Digging Dirt on Inductors:
Experiments with Custom Magnetics Made from “Black Sand”

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1.0 Introduction

“What's that?” I asked.

It was my first visit to Arizona and my girlfriend and I were out hiking the desert. The trail had just descended into a bone-dry wash. The wash was filled with clean, sun-bleached sand like the kind you'd find on any beach. What caught my attention was a peculiar vein of black and charcoal gray material that striped the surface of the sand and meandered down the length of the wash (Figure 1a). I dropped to one knee and looked more closely. The streaks were comprised of tiny grains of something dense, black, and crystalline. It had obviously been transported and deposited there through the action of moving water during the monsoon season.


Figure 1a: Black magnetite sand as it appears in desert washes near Tucson, Arizona.

That was decades ago, but the novelty of this “black sand” has held my interest ever since. Over the years, and now as a long-time resident of Arizona, I've subsequently had endless opportunity to collect, refine, and experiment with it.

I’ve long argued that the interesting physical, electrical, and magnetic properties of black sand naturally prompts the question as to whether it could be put to use in radio craft—perhaps in the fabrication of custom inductors, for example.

As you'll see momentarily, in many cases, the answer to that question seems to be “yes.” With a bit of creativity and craftsmanship, a bucketful of the right kind of “dirt” can be converted into magnetic cores for inductors suitable for use in tuners, oscillators, amplifiers, transformers and antennas. Using the processes I’ve developed, (along with additional materials, which I’ll describe later), its possible even to build transformers, motors and alternators!

In the sections that follow, I describe some of the physical and electrical attributes of this black sand, a technique for its harvesting and refinement, experimental application of refined sand in its unbound state, and an introduction to a sand-and-resin mix from which a wide variety of devices can be fabricated.

Following that, I describe a number of specific devices I've built and tinkered with including those that appear to work, those that don't work, and those that might be made to work with additional experimentation.

In an expansion of the initial premise, I also discuss the alternative use of powdered cast iron, and describe a potentially unrecognized source of cheap material for experimentation, along with a manner in which to process it in preparation for use. As evidenced by the projects described, the higher permeability of iron allows for the construction of devices that would be impractical using black sand.

To be clear: This is not intended to be an academic dissertation or a engineering white paper, and should not be judged as such. I would add that some of these experiments were conducted as many as five years ago. Some of the models, records, and technical details I would like to have shared here have regrettably disappeared.

Thus, this paper is intended merely to introduce the reader to some creative (and possibly original) technical ideas, as well as document some paths of exploration that I have already taken. If this paper inspires replication or further development of any these ideas, then it will have served its purpose.

2.0 What the Heck Is Black Sand?

Of the 92 naturally-occurring chemical elements found on Earth, iron reigns among the most dominant. Thirty-five percent of our planet is composed of iron and, while it's true that most of it situated at the core, even at the crust it's present in quantities of about five percent. Stated simply, there's an awful lot of iron around.

Iron is chemically active, which is why it tends not to remain in its pure or elemental state very long. As a prior resident of Michigan, I can testify that iron readily reacts with wet snow and salted roads to produce rusty gaping holes in car fenders, doors, and floor pans. In nature, iron happily reacts with oxygen and other elements to produce iron-bearing minerals like hematite (Fe2O3) and magnetite (Fe3O4), geothite (FeO(OH)), ilmenite (FeTiO3), lepidocrocite (γ-FeO(OH)), siderite (FeCO3), molysite (FeCl3), marcasite (FeS2), and iron pyrite (FeS), to name just a few.

Among these, magnetite is the most relevant to this particular discussion, as it seems to be the principle constituent of the black sand so ubiquitous in my part of the world.

3.0 Physical Properties of Magnetite Sand

Descriptions of the properties of magnetite mesh well with the observed characteristics of the black sand I introduced earlier. For example, both are opaque black or grayish black in color, with a noticeable metallic luster or sheen.

Magnetite is expressed as isometric - hex-octahedral crystals. In the case of black sand, it stands to reason that abrasion between particles can obliterate the features of intact crystals and yet, under the microscope, broken pyramid points and other fragments of proper crystal geometry can still be found. I have also observed evidence of what I judge to be conchoidal fracturing—another attribute of magnetite. See Figure 3a.

Magnetite is a comparatively hard material, 5.5 to 6 on the Mohs scale. This characteristic would seem to be of little consequence to an electronic application—until you try to drill, shape, or machine something made from it. Ordinary high-speed tool steel does not fare well against it and is rapidly dulled by the abrasive action of the sand. I'll comment more on this later.

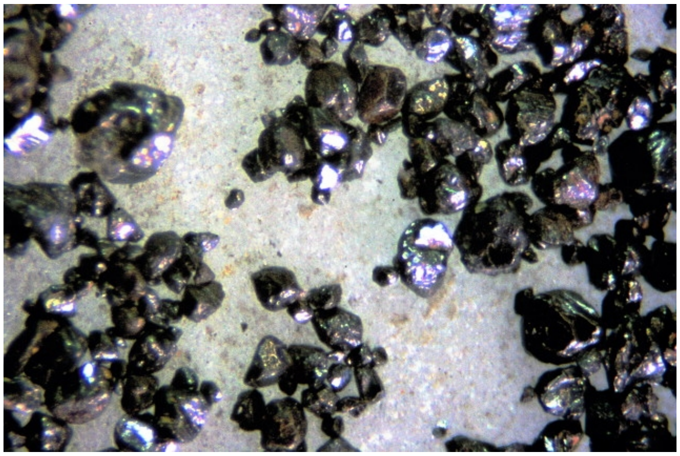


Figure 3a: Grains of black magnetite sand as viewed under the microscope.

Magnetite is a relatively dense material—it's about five times as dense as water and twice as dense as ordinary sand. Because of this, it's not easily carried by flowing water. It tends to settle out and leave deposits wherever the velocity of a water stream begins to wane. This accounts for the black streaks in the desert washes I described earlier. The tendency to rapidly settle parallels the behavior of other dense minerals like placer gold, which is why the two are sometimes associated and found together in the field.

