrease weight and provide potential for more heater area. A sort of pancake engine.
2. A hemispherical heater, to make use of the end of hot cap as active heater area, as well as the sides, and to absorb the radiant heat of a luminous fire.
3. Overhung cranks, with larger diameter crank discs, to allow complete balancing to be done with single disc per crank.
4. Crank discs also doubling as synchronizing gears.
5. An extruded finned aluminum cooler sleeve, to simplify manufacture and increase cooler effectiveness.
6. A pivoted power piston yoke to assure equally distributed bearing loads; the displacer yoke would remain one piece to provide guidance for the displacer shaft.
7. A specially designed light weight stove, possibly with simple air preheating.

Once the end of the hot cap is used as active heater area, a great deal of extra surface area becomes available for the heater. If one builds larger engines by increasing the bore, not the stroke, then available surface area increases in proportion to volume. An engine of 6 inch bore and .75 inch stroke, with the modifications set forth above, could conservatively be expected to produce over 160 watts (1/5 hp), atmospheric, and yet be considerably more compact than the project engine.

Another application is as a smaller 100 watt general purpose test engine. Such an engine would essentially be a large bore, short stroke version of the small engine.

Such an engine would burn propane or kerosene, and would self-pressurize to approximately 30 psig. With a 3 inch bore, and a .5 inch stroke, it would be roughly half the size of the small engine. A comparative drawing is shown on Chart 3. I believe this engine could weigh under 3 pounds.

Such a machine is small enough to lend itself to modification and experimentation with the facilities of only a small workshop. Yet it is powerful enough to propel a bicycle or canoe, or to power other devices requiring one "person power".

One does not have to be in the Stirling field long before realizing how inhibiting on independent development is the present lack of a moderately priced research engine. The engine described could be made in limited numbers initially to be sold as a small research engine. With even fifty such engines in the hands of competent researchers, graduate students, and other interested persons around the world, one would expect a great number of modifications to be tested and various improvements to be made. Considering how eagerly people working in the Stirling field covet the few remaining Philips 200 watt air engines, I believe one could easily sell fifty or more of the engines I have described for somewhere under \$1000 apiece. As production increased and the price was lowered, campers, bicyclists, fisherman and hobbyists could become interested customers.

The potential bicycle application illustrates some of the intriguing possibilities of a small power Stirling. The average bicyclist produces about 75 watts of power [Reference 11], so a 100 watt Stirling, less reasonable transmission losses, could become a "person power" bicycle motor. Such a silent, appropriately powered bicycle should arguably be permitted on bicycle paths where conventional mopeds (with typically 750 watts of power) are reasonably excluded because of (1) their noise potential (many owners cannot resist removing the mufflers), (2) their high relative speed potential compared with joggers and average bicyclists, and (3) their unpleasant and unhealthy exhaust fumes.

Turning now from the general prospects of this work to the specific engine created under this project, I would recommend continued testing of the project engine. A first step would entail complete instrumentation, to see what really is going on in the working gas. Somewhere down the line an endurance test would be appropriate.

Adequate pressure tests would also be useful. There is no question that a great deal can be learned from this existing machine, despite its imperfections.

I sincerely hope this report will help stimulate interest among other investigators in low pressure high speed Stirling air engines, which seem to have such promising potential for small power applications.

PART V. REFERENCES

1. Finkelstein, T. (1959), "Air Engines". Engineer, London, v. 207 pp. 492-497, 522-527, 568-571, 720-723.
2. Ross, A. (1977), Stirling Cycle Engines, Solar Engines, Phoenix, 121 pages.
3. van Weenen, F. L., (1947), "The Construction of the Philips Air Engine". Philips Technical Review, v. 9, pp. 125-134.
4. de Brey, H., et. al., (1947), "Fundamentals for the Development of the Philips Air Engines". Philips Technical Review, Vol. 9, pp. 97-104.
5. Rinia, H. and Du Pré, F. K., (1946), "Air Engines". Philips Technical Review, Vol. 8, pp. 129-136.
6. Meijer, R. J., (1959), "The Philips Hot Gas Engine With Rhombic Drive Mechanism". Philips Technical Review, Vol. 20, pp. 245-276.
7. Percival, W. H., (1974), "Historical Review of Stirling Engine Development In the United States From 1960 to 1970". ERDA, No. NASA, CR-121097.
8. Michels, A.P.J., (1976), "The Philips Stirling Engine; A Study of its Efficiency as a Function of Operating Temperatures and Working Fluids". Proceedings of 11th I.E.C.E.C., Paper No. 769258, Lake Tahoe, Nevada, September 12-17.
9. Rice, G., Buckingham, J. F., (1978), "Conversion of A Standard Single Cylinder i.c. Engine into a 'X' Configuration Air Charged Stirling Engine". SAE Paper No. 789196, pp. 1805-1811.
10. Ward, G.L., Slowley, J., Walker, G., (1977), "Performance

