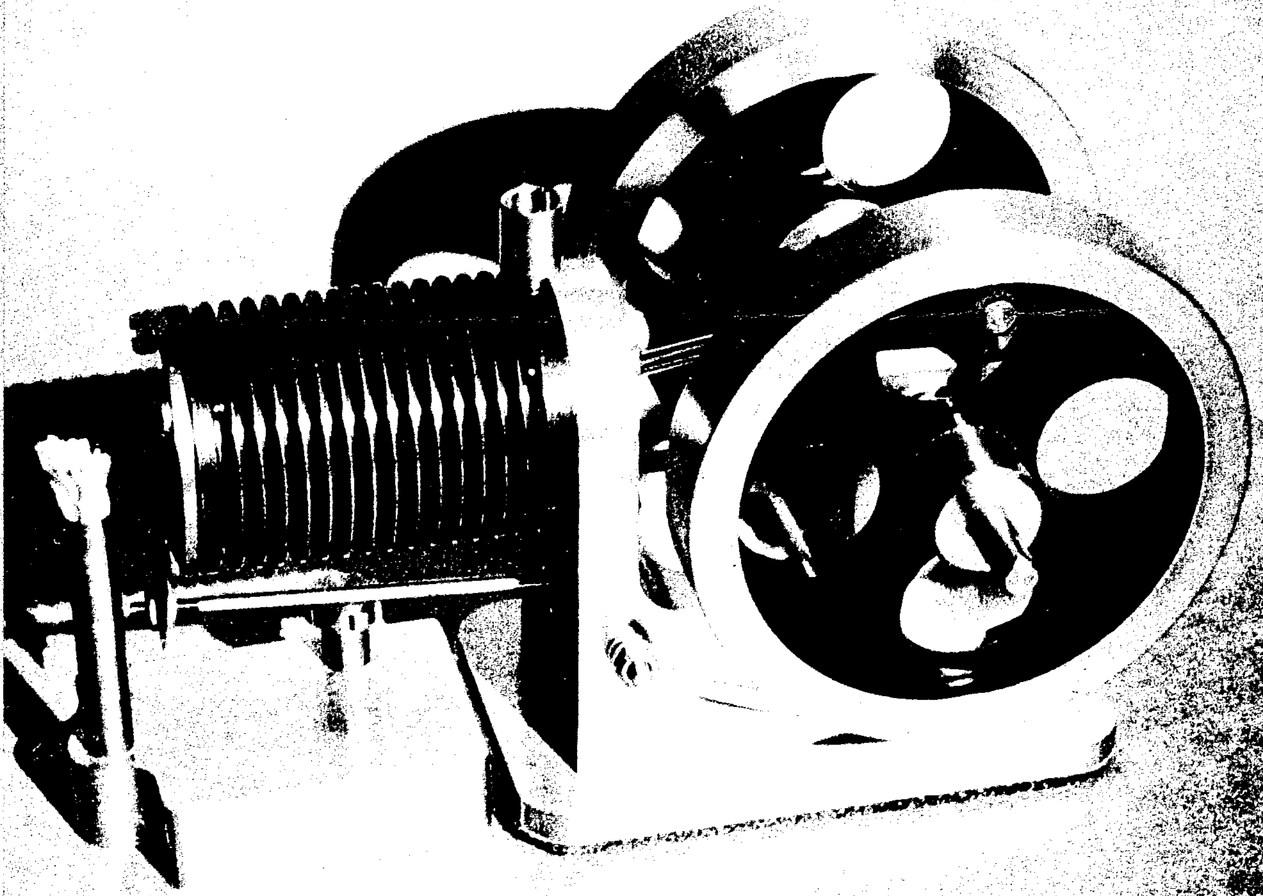
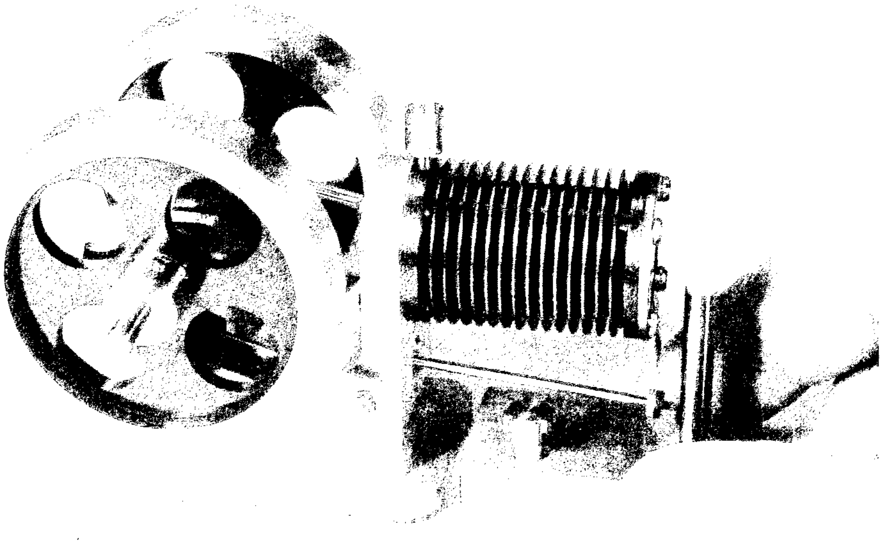