Finally, and perhaps most importantly, magnetite is a strongly magnetic material. It readily sticks to a magnet. In placer gold mining operations, this attribute is used to advantage to separate and remove the black sand from gold concentrate. I have made similar use of magnets to harvest and refine magnetite sand for use in my experiments.

4.0 Magnetic Properties of Magnetite Sand

Initially, the idea of using magnetite sand as a core material for home-brew inductors was just a flight of fancy. I knew the sand to be magnetic, and it bore at least a passing resemblance to the gray, brittle, ceramic-like materials from which so many toroids, pot cores, and loop-sticks are made. The trouble is that while there's a fair amount of information concerning magnetite on the Internet, the available data typically lacks the kind of detail that would help determine its usefulness in a home-brew inductor application.

One of the key attributes of any magnetic material is its permeability. Permeability (typically represented by the Greek letter mu) is a number that expresses the ability of a material to support magnetic field development. Permeability is a measurable feature of the universe itself, and there is a value associated with it—even in the vacuum of space where no matter resides. This value, referred to as mu-naught, is defined as:

$$\mu_0 = 4\,\pi \times 10^{-7}\ \mathrm{H\ m^{-1}}$$

Because raw mu values are cumbersome to deal with, it's useful to speak in terms of *relative* permeability. The idea here is to normalize all observed mu values with respect to mu-naught. Thus, a substance whose mu is twice as large as mu-naught would be said to have a relative permeability (relative mu) of 2. A substance whose mu is five times as large as mu-naught is said to have a relative permeability of 5, and so forth.

$$\mu_r = \mu \,/\, \mu_0$$

Since I could not find permeability information for magnetite sand, either in my personal library or on the web, I endeavored to measure it indirectly.

I started with a thin-walled plastic tube, 4.5 inches long with a diameter of approximately 0.85 inches. At the center of the tube, I wound a close-wound coil comprised of 115 turns of 30 AWG wire-wrap wire. The external width of the wire was 0.019 inches. (Note: These specifications are not critical. I mention them only because I'd recorded them.)

Connected to my LCR meter, I measured the inductance of this essentially-air-cored solenoid at 109.7 microhenries. Next, I filled the tube with refined black sand (I'll explain the refining process later), tamped it down to preclude any voids, and measured the inductance again. This time the coil measured 248.9 microhenries. The relative permeability of the magnetite is reflected in the ratio between those two values, i.e., about 2.27.

I will grant that the presence of the plastic tube in the bore of the coil introduces error, as does the relationship between the length of the plastic tube and the length of the coil itself. In addition, I have observed some variation in the calculated permeability as different batches of sand were analyzed. All that said, a 2.3 value is sufficiently precise for first-swag experimental purposes.

To place this number in perspective, consider this: A common toroid found in ham radio projects is composed of so-called “Type-2” material. It's made from a powdered iron. A check of manufacturer documentation shows that Type-2 material has a relative permeability of 10.

Another common toroid material, also a type of powdered iron, is called “Type-6.” Type-6 material has a relative permeability of 8. Ferrite materials like Type-67 have an advertised permeability of 40 and the relative permeability of Type-43 is a staggering 800.

Sadly, as core materials go, magnetite sand is not comparable to, nor a replacement for, any of these commercial materials. However, that does not preclude it from being useful as a core material in its own right. It simply means that more turns of wire are required to produce a given amount of inductance. Since more turns means more wire, and with more wire comes greater resistive loss, one must be mindful that this can negatively impact circuit performance in sensitive designs.

5.0 Potential Losses in Magnetite Sand

When an alternating current is applied to an inductor's windings, parasitic electric currents called “eddy currents” can be induced in the coil's core. In power conversion devices and motors, for example, eddy currents waste energy and produce unwanted heat. Fortunately, eddy currents can be discouraged by eliminating paths for electrical conduction in the core.

In the case of power transformers and motors where core materials are usually made from steel, solid metal cores are avoided in favor of sheet-steel laminations which are layered and stacked like the pages of a book. The laminations are lacquered or oxide-coated to discourage the passage of induced electric current from one lamination to the next.

As operating frequency increases, laminations must be made thinner and thinner to remain effective. As we approach radio frequencies, powdered metals work better than laminations. Ferrites, which are intrinsically non-conductive, are not subject to eddy current problems and can be used in applications up to many hundreds of megahertz.

To gauge the magnetite sand's proclivity to support eddy currents, I simply measured its resistance. I plunged the probes of my digital ohmmeter into a glass jar filled with a sample of refined black sand. I swished the probes around and even brought them as closely together (without touching) as I could, but the meter never registered anything but an open circuit.

Interestingly, I found a research paper which reported magnetite's bulk resistivity on the order of $1 \times 10^{-5}\ \Omega$ m, which is quite low. The author described magnetite as having the “lowest resistivity of any oxide” and “almost metallic good conductivity.” Another paper classified Fe3O4 as a “semiconductor.“

What appears as irreconcilable disagreement between these sources and my own observations might be explained in one or more ways:

- The $1 \times 10^{-5}\ \Omega$ m value is probably associated with a single crystal or monolithic piece of magnetite, as opposed to an aggregation of tiny particles in a jar of black sand.
- Particle cross-section of individual particles in the black sand is very small, raising the effective resistance.
- Despite dense packing, actual grain-to-grain contact is imperfect, and is probably limited to projecting points, edges, and irregular surfaces. This would further impede the flow of electric current.
- The magnetite crystals in my sample may be chemically adulterated, as a consequence of having been produced through natural processes
- Finally, the surface of the magnetite sand grains may have been chemically altered by exposure and weathering, so as to render them entirely non-conductive.

Whatever the reason for the high-resistance I observed, my measurement suggested that any eddy current losses in a magnetic core made from magnetite sand would be so small as to be negligible—which is a good thing.

Other losses are possible in magnetic core materials. One of these is hysteresis.

If we fashion a bar of some magnetic material and wind a coil of wire around it, it seems reasonable to assume that the flux density in the core will be proportional (in some fashion) to the field generated by the coil wound around it. In many cases this is true.

But some magnetic materials exhibit a tendency to retain magnetism after an external field has been applied and then removed. They are said to exhibit hysteresis.