Characteristics of a Small Philips Stirling Cycle Air Engine". Stirling Engines conference, Institution of Mechanical Engineers, Reading, U.K., March, 1977.

11. Whitt, F.R., and Wilson, D.G., (1974), Bicycling Science, Ergonomics and Mechanics, The MIT Press, Cambridge, Mass.
12. Walker, G., (1973), "The Stirling Engine". Sci. Am., Vol. 229 (2), pp. 80-87, August.
13. Walker, G., (1980), Stirling Engines, Clarendon Press, Oxford.
14. Martini, W.R., (1978), A Stirling Engine Design Analysis Manual, D.O.E., Hwy. Veh. Syst. Cont. Coord. Mtg., Troy, Michigan.
15. Rider-Ericsson Engine Co. Catalogue, (1906), Reprinted by Alan G. Phillips, P.O. Box 20511, Orlando, Florida 32814.
16. Schrader, A. R., (1951), "1015 hr. Endurance Test of Philips Model 1/4D External Combustion Engine". Naval Eng. Experiment Station, EES Report No. C-3599-A(3), NTIS #AD 494926, Feb. 1.
17. Sunpower, Inc., Athens, Ohio, offers a 100 watt free piston research engine which it expects soon to have in limited production.
18. Solar Engines, Phoenix, Arizona, offers several inexpensive model Stirling engines, including one operated by a solar collector.
19. Ross, A., (1976), "A Rhombic Drive Stirling Engine". Model Engineer, Vol. 142, pp. 760-762, Aug. 6, pp. 796-799, Aug. 20.

CHART 1

CHART 2
BREAKDOWN OF PROJECT ENGINE WEIGHT

1. Aluminum pressure can, seal, and screws	329 grams
2. Flywheel, clamp, screws, and stub shaft	1077 grams
3. Hot cap, regenerator, insulator, cooler, displacer cylinder ass'y.	1327 grams
4. Propane burner, with mixer tube and clamp ring.	403 grams
5. Displacer, rod, seal, piston, three rings, yoke screws.	565 grams
6. Power cylinder, flange plate, and engine mounts.	851 grams
7. Power take-off crankshaft, three connecting rods, two main bearings.	1071 grams
8. Other crankshaft, three con-rods, both yokes, all wrist pins, and two main bearings	1149 grams
9. Main frame, bearing caps, and screws.	<u>538 grams</u>
TOTAL ENGINE WEIGHT:	7310 grams (16) lbs.)

SMALL ENGINE
 $\frac{1}{2}$ SIZE

1" STROKE 2.125" BORE
11 sq. in. SUR. AR. HEATER

CHART 3

MOD. SMALL ENGINE
 $\frac{1}{2}$ SIZE

.5" STROKE 3" BORE
17 sq. in. SUR. AR. HEATER

CHART 4

DESCRIPTION OF ENGINES

	<u>SMALL ENGINE</u>	<u>PROJECT ENGINE</u>
Power Piston dia.	2.125"	4.54"
Displacer dia.	2.280"	4.54"
Effective Stroke	1.12"	1.12"
Crank Throw	1"	1"
Concrod Center Distance	1.5"	1.5"
Crank Center Distance	2.25"	2.75"
Wrist Pin Path Offset		
From Crankshaft Centers	.625"	.625"
Piston Swept Volume	3.97 cu. in.	18.1 cu. in.
Displacer Swept Volume	4.57 cu. in.	18.1 cu. in.