POPPIN



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POPPIN

an air-cooled vacuum engine

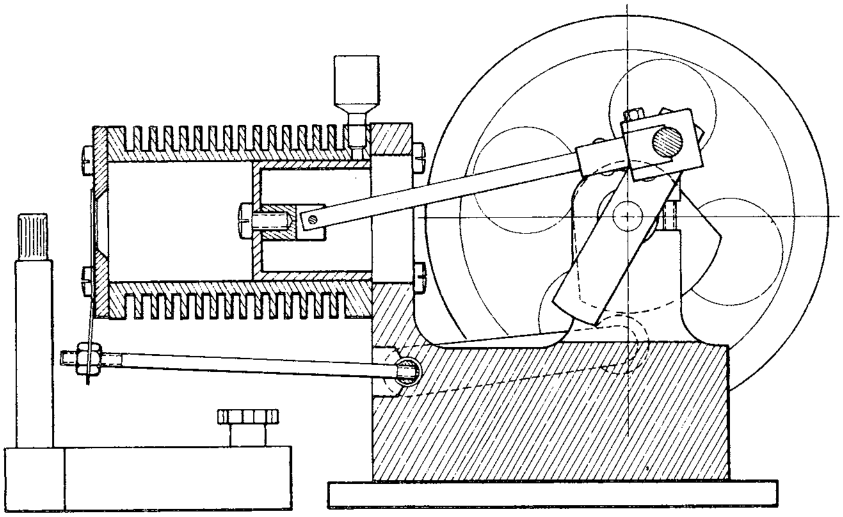
by Dr. J. R. Senft

Miniature vacuum engines are fascinating examples of heat engines, devices for the continuous conversion of thermal to mechanical energy. Their principle of operation is readily understood, the heat source in the form of an open flame is quite visible, and the engines exhibit an abundance of mechanical motion accompanied by unique sound effects. Accordingly, these engines have been popular for some time among heat engine enthusiasts and lovers of unusual mechanical devices in general.

These engines essentially consist of a crank-driven piston in a cylinder fitted with a single cam-operated valve controlling a port to the exterior. Immediately outside the valve port is positioned a flame, and during the outstroke of the piston, the valve remains open permitting hot gas from the flame to be drawn into the cylinder. Near the end of the outstroke, the valve closes the port. As the enclosed gas transfers heat to the relatively cool cylinder wall, its pressure drops below atmospheric and the piston is driven inward for the power stroke. The valve then opens and flywheel momentum carries the engine through to its next power stroke.

Thus the operation is entirely analogous to the early steam engines, but the cycle is much more rapid. Like the early steam engines, these engines are also sometimes referred to as atmospheric engines and were once commercially made in sizes large enough for practical use. In those sizes, combustion of the fuel was, in the interest of efficiency, carried out within the cylinder, but the cycle of operation was otherwise the same. A history of these machines is to be found in the excellent book of Lyle Cummins, *Internal Fire.* Our interest here is in the smaller external combustion variety.

In tiny sizes, these engines are



excellent subjects for the model engineer. Although perhaps robust in appearance and bold in their sounds, these miniatures are quite modest in power output — rather comparable to atmospheric Stirling engines — and are quite delicate in adjustment. Hence building a small vacuum engine is a project well worthy of the proven skill and patience of the veteran model engineer, and as rewarding as any to be had.

POPPIN, the engine illustrated here, is the author's latest venture in the miniature vacuum engine realm. It incorporates a number of features proven in earlier engines by the author. One feature of particular note is the front flexible valve. Its frontal location simplifies cylinder construction and does not require the incoming gas to execute an abrupt turn. The thin valve, by virtue of its flexibility and low mass, minimizes the buildup of backpressure at the end of the power stroke. The frontal location also permits the valve train to operate about a rocker shaft, which gives very low friction operation.

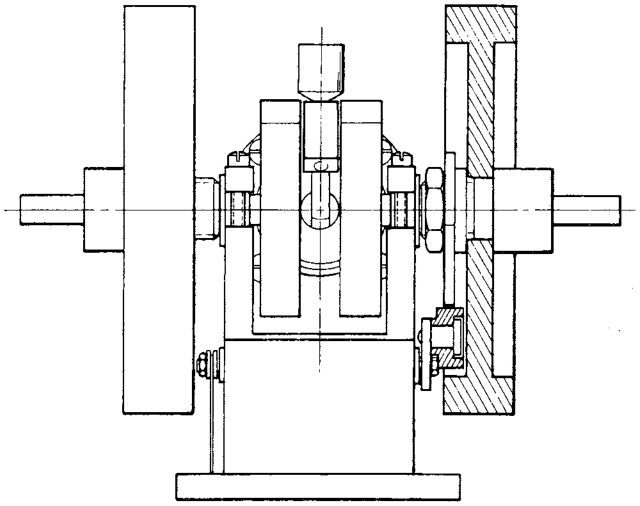
The engine is a very consistent runner and is easy to start. By varying the size and proximity of the flame, engine speed can be regulated from about 200 rpm up to 1000 rpm. Higher speeds are possible if desired with a tighter valve spring and longer cam dwell. I enjoy displaying **POPPIN** running at about 350 rpm; at this speed it appears to be idling, standing by, keeping warm, and ready for work; it looks and sounds very much like the gas engines one sees at the threshing shows.