Hysteresis is a useful property if the magnetic material is to be used as a bit core in a computer memory system, or the coating on a hard drive platter or strip of digital magnetic tape. In these applications, we *want* the material to “remember” a prior application of external magnetic field. The residual flux in the material is used to represent data.

On the other hand, in inductors intended to carry alternating currents, hysteresis is a real problem. This is because, by definition, the polarity of the electric current in the coil—and therefore the flux in the core—must flip back and forth with every cycle. In magnetic materials with hysteresis, we can’t reverse the flux in the core without supplying enough additional energy to overcome the residual magnetism left from from the prior cycle.

It should be intuitive that doing and undoing the same work over and over again is inherently wasteful and that the energy required to do this nonproductive work must come from somewhere. In practice, hysteresis manifests itself as an apparent loss in the inductor and as a burden on the surrounding circuitry.

Even in materials with no hysteresis, problems can arise if a core is driven too hard. Simply put, there is a limit to the amount of magnetic flux a core of a given size and composition can carry. If a core is driven beyond that point, it is said to be “saturated” and ugly things can happen. Among these, the permeability of the core may change or decline precipitously—which is bad news if the inductor is part of a tuned circuit.

Having said all this, I wondered how easily magnetite sand would saturate, and wondered how bad its hysteresis losses might be. I don't have equipment to measure these properties in any objective or scientific way. However, I have long heard that enterprising hams are not above enlisting the family's microwave oven for subjective testing of this type. A 900-watt microwave oven typically produces a 2.45 gigahertz RF signal of roughly half that power.

I placed a glass jar filled with magnetite sand into my microwave oven, along with a coffee mug filled with water to act as a ballast. I programmed the oven for five seconds on “high.” There was no detectable effect on the sand or its temperature. I repeated the test at 10 and 15 seconds with similar results. Only after running the oven for 30 seconds did I begin to feel any warmth in the sand at all.

This observation suggests that magnetic cores made from magnetite sand might not be terribly lossy, even at very high frequencies and at relatively high energy densities.

6.0 <u>Mining and Refining Magnetite Sand</u>

Magnetite sand is where you find it. Where I live, it's abundant in desert washes and on the curbs of dirt roadways. It can be collected with a small scoop or shovel, or better yet, with a magnet.

Note that simply plunging a magnet into a vein of black sand is a recipe for failure. Sure, the magnet will attract the sand, but once attached to the magnet, there is no easy way to release it into your collection bucket. My initial solution was to double-bag my magnets in zipper-top sandwich bags. The sand readily sticks, but can be released by manipulating the magnet inside of the bags so as to cause separation. This technique works, but is somewhat cumbersome. In addition, the bags are prone to rip because of the abrasive nature of the sand.

Figure 6a: Magnetite sand as initially harvested.

A better approach, I found, was to place a strong magnet—a magnet salvaged from an old hard drive is excellent—inside a sealed plastic food container. If you plunge the container into a magnetite vein, globs of black sand will adhere to the plastic (under the influence of the magnet inside). To release the collected material, you suspend the container over your collection bucket and shake it. The magnet inside will rattle around, releasing the sand.

Figure 6b: Magnetite sand, partially refined.

A commercial version of this idea, creatively called a "black sand magnet" can be purchased from dealers of gold prospecting supplies. Like my tool, black sand magnets feature a plastic container with a magnet inside, but add the convenience of a handle with a spring-loaded actuator to manipulate the internal magnet (and release the sand) without having to shake or bang the container about.

This accounts for collection, but for quality purposes, the sand must be refined. My practice is to soak the collected sand in a 5-gallon pail of water. This not only cleans the magnetite particles of contaminants but serves to break up any attached particles of caliche. I like to stir the sand into a whirlpool with my hand while agitating it with the spray of a garden-hose nozzle. I allow the water to slosh over the rim of the bucket, so as to carry away contaminants and most of the less dense, non-magnetic silica sand.

Figure 6c: Magnetite sand after several refinement cycles.

Once the black sand is judged clean, I submerge my magnets into the water-filled bucket and draw off the magnetite. The collected material is deposited in a second bucket where it is soaked and washed once more. This wet refinement process may be repeated several times. With every iteration, some material is left behind, but the magnetite sand that advances is always much more pure.

After the sand reaches a certain level of refinement, I find it best to let it dry out. Then, using an old teaspoon, I dump a scoop or two of the refined magnetite sand onto a sheet of cardboard, spread it thin, and then apply my magnet again. With repeated dry refining, you eventually end up with homogeneous, pure, black magnetite sand. Figures 6a through 6c illustrate this transformation.

A final note on the collection/refinement of magnetite sand: For those readers living in places where black sand is not easy to come by, or for the incurably lazy, take heart. Placer miners and other individuals refine and sell black sand for use in aquariums, for claimed therapeutic, decorative, and other purposes. A quick Internet search or a visit to to your favorite Internet auction site will present numerous opportunities for sand acquisition.

Having introduced magnetite sand and having touched upon the topics of its constitution, properties, and where and how to obtain it, let me now share some of the electrical experiments I've conducted with it.

7.0 An AM-Band Magnetite Bar Receiving Antenna

The apparent similarity between magnetite sand and the ferrite material from which bar antennas are fabricated got me wondering if the former could be used to replace the latter. To explore this idea, I obtained an old AM radio at a local thrift shop, dismantled it, and unsoldered and removed the set's ferrite bar antenna. Using my LCR meter, I measured the inductance of the coils wound on the ferrite and recorded those values in a notebook.

Next, I cut a 10-inch length of ½-inch PVC water pipe. I glued on a slip cap to permanently seal one end of the tube. At the other end, I glued an NPT fitting with a threaded cap. The cap can be removed and replaced at will.