Heater:

Type	annular	annular
Annular Gap	.020"	.035"
Length	1.5"	2"
Surface Area	11.3 sq. in.	30.2 sq. in.
Cross Sectional Flow Area	.148 sq. in.	.520 sq. in.
Dead Volume	.222 cu. in.	1.04 cu. in.

Regenerator:

Cross Sectional Area	1.21 sq. in.	2.95 sq. in.
Total Volume	.91 cu. in.	2.95 cu. in.
Fill Factor	approx. 16%	approx. 16%
Dead Volume	.76 cu. in.	2.48 cu. in.
Length	.75"	1"
Matrix	woven .004" wire	woven .004" wire

Cooler:

	<u>ORIGINAL</u>	<u>PRESENT</u>	
Type	drilled	finned	drilled
Length	1.5"	1.5"	1.5"
Surface Area	15.8 sq. in.	29.7 sq. in.	47.4 sq. in.
Cross Sectional			
Flow Area	.277 sq. in.	.15 sq. in.	.831 sq. in.
Dead Volume	.416 cu. in.	.225 cu. in.	1.248 cu. in.
No. of Holes or			
Slots	32	120	96
Dia. of Holes or			
Slot Dimensions	.105"	.202" x .0625"	.105"

CHART 4 CONT'D

	<u>SMALL ENGINE</u>	<u>PROJECT ENGINE</u>
Burner:		
Fuel	propane	propane
Type	annular	annular
Jet dia.	.0625	.0625
No. of jets	144	352
Mixer Tube Dia.	.375"	.933"
Mixer Tube length	2"	5"
Orifice dia.	.013"	.018"
Piston rings:		
Type	low tension	modified standard
No. on piston	2	2
No. on displacer	1	1
Width	.025"	.075"
Radial Thickness	.080"	.125"
Material	chrome plated steel	cast iron
Maximum Engine speed:		
Air 1 atm.	2100 rpm	1950 rpm
Air 2.7 atm.	2000 rpm	---
Helium	3000 rpm	---
Bearings:		
Conrods (both ends)	plain	needle
Crankshaft	ball	ball
Displacer Rod Seal	rulon with o-ring tensioner.	rulon with o-ring tensioner.

CHART 5

COMPARISON OF PROJECT ENGINE WITH RIDER AND ERICSSON HOT AIR PUMPING ENGINES, FROM 1906 RIDER-ERICSSON CATALOGUE [REFERENCE 15]

	<u>HEIGHT</u>	<u>WEIGHT</u>	<u>SPEED</u>	<u>POWER</u>	<u>THERMAL EFFICIENCY</u>
Project engine	12"	16 lbs.	1150 rpm	112 watts	--
Small engine	11.5"		1600 rpm	81 watts	4%
5 inch bore Ericsson	4' 2"	550 lbs.	est. 250 rpm	27	--
6 inch bore Ericsson	4' 5 1/2"	800 lbs.	---	54	--
8 inch bore Ericsson	5' 5 1/2"	1000 lbs.	---	89	--
10 inch bore Ericsson	5' 6"	1700 lbs.	---	179	--
8 inch bore Rider	7' 2"	3200 lbs.	120 rpm	359	--
10 inch bore Rider	7' 9"	3700 lbs.	110 rpm	625	1%

1. Power of antique engines calculated from pumping rates listed in catalogue, assuming the pump was 90% efficient, 90% was figure given in standard mechanical engineering handbook for crank and flywheel water pumps of 6 inch stroke.

PHOTO 1

The original crank and slider mechanism around which the project engine was to be built.

PHOTO 2

The 65 cc "small engine" which was treated as a part engine in the design of the project engine.

PHOTO 3

The rhombic drive mechanism that was used in place of the original crank case and slider.

PHOTO 4

The project engine on its power test stand, with torque arm brake and tachometer.

LOW PRESSURE STIRLING
GRANT DE-FG02-79R5 10142
By ANDY ROSS 11-7-79
FULL SIZE SHEET 1 OF 2

LOW PRESSURE STIRLING
GRANT DE-EG02-T9R5 10142
BY ANDY ROSS 11-7-79
FULL SIZE, SHEET 2 OF 2