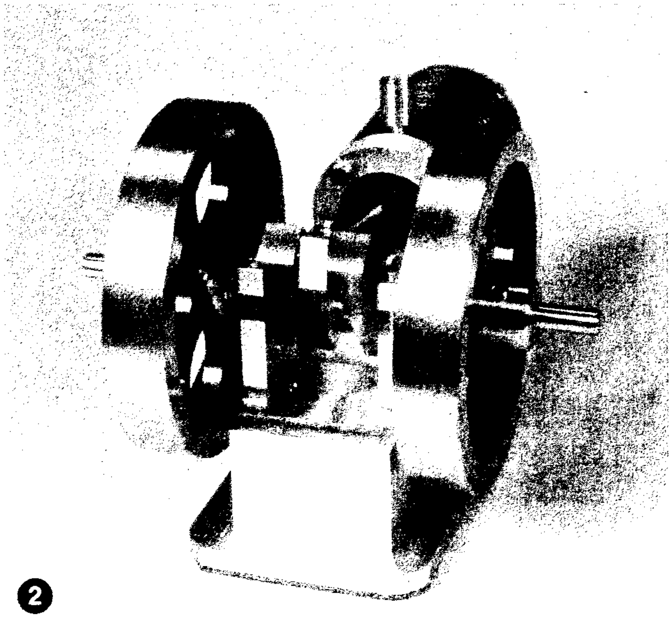
The cooling fins shown are quite adequate for normal operation. In fact the engine will run indefinitely below 800 rpm, as long as fuel and oil are supplied, without exceeding a cylinder temperature of 200° F. If run faster, the temperature will no doubt eventually rise until the point is reached where some form of cooling assist will be required to keep below the flash point of the lubricating oil. If that is your interest, you can fit a fan or try water cooling, both of which have been successfully employed on various vacuum engines built by the author. In any event, a few words about construction techniques may be helpful to those wishing to run their own version of **POPPIN.**

I began construction with the **Cylinder;** this is my usual starting point on tiny engines because it is so vitally important to the satisfactory performance of the engine. This is particularly true in the present case, namely of a small low specific power engine. Probably one of the best choices of material for the cylinder and piston of a vacuum engine is cast iron; in my case Meehanite bar was used. A length was chucked in the 3-jaw, faced, and centerdrilled for support while turning the O.D. and machining the fins with a parting tool. The latter operation is an easy one on a lathe such as the Myford which is equipped with a graduated dial on the carriage leadscrew; on other lathes, set the topslide parallel to the lathe axis and use its dial feed to uniformly space the fins. Before being removed from the chuck, the cylinder was drilled 9/16″ diameter. After parting off, the piece was rechucked with the other end out for facing and boring. Lay some brass strips under the chuck jaws to protect the fins and do not overtighten; we only need to face the end and take a series of light boring cuts to bring the I.D. to about ⅝″ dia. with as smooth and straight a result as our lathe permits. After drilling and tapping, the bore should be finished by lapping. For information on the subject of lapping, see the October 1979 issue of **LIVE STEAM.**

The **Piston** can then be turned on the end of a chucked piece of Meehanite, polished to fit the cylinder, and parted off. Actually I used my small Dunmore toolpost grinder to finish the piston to size. Remember that we want a close but very free fit. The piston should literally "fall" through the bore when let go. If it does not, then there is insufficient clearance or the surfaces are too rough. Plug the hole in the piston with a bolt, nut and gasket washer to check the seal between the piston and cylinder. With one end of the cylinder capped with your thumb, the piston should strongly resist being pulled or pushed and should bounce back if pulled out a bit and let go. These checks of course should be carried out with the cylinder and piston clean and dry.

In actual practice, the piston and cylinder of miniature vacuum engines are lubricated with light oil of the "sewing machine" variety. I usually use Marvel Lubricating Oil because of its pleasing red tint and agreeable fragrance in addition to its apparently typical lubricating qualities. In these engines, not only does the oil perform the important function of lubricating, but it equally importantly prevents the adherence of products of incomplete combustion. Without oil, buildup would quickly stop the engine. In fact, if the oil is not continually renewed, it will increase in viscosity as it captures condensates. Thus the **Oil Cup** described here is an important feature for long operation. **Figure 3** shows an extremely simple way of adjustably regulating the oil feed which I introduced some years ago. On this engine, the regulating wire is adjusted to deliver about 1/3 drop per minute at operating temperature which seems to be an adequate and economical rate. Occasional cleaning of the cylinder and especially the valve and port face with solvent is important to maintain easy starting





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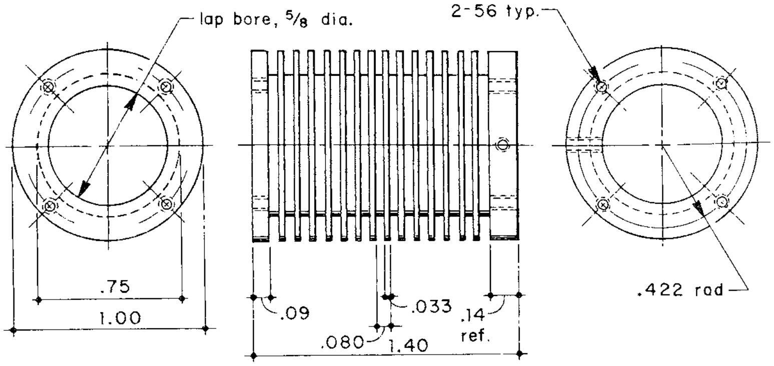
and optimal operation.

The **Cylinder Head** was cut from 1/16″ thick flat stock. Note the deep countersink of the port which opens to the interior of the cylinder; its purpose is to allow the edges of the port to assume rather high temperatures to minimize "quenching" of the incoming gases. To what extent it contributes to the ideal working of the engine is unknown, but it is correct in principle and easy enough to do. After the machining was finished, both sides of the head were trued on the surface grinder as was the front end face of the cylinder. This permitted a gastight joint without a gasket, and also of course a true smooth surface for the valve. If you do not have access to a surface grinder, lapping against a flat surface will work as well or better.