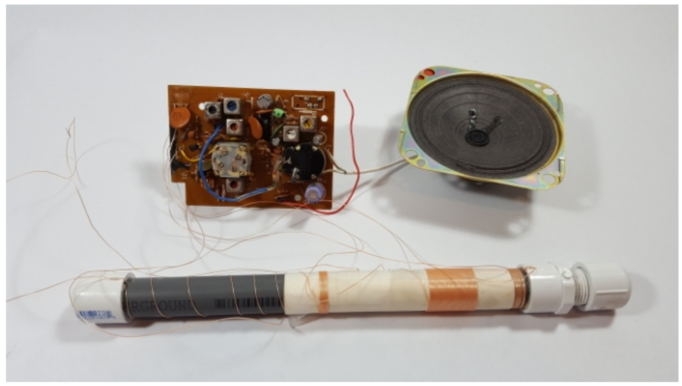


Figure 7a: In this modified radio, the normal ferrite bar antenna has been replaced with coil windings on a PVC tube, filled with magnetite sand.

I removed the threaded pipe cap and filled the bore of the pipe with refined magnetite sand. I tamped down the sand with a wooden dowel to eliminate voids or air pockets. Then I replaced the cap and screwed it tight.

I wrapped an index card around the pipe (forming a bed on which to wind wire) and laid down two single-layer coils comprised of 30 AWG wire-wrap wire. The number of turns in each coil was adjusted so that the measured inductance would match the inductance observed in the coils of the original antenna. When I was satisfied that this match had been achieved, I soldered the leads of the new antenna to the receiver's circuit board. The modified receiver appears in Figure 7a.

I switched on the radio set. To my great satisfaction, it played just fine! In fact, it's my subjective impression that the radio set with the magnetite sand antenna is actually more sensitive to weak stations than it was in stock condition. If true, this is probably due to the fact that the core of the magnetite antenna is substantially larger than the ferrite core it replaced.

Interesting proof of the magnetite sand's contribution to the proper function of the set was observed when I uncapped the PVC tube and dumped out the sand. The moment it left the bore of the tube, the radio went silent. When I poured the sand back into the pipe, the radio resumed operation.

Among technicians and engineers in the electrical world there is a long-running inside-joke about the "magic smoke" said to be essential for the operation of all electrical devices. Do something stupid to "let out the magic smoke," and a device will cease to function...usually permanently.

Well, here is a demonstrable case of a radio that requires "magic sand" to function. Pour the sand out of the antenna tube and the radio is effectively broken. Pour the sand back in, and the radio is fixed!

8.0 <u>A Cast Bar Antenna</u>

8.1 Casting Magnetite Sand Into a Bar

Success with the black sand bar antenna described above encouraged me to take the next logical step: combine the magnetite sand with a binder and cast it into a rod or bar. Doing so would eliminate the need for a tube or pipe-like container, and result in an inductor much more like the bar antennas normally seen in radio sets.

I considered several possible binding agents including liquid epoxy, but settled on polyester casting resin. There were several reasons:

- Polyester resin is easy to mix and work.
- It doesn't set up too quickly.
- Its viscosity is low enough to allow it to flow, even when heavily-laden with sand.
- Polyester resin shrinks slightly on curing (which facilitates removal from rigid molds).
- Polyester appears to have good dielectric properties.

Figure 8a: Magnetic structures can be cast with a slurry comprised of refined magnetite sand and a polyester resin binder.

It didn't hurt that I already had some resin and hardener in stock, left over from another project.

My first order of business was to create a mold. I started with a sheet of heavy paper of appropriate size. To render the surface of the paper "non-stick" I carefully covered it with long, overlapping strips of 2-inch plastic packing tape.

Figure 8b: A bar of cast magnetite sand emerges from the a paper mold. Note the packing-tape-plastic lining in the mold.

With the paper thus treated, I rolled it around a dowel so as to form a tube (with the taped-treated surface on the inside). I used additional plastic tape to secure the seam and to cover the bottom of the tube.

I measured out a quantity of polyester resin and added drops of hardener according to the manufacturer's instructions. When the two components were thoroughly mixed, I added magnetite sand and stirred the suspension with piece of wood lath (Figure 8a). I continued adding sand until the mixture was a thick, black slurry.

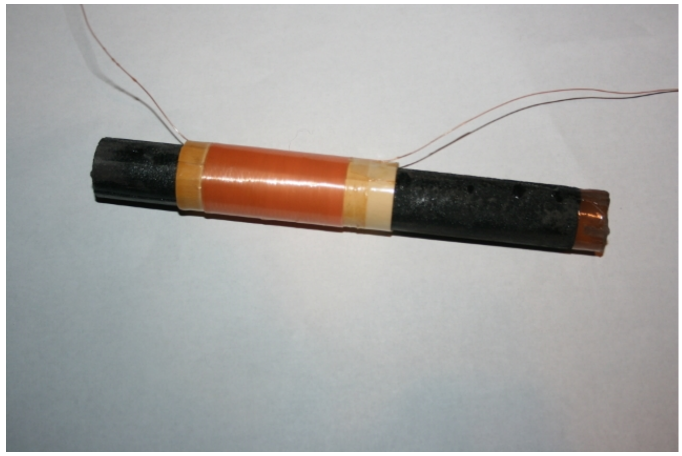


Figure 8c: Cast bar, trimmed, fitted with paper sleeve and coil.

Using an old spoon, I transferred the slurry to the mold. With the mold filled to the top, I set it in a secure place where the chemical reaction could run to completion without being disturbed. Twenty-four hours later, I was satisfied that the resin had set. Happily, the packing tape used to surface the interior of the mold functioned as intended. Extracting the finished bar was a simple matter of unraveling the paper tube. This is depicted in Figure 8b.

Wound with a test coil comprised of an index-card-paper sleeve and some light-gauge wire-wrap wire, I measured 195 uH (Figure 8c). Combined with a standard 365 pF broadcast variable capacitor, I was able to throw together a quick-and-dirty crystal-set tuner for most of the AM broadcast band.

Several observations on the fabrication process of the bar are worth sharing:

I found it difficult to predict precisely how much resin to prepare, as it is impossible to specify a "correct" or optimal ratio between sand and resin. Mixing too much resin is clearly wasteful. On the other hand, a wet slurry—that is to say a sand mixture with excess resin—does a better job of combining with (and wetting) the sand. It also results in a slurry that will more easily penetrate crevices or irregularities in a mold.

The mixing process creates a suspension of the magnetite sand in the resin. Once the mix is transferred to the mold, there is nothing to sustain this suspension and gravity will cause the sand to settle. The part of the mold where the sand settles produces a beautiful, dense, bar of composite magnetite. The upper part of the mold may not contain any sand at all. Thus, in recognition of this behavior, it is important to design molds with sprues of sufficient volume to account for this.

Figure 8d: Test bars, used for evaluation of grain packing methods, cast in a syringe body.

In the case of this particular casting, about two-thirds of the resulting bar was usable magnetite. The upper third was nothing but dirty, clouded plastic, which I later cut off with a hack saw.

It is possible to add additional dry sand to the liquid resin while in the mold, so as to maximize the sand fill. However, this must be done with care to assure the added sand is properly wetted, that there is no introduction of air bubbles, and that additions are made well before the resin has begun to set.

Figure 8.0e: Multiple examples of test bars and test coils.

I ran into a several occasions where the resin took an inordinate amount of time to harden, and in at least one case, it never hardened fully at all. I suppose it’s possible that the age of the chemicals I used might account for this (does hardener go stale?) but I got the impression that the sand itself, in some way, sometimes retarded the chemical reaction responsible for hardening. Once I began the practice of adding a few extra drops of hardener to the mix, my problems went away.

8.2 Packing Factor and Its Effects on Relative Mu

As one might expect, variation in the packing density of magnetite grains can affect the relative mu of the object cast with the magnetite/resin mix. To explore this, I cast numerous identically-dimensioned bars of magnetic material, using a syringe body as a mold (whatever the material syringes are made from, the polyester resin will not adhere to it). The syringe mold and a couple of examples of test bars appear in Figure 8d.

I slid these bars into test coils which were wound upon bobbins that I had prepared from cardboard scrap. Examples of some of these test coils and a plethora bar samples appear in Figure 8e.

As a control, I first mixed the magnetic material and resin and cast it without regard to efficient packing.

In another case, I used the motor and eccentric harvested from a seat-cushion-massager unit to vibrate the slurry while it was setting.

In a third instance, I applied a strong permanent magnet to the exterior of the mold, to induce the grains to self-adhere and clump.

Finally, I tried ball-milling the magnetite material to a finer gauge.

All of the tactics above resulted in improvement and the effects of employing multiple techniques were additive. In the case of powered iron (which I will introduce, along with a discussion of ball-milling, in section 16.0) the improvement in packing resulting in relative mu improvements of as much as 15%.

9.0 Leftover Materials

A common demonstration in the science classroom involves placing a bar magnet beneath a sheet of paper, and then sprinkling iron filings on top. Under the influence of the magnetism, the particles align themselves to "draw" bowed lines that begin at one magnetic pole, curve around, and terminate at the other, thereby revealing the magnet's lines of flux . Many have witnessed this in elementary school, many more have seen pictures in a book or on the Internet.

Figure 9.0a: In proximity to the pole of a magnet, magnetite grains can self-assemble into beautiful three-dimensional shapes.

A neat trick is to "freeze" that pattern on the paper by carefully spraying the filings with clear acrylic. The acrylic coats and bonds the particles to the paper, creating a permanent record that remains even after the magnet has been removed.

As pretty as these images are, one the of the inherent limitations of the paper-and-filings technique is that the patterns are flat, that is to say, they record the influence of the magnet's flux only in the plane of the paper sheet.

If you've ever had the (mis)fortune of dropping a magnet into an unconfined pile of filings, you quickly note that flux is radiated from the magnet's poles in *three* dimensions. The geometric shapes that emerge when the filings are unrestrained are even more impressive than those captured on paper. If only there was a way to freeze *those* representations!

In the prior section, I described my black-sand-and-resin casting process, and confessed that I found it difficult at times to properly gauge how much resin to mix. This forced me to adopt the tactic of mixing more slurry than I expected to need.

If this sounds wasteful, it is, and it prompted me to consider what I might be do with the excess material before it hardened. The answer—three dimensional flux images!
The process is very similar to the iron-filings-on-paper technique. Instead of paper, I start with a plastic jar lid...something that the casting resin won't bond to. The lid from a whipped-diary substitute container works great.

Beneath the lid I tape a magnet. Rare earth magnets, like those harvested from scrapped hard drives are preferred because of their unusually high strength, but any magnet of reasonable strength will do.

When I'm through with my casting, I use an old spoon to deposit a healthy dollop of leftover slurry on the top of the plastic dairy lid. Under the influence of the field from the magnet beneath, and because the slurry is still liquid, strange and amazing shapes will rise from the lid. Some have the shape and beauty of exotic mineral crystals. Others remind me of bottom-dwelling sea creatures.

Shapes can be altered by adding more magnets to the bottom of the lid. Patterns can change dramatically depending upon whether adjacent magnets' poles are in opposition or alignment.

Sometimes the structures can be encourage to grow taller by suspending or moving an additional magnet *above* the slurry.

Eventually the resin hardens and these wonderful shapes become frozen and permanent. I've attached several images (below) by way of example.


Figure 9.0b

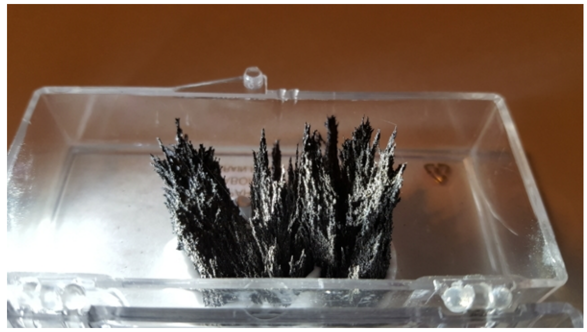


Figure 9.0c


Figure 9.0d


Figure 9.0e


Figure 9.0f

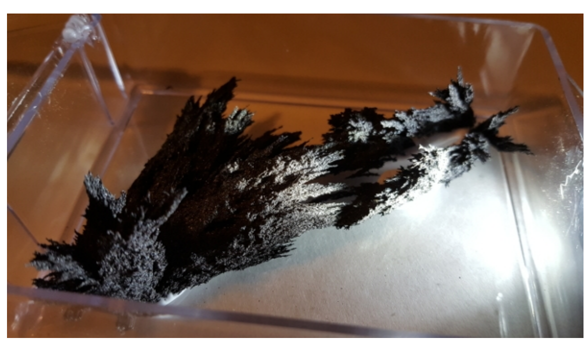


Figure 9.0g

10.0 <u>Toroids</u>

10.1 Toroid Fabrication

Some of the most common types of inductors found in contemporary ham radio electronics are those wound on toroids. I set about fabricating some from refined black sand so that I could play with them.