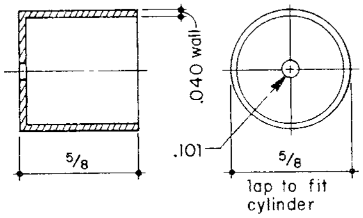
The **Standard,** if taken next, will provide a nice change of pace, being primarily a milling job. Readers familiar with my smaller water cooled vacuum engine design will recognize the similarity of form of the two standards. But the earlier one was made from four separate pieces, whereas this one is one piece as shown clearly in **Photos 4 and 5.** I think that it possesses a bit more in the way of elegance and is easier to make. I began by milling the profile to shape on the end of a 1″ by 2″ bar of aluminum alloy. At the same setup the form was drilled and reamed 5/32″ dia. for the valve shaft bearings and 5/16″ dia. for the crankshaft ball bearings. These bearings are available from Stock Drive Products (#7Y55-FSS3115), another **LIVE STEAM** advertiser. If you have another source, make sure the bearings are not sealed since the seals will introduce too much drag. I used flanged double shielded bearings; both features are highly desirable but not essential. The engine will run, by the way, with plain bearings if well fitted and oiled, but performance will be inferior especially at the lower speeds.

The .16″ wide slots which intercept the bearing bores permit the 5/32″ dia. journals of the crankshaft to pass through; then the bearings are slid along the shafts into the 5/16″ dia. bearing bores. The bearings are retained by inserting and lightly tightening the two 0-80 screws. This feature avoids the complication of separate bearing caps. Take care when milling or filing the slots however, for the top portion is rather susceptible to bending. Of course, drill and tap for the screws first; then you can clamp thick washers or strips of flat stock on both sides of each upright while cutting the slots. But this operation must wait until the uprights are formed!

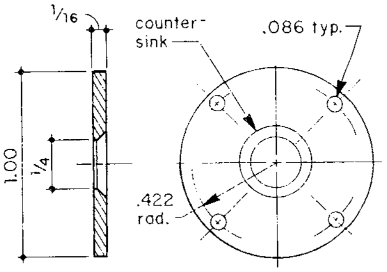
Before getting on to that, the bar was turned 90 degrees in the vise of the milling machine and the 11/16″ dia. hole bored in the front upright. At this setting one can also jig drill the four .086″ dia. holes for cylinder mounting screws as well as the shallow 1/4″ dia.



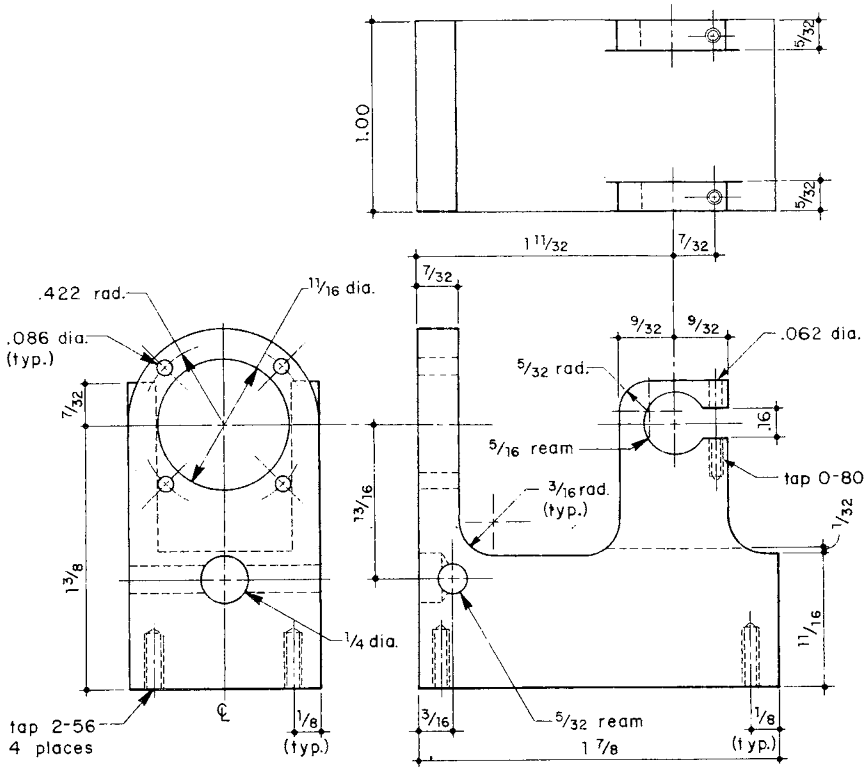
CYLINDER
Cast Iron



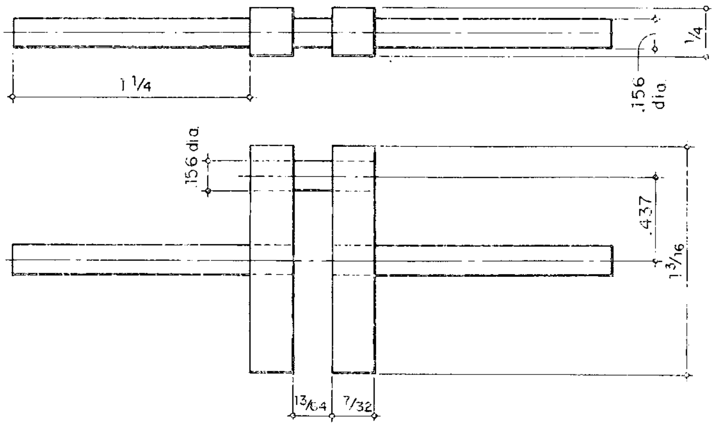
PISTON
Cast Iron



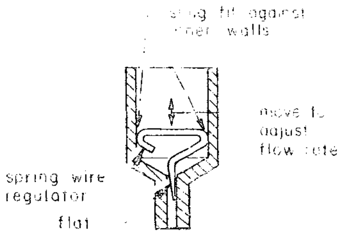
CYLINDER HEAD
Steel



STANDARD
Aluminum

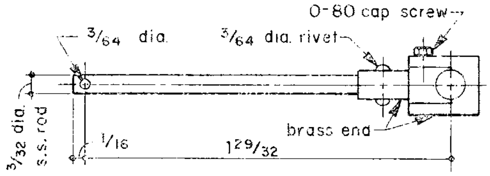


CRANKSHAFT
Steel

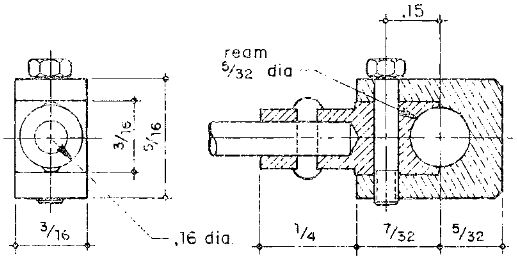


SIMPLE ADJUSTABLE FEED OIL CUP

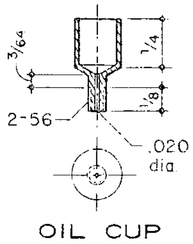
FIGURE 3



CONN. ROD ASSEMBLY

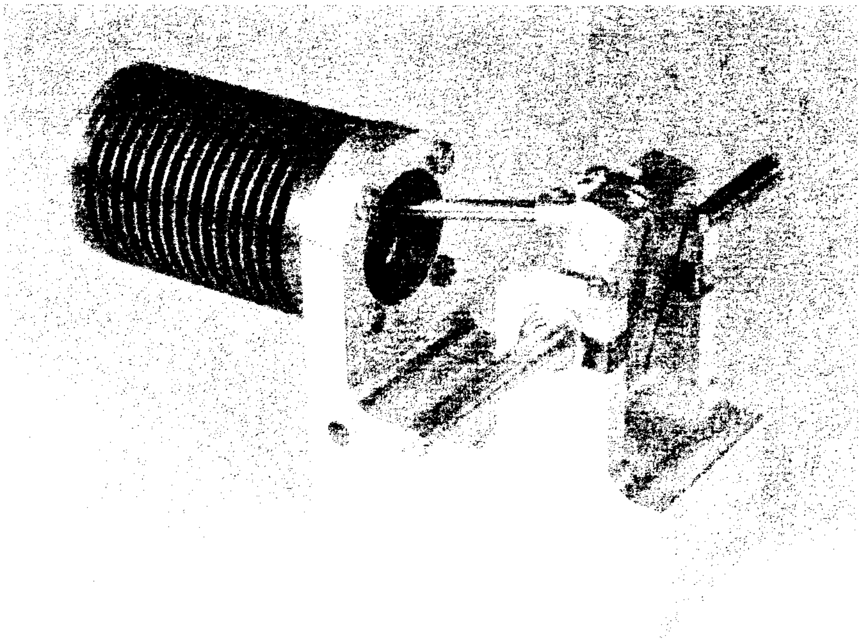


ROD END DETAIL



OIL CUP
Brass

4



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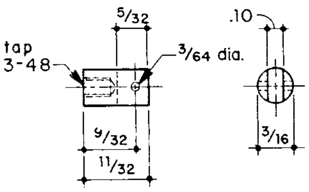
hole. This latter hole communicates with the 5/32″ dia. reamed hole for the valve shaft, permitting the valve rod to pass.

The developing standard can now be sawn from the parent bar and the bottom milled flat, drilled and tapped for mounting the baseplate. The part can next be settled into the milling vise and the bearing uprights formed by cutting away the material between. The slots to the bearing bores can finally be cut as already discussed. The finishing operation on the standard was rounding the top of the front upright. I did this by filing with the aid of two filing buttons quickly turned up from C.R.S. and left soft.

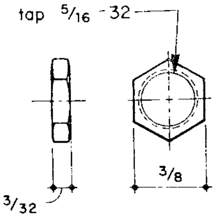
The **Crankshaft** is fabricated from four pieces. The two webs can be made from ¼″ square stock. Rough cut to length and reduce the thickness by 1/32″ in the milling machine, and jig drill and ream 5/32″ dia. at the same setup. The ends of these pieces in my case were finished to a smooth radius in a special but quickly made lathe setup shown in **Photos 6** and **7**. Two lengths of 5/32″ dia. rod were then prepared; one short piece for the throw, and the other long for the main shafts. Assembly was carefully made with *Loctite* in the joints and put aside to fully cure. Next day, the center portion of the main shaft was cut out leaving a true running crankshaft. I did take the extra precaution of drilling and pinning each of the four joints on this particular engine, but often have abstained on other engines. Incidentally, 303 stainless was used as the crankshaft material and the main shafts were carefully polished to accept the ball bearings with an easy push fit.

The **Connecting Rod** end is not as difficult as it may at first appear, despite its small size. Begin the inner piece by centrally chucking a length of 3/16″ square brass rod in the 4-jaw and turning a ¼″ long spigot .16″ in diameter. Then drill and ream 3/32″ dia. for the rod. Saw off a bit long, chuck by the spigot, and face to length. Now begin making the strap end from a length of 3/16″ flat brass bar stock. I used ⅜″ wide stock and milled to the required 5/16″ width at the end. Mill a 3/16″ wide notch to a depth of 7/32″; the notch should snugly fit over the inner piece. Now glue the inner piece in place in the notch using cyanoacrylate, and drill and tap 0-80 for the screw. With the screw in place for added security, drill and ream 5/32″ dia. for the crankpin. Cut the end from the bar and heat to break the glue joint. The result is a nicely fitted strap-type conn rod end!