An obvious way to create a toroid using the black-sand-and-resin slurry would be to employ a mold. I tried creating some impromptu molds using a commercial toroid as a “positive,” which was pressed into a glob of modeling clay to create the “negative” mold. This works, but the toroids produced in an open-face mold like this require a fair amount of clean-up. I was less than impressed.

Figure 10a: Toroids machined from a bar of cast magnetite sand.

I think a better solution would be to create a legitimate two-piece mold of silicone casting rubber fashioned with an appropriate sprue for filling. I’ve seen reference to dental alginate used for hobby use in casting resins, and so this might be an alternative.

As silicone rubber casting components are relatively expensive, and as I did not have alginate, I decided that it might be possible to simply machine my toroids. By this time I had cast several round bars of the magnetite material, and I knew a machinist who found some of my science projects interesting. He had consented in the past to machine the occasional piece or part for whatever mad-science project I had involved myself in.

I gave him a bar of the magnetite sand, explaining how I had mined, refined, and cast it. I described my objective of creating toroids from the bar and asked if he could chuck the bar in his lathe, turn the outside surface to uniform roundness, bore the center to create a hollow tube, and then use a parting tool to cut off separate “donuts.” He thought my proposal feasible and agreed to to try it. Off he went.

Figure 10b: Close-up of a black sand toroid.

Some time later he approached me with an amused expression on his face and a fistful of the most exquisitely-fabricated toroids. To my eye, they were perfect and physically indistinguishable from commercial toroids that I had used in numerous other projects. See Figure 10a through 10c.

“What the hell *is* that stuff?” He suddenly asked, laughing. He extended his other hand to show me a set of cutting bits, the edges of which had been utterly ground off. These were high-speed tool steel.

“Wow,” I responded apologetically, “I’m really sorry about that.” He waved off my concern and explained that once he switched to carbide bits, the machining was quick and without incident. In retrospect, given the relative hardness of magnetite and the hardness of tool steel, the destruction of his steel cutting bits was inevitable.

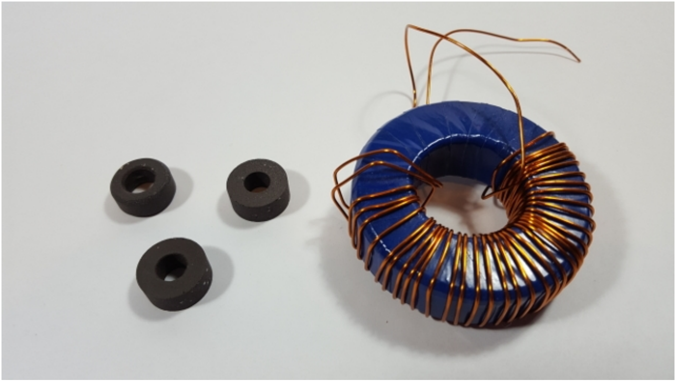


Figure 10c: More toroids, big and small. Note the large toroid wrapped in tape to protect the wire insulation from the abrasive properties of the casting material.

Machining may leave sharp edges on the work. My first step is to “break” or chamfer the toroids with a grinding bit chucked in a rotary tool. Sometime a stroke or two with sandpaper will fix the issue. In some cases, I have wrapped the core in vinyl or Teflon™ tape before installing the windings.

10.2 The Joule Thief

The “Ingenuity Unlimited” column in the November 1999 issue of *Everyday Practical Electronics* describes several voltage-boosting circuits. Their novelty lies in their ability to drive an LED (which may require a couple of volts to light it), from a single flashlight cell whose terminal voltage is 1.5 VDC or less. It appears that Clive Mitchell did much to popularize one of these circuits through his application of a clever pun.

In most cases, “dead” flashlight cells that are headed for the trash bin still contain some usable energy, albeit at a greatly-reduced terminal voltage. Mitchell’s observation that the voltage-boosting circuit seemingly “stole” every last Joule (unit of energy) from the dying battery led him to refer to it as a “Joule thief.”

The Joule thief is comprised of coil (with two windings), a transistor, a resistor, and an LED (light-emitting diode). See Figure 10d.

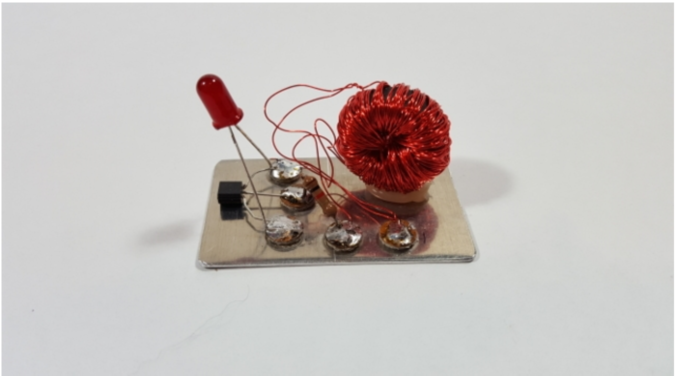


Figure 10d: A Joule thief prototype based upon a magnetite toroid inductor.

As evident in Figure 10e, the circuit is an oscillator. Transistor Q1, biased by the 1-kilohm resistor R1, turns on, energizing coil L2. The rise of the magnetic field in L2 induces a voltage in L1. Because of the phasing between the two coils, voltage in L1 drives the transistor even harder in the “on” direction. The overall effect of this positive feedback is to force Q1 to snap to the “on” state very quickly.