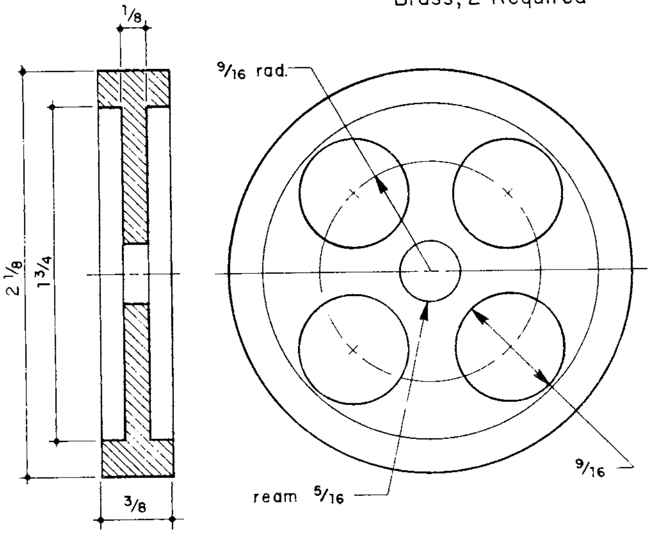
I used a piece of 3/32″ dia. stainless steel for the rod portion. Crossdrill near the end 3/64″ dia. for the wristpin, and *Loctite* into the brass end after checking for correct length; make sure the axes of the wristpin and crankpin holes are parallel. After curing, crossdrill through the joint for a rivet or pin for added security. The wristpin, since



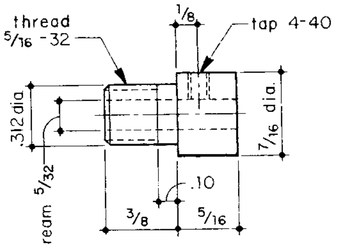
PISTON YOKE
Brass



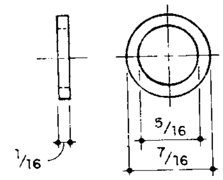
FLYWHEEL NUT
Brass, 2 Required



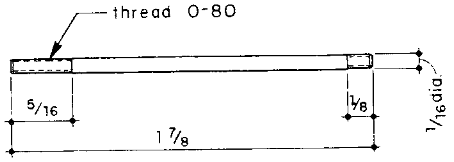
FLYWHEEL
Brass, 2 Required



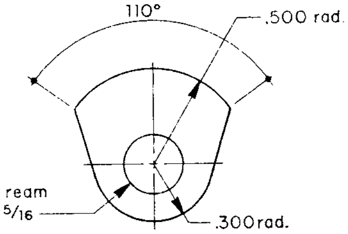
FLYWHEEL HUB
Brass, 2 Required



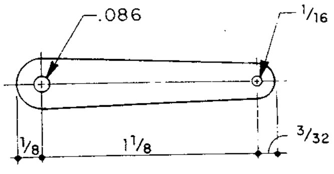
CAM WASHER
Brass



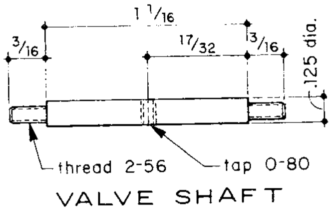
VALVE ROD
Steel



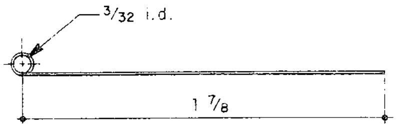
CAM
.047 Thick Steel



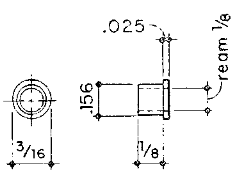
VALVE ROCKER ARM
.047 Thick Steel



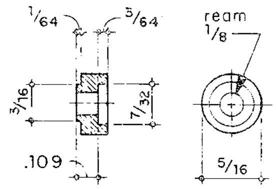
VALVE SHAFT
Steel



VALVE SPRING
.020 Spring Wire

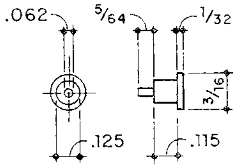


VALVE SHAFT BEARING
Bronze, 2 Required

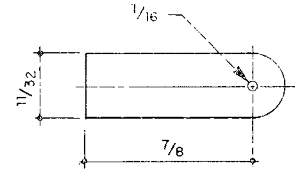


ROLLER
Steel

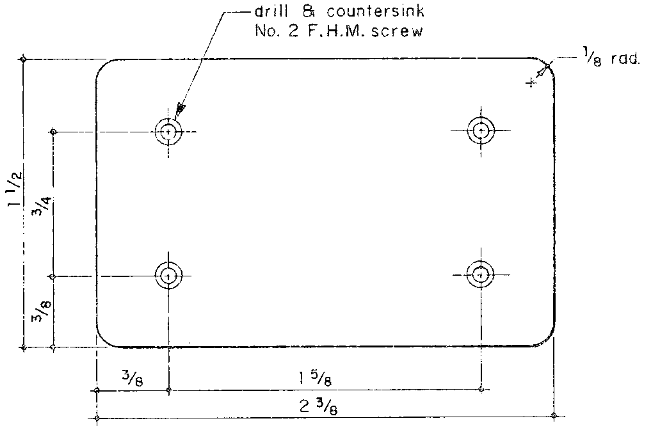
Materials for building this engine are available from Medallion Materials although prices are not available at press time. See their ad on page 44 and write them for prices.



ROLLER PIVOT
Steel



VALVE
.002 Spring Steel



BASEPLATE
1/8 Thick Aluminum

it is rather small in diameter, should be hardened; a piece of 3/64" dia. drill shank is ideal.

After completing the **Piston Yoke**, the group of finished pieces can be assembled on the standard as shown in **Photo 5** to test for free movement. The mechanism must be virtually absolutely free for the engine to run satisfactorily. You should be able to push the crank around with the proverbial feather.

I would suggest continuing from here with the **Flywheels, Hubs, Nuts**, and **Cam Washer**, each a routine lathe job. The **Cam** in my case was rough cut from a scrap of stainless steel sheet after drilling and reaming the hole. The profile was filed to final shape except for the outermost arc; this was finished by lathe turning while mounted on a shouldered mandrel.

Next, go on to the **Valve Shaft**, **Valve Rod**, and **Valve Shaft Bearings**. These latter items are to be a light push fit in the reamed hole in the standard. Make certain that the valve shaft is a free running fit. The valve shaft is operated through the **Valve Rocker Arm**, which carries a **Roller** on its end to ride against the cam. The small end of the **Roller Pivot** is peened over to secure it to the arm after checking the free operation of the roller; the bearing surface of the pivot should be polished.

The **Valve Return Spring** is made from spring or music wire. The eye end is captured between two washers and secured by a nut on the valve shaft as shown in **Photo 8**. The free end bears against the **Baseplate**. At this point it would be well to check for the free working of the valve gear; remove the conn rod from the crankthrow to increase sensitivity during the examination.

Only the **Valve** remains to be made. Take care when making it to avoid creasing the thin stock which could prevent a really good seal against the port face. The seal must be virtually airtight against vacuum and the flexibility of the valve will assist the matter; the partial vacuum formed as the piston moves out tends to fully seat the valve once it establishes a sufficiently good partial seal. You will have to bend the valve slightly so that it lies flatly against the port face as the valve is closing; in the wide open position it should be clear of the port face entirely. There are two other adjustments to be simultaneously made: the angular position of the arm on the valve shaft and the lateral position of the valve on the valve rod. Of course the desired end result of the adjusting is that the valve just cover the port when the cam stops moving the rocker arm (the overtravel should be slight — about 1/64"), and that the valve fully seal in this position.

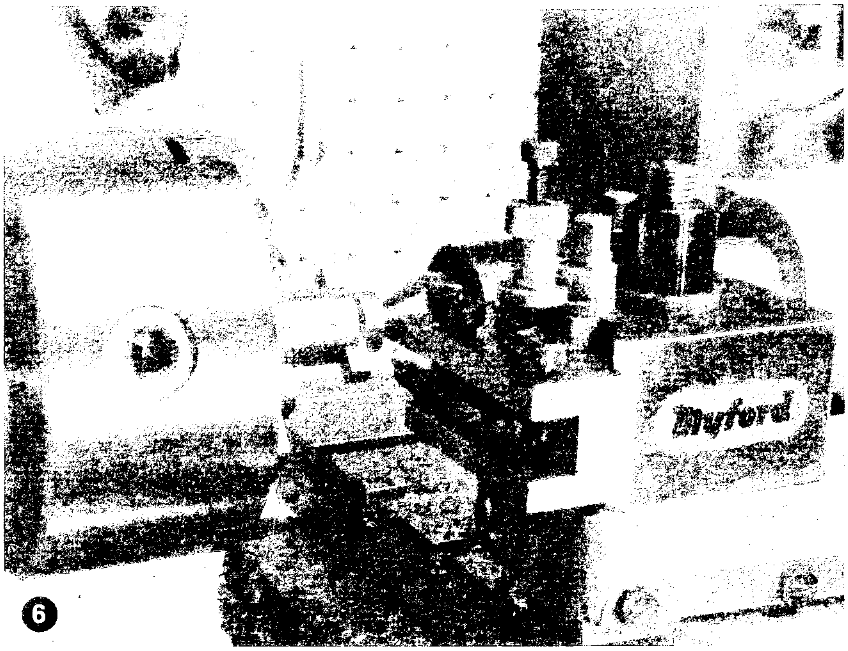
Once those adjustments have been made, timing can be set; this is quite simple and rather non-critical. Choose a direction of rotation and initially position the cam/flywheel on the crankshaft so that the valve closes the port when the piston has completed about 85% of its outward motion, that is about 45 degrees before outer dead center; note that some degrees of advance is necessary for efficient running. The setting is not critically important for running; my engine will run with any setting between 10 and 55 degrees with the cam shown in the drawing. But 45 degrees seems to be about the best position for consistent running. In the 55 degree position by the way, the engine will run in either direction!

Do not be puzzled by this bi-directional behavior at this cam setting. It may seem that because the valve is closed only as long after outer dead center as it is before, the engine could not produce any power. But it is the time lag in heat transfer from the enclosed gas to the cylinder wall that actually permits it. In addition, depending upon the spring tension, the valve is, in fact, closed longer after outer dead center than before due to two easily understood effects. The first is valve train inertia by virtue of which the valve is closed faster by the cam than it is opened by the spring, if it is relatively weak. The inertia effect is predominant at high engine speeds. The other effects may be called "friction latching". Once the valve closes and a vacuum is formed in the cylinder, the resulting normal force between the valve and the port face will tend to keep the valve from sliding to the open position until the pressure difference across the valve diminishes to a small value. Thus with a sufficiently weak valve spring tension, the cam serves only to close the valve, and its opening is "automatic" after the power stroke is essentially complete. This effect is most influential at low speeds. Of course, both effects act under all circumstances, but cam timing, and spring tension can effectively overcome their influence.