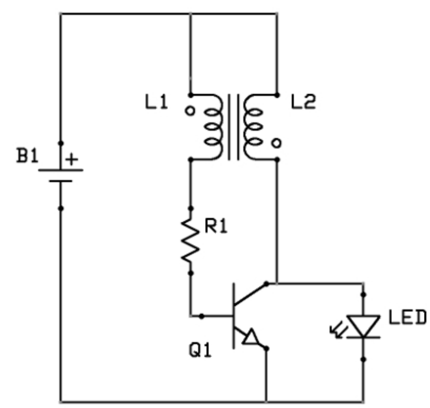


Figure 10e: The Joule thief circuit.

With Q1 on, the current in L2 rises and at some point, it maxes out. Without a change in flux, the voltage induced in L1 goes away, reducing the drive to the transistor. The transistor begins to turn off. This causes a corresponding decline in current in L2. The change in flux induces a new voltage in L1, this time in the opposite direction. The reversed voltage present on L1 has the effect of driving the transistor to the “off” condition very rapidly.

Consequently, the field in L2 collapses, and in doing so, generates a voltage spike. The spike is narrow, but its amplitude can be many, many times the voltage of the battery that powers the circuit itself. The LED serves both as a load (it flashes as it consumes the energy in the spike) and it protects the transistor.

Depending upon the characteristics of the components, the cycle just described can repeat tens of thousands of times per second. The fact that the LED is actually flashing is not evident. Rather, because of the physiology of the human eye, it appears to be lit constantly.

The novelty and popularity of this circuit, combined with the fact that it is typically constructed with coils wound upon a toroid, prompted me to try building one using one of my black-sand toroids.

My Joule thief test circuit was constructed “Manhattan-style” on a little piece of aluminum. The core was a black-sand toroid, 0.75 inches in diameter, 0.37 inches thick, with a 0.37-inch bore. I wound the coils with some scrap magnet wire, probably #30 AWG. Each coil contains 135 turns (approximately 110 uH). The number of turns was arrived at experimentally, and is somewhat higher than the number that “cookbook” recipes usually call for. This is undoubtedly due to the lower permeability of the black sand material.

That aside, the circuit works flawlessly and is capable of illuminating a red 2-volt LED from a "dead" battery whose terminal voltage is as low as 0.4 VDC.

10.3 HF Oscillator Experiments

Since one of the primary motivators for creating my magnetite toroids in the first place was to explore their possible application to radio circuits, I decided to build a small RF oscillator. See Figure 10g.

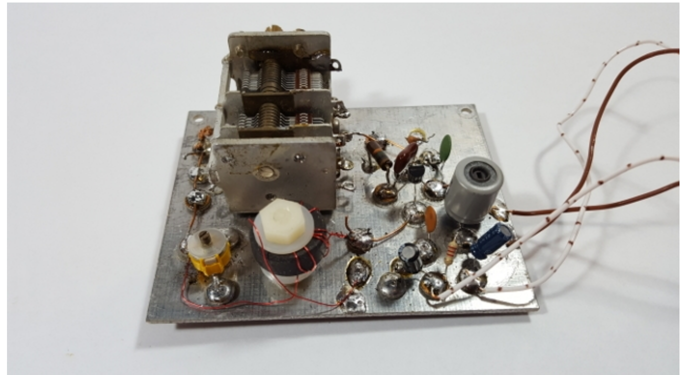


Figure 10g: A Hartley oscillator utilizing a magnetite sand toroid inductor.

The circuit I used is a Hartley configuration featuring a J310 FET. The prototype, which was built "Manhattan style" on a piece of tinned copper-clad board, features a couple of different variable capacitors to allow for frequency adjustment. The schematic in Figure 10h depicts a 6-volt battery as the power source; in fact I used a variable-voltage bench supply.

The magnetite toroid used in this case measured 0.74 inches in diameter, 0.33 inches in thickness, and had 0.36-inch bore.

The number of turns wound upon the toroid was determined experimentally, and the values of some of the support components were altered to optimize the circuit depending upon the desired operating frequency.

I can report confirmed functionality throughout most of HF band. The lowest frequency I tested at was 7 MHz, the highest frequency was 27 MHz. These values should not be construed as limits to the toroid's usefulness, rather, they simply represent the scope of my testing at the time.

What I did not test for (but I think would be useful to know) is the temperature coefficient of a magnetite toroid fabricated in this manner. It would also be interesting know if the temperature coefficient—whatever it might be—is dominated by the attributes of the magnetite or the physical behavior of the binder.

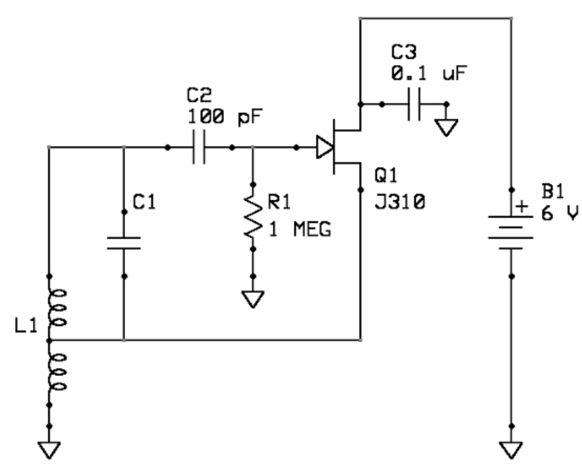


Figure 10h: A basic Hartley test oscillator.

If the inductance stability of a magnetite-sand-based toroid over temperature is good, this might justify its use in home-built VFOs for small direct-conversion and QRP rigs.

Based upon my oscillator work, I can't see any reason why these homemade toroids could not be employed in HF tuners, filters, or IF circuitry. Figure 10k shows a simple tapped LC circuit prototyped on a strip of copper clad.

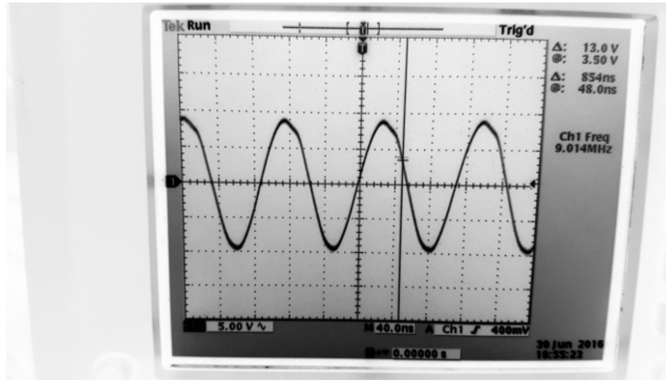


Figure 10i: A sample waveform from the black-sand Harley oscillator at 9MHz.