Any alcohol flame about the size of that of a common kitchen match will serve to run the engine. The alcohol lamp shown in **Photo 1** is simply a rectangular brass tank with a threaded filler cap and a thinwall 3/16" O.D. stainless steel wicktube. The capacity of the tank is about 4 cc which is enough for about 15 minutes of running. The tube is loosely packed with common cotton string as a wick.

I have seen grown healthy men tire to near exhaustion trying to start tiny flea-power vacuum engines. The problem in such cases usually turns out to be a mechanical defect and, more often than not, a subtle defect rather than an obvious one. For example, a piston which fits pretty well but not quite well enough, or one that is a bit too "draggy", or a valve not seating fully, or a slight bind in the conn rod bearing.

If, however, the engine is mechanically perfect, starting is simple and sure. It is only necessary to spin the engine over by hand a minute or two to warm up the cylinder and port face. As it warms, the first sign of life to be observed will be a tendency for the engine to "kick back" before the piston reaches outer dead center. Later, the engine may even begin to oscillate — bouncing back and forth but not quite making it over center. Finally, when warm enough, the engine will take off running to the tune of a loudly popping valve as it opens at the end of each power stroke.



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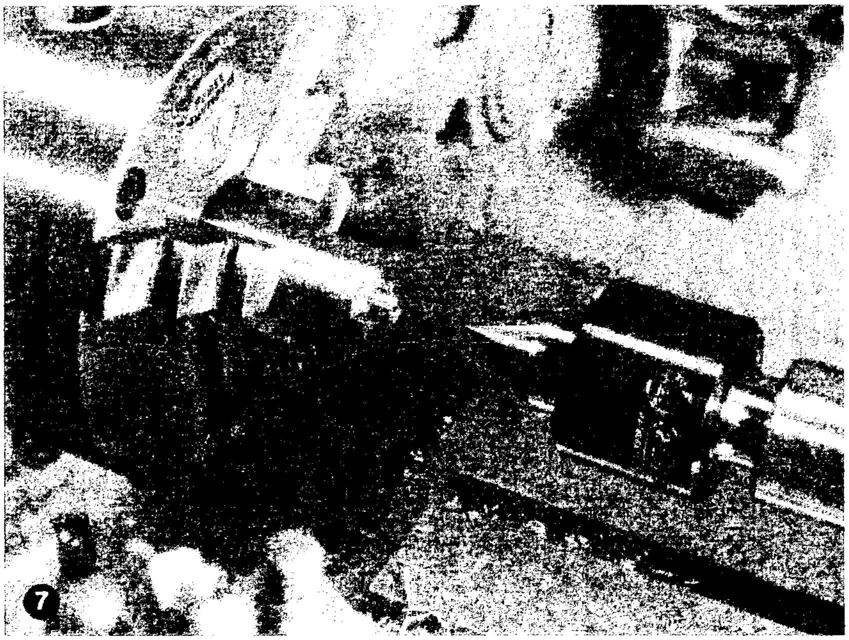

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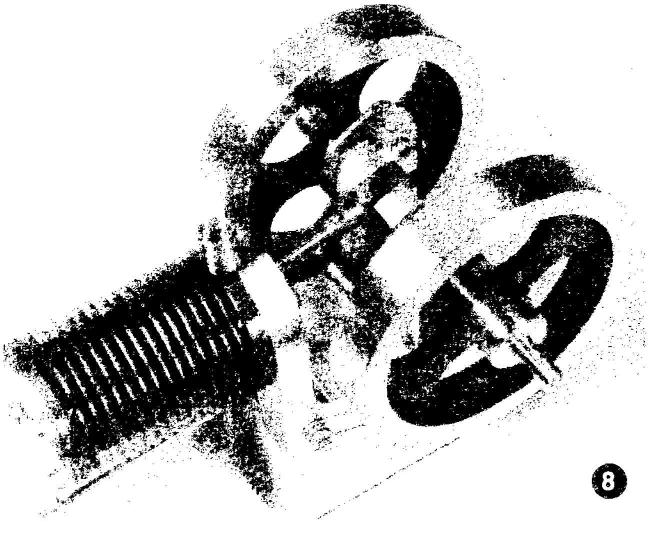

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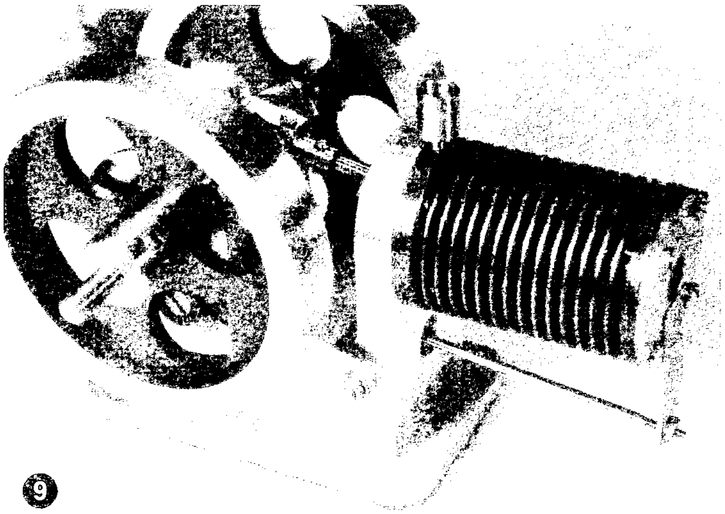

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