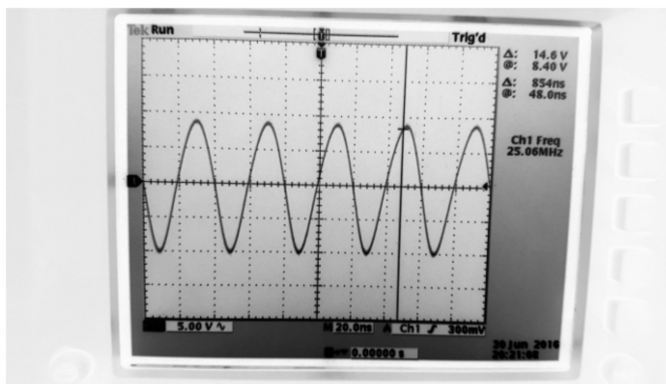


Figure 10j: A sample waveform from the black-sand Harley oscillator at 25MHz.

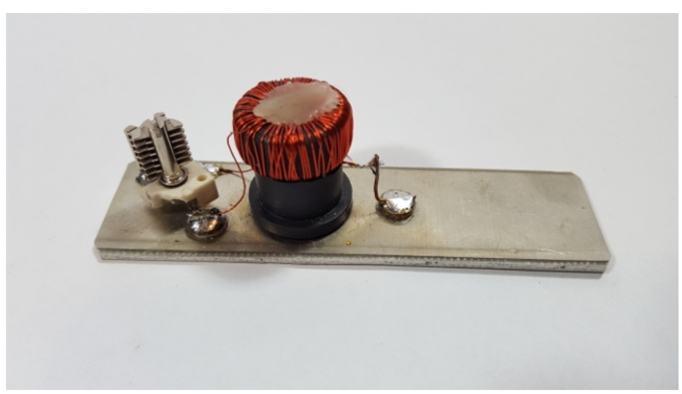


Figure 10k: A simple black-sand tapped LC circuit, possibly suitable for use as a trap or pre-selector.

11.0 Adjustable Loop Sticks

Adjustable loop sticks are a type of variable inductor. They consist of a coil wound on a paper tube. In the bore of the tube is a cylinder of ferrite material called a slug, that can be slid into or withdrawn from the interior of the coil, so as to change its inductance.

In typical practice, slugs were attached to a thin brass threaded rod which engaged a cap at one of the tube. This allowed the slug to be screwed into and out of the coil's bore with some degree of precision and repeatability. See Figure 11a.

Figure 11a: Parts of an adjustable loop-stick include the body (on which a coil is ultimately wound), a cap, and an adjustable slug. These parts were fabricated as described in the text.

If you built a simple radio tuner, crystal set, or phono oscillator from plans in the 60's and 70's, you are likely to have used an adjustable loop-stick as part of the tuned circuit. Sadly, I am not aware of anyone who manufactures them anymore, they have all but vanished from surplus, and the few that remain command absurd prices. I recently saw an adjustable loop stick from Radio Shack posted on Ebay. It was new/unused, in its original packaging (which displayed the original 99-cent price tag). The seller was asking $78 dollars! Sorry… In my book that's utter insanity.

So...once again... I wondered if the black-sand-and-resin slurry could be applied to the fabrication this component, too. My experience suggests the answer is yes.

The slugs for my loop-sticks were cast in the bodies of small insulin syringes. I discarded the syringes' plungers. Lengths of 6-32 brass threaded rod were screwed into the syringe bodies though the port to which a needle would normally be attached. The threaded rod was advanced until it projected some distance into the syringe body. See Figure 11b.

Figure 11b: Close-up of the cast black-sand slug and threaded brass stem.

I mixed a batch of magnetite sand and resin, poured it into the syringes, and let it set. The plastic from which medical syringes are fabricated does not stick to polyester resin, which is a good thing. The easiest way to extract the finished slugs is screw them out. If that fails, careful application of some side-cutters to the syringe body will set set the slug free.

Note: If you should observe any tendency of the slug to fall off or otherwise become detached from the threaded rod while in use, it can be re-attached with a drop of cyanoacrylate glue. The better approach is proactive—by slightly deforming the portion of the rod to be embedded in the slug, the liquid resin can lock on more effectively. Prior to casting, the rod end can be flattened with a hammer just a bit, or it can be “roughened” by squeezing it several times between the serrated jaws of some slip-joint pliers.

Figure 11c: A close-up of the loop-stick body. Note the wound paper flanges (to confine the coil windings), the wound paper terminal block, and the brass cap, which engages the threads on the stem of the slug.

The bodies of my loop-sticks are comprised of ordinary printer paper (Figure 11c). I start with a mandrel (a piece of metal tube or a wooden dowel, wrapped with wax paper to prevent adhesion). I wrap the mandrel with the printer paper so as to form a paper tube. I roll up several layers of paper, generously coated in white or yellow carpenter’s glue. Just how many layers needed is the subject to personal preference and experimentation, but the tube should have sufficient layers that, when thoroughly dry, it’s hard and rigid.

The paper from which the tube is rolled is pre-cut/trimmed to reflect the desired length of the finished tube. I find it easier to cut the printer paper to size and fabricate the tube, than to fabricate the tube in some arbitrary length and then attempt to cut it to length.

At the risk of stating the obvious, let me point out that the mandrel is must be chosen to reflect the diameter of the slugs you intend to use. In fact, the mandrel is slightly over-sized, to allow for some narrowing of the bore when the paper is later impregnated (more on that in a moment). The bottom line: The slug must slide freely through the bore of the paper tube.

Figure 11d: The fabrication process described in the text is repeatable. Here, three loop-stick “sisters” await the winding of their coils.

Next, I cut thin ribbons of paper, saturated them in glue, and rolled them onto the tube in various places, so as to produce the “flanges” between which the coil windings can be laid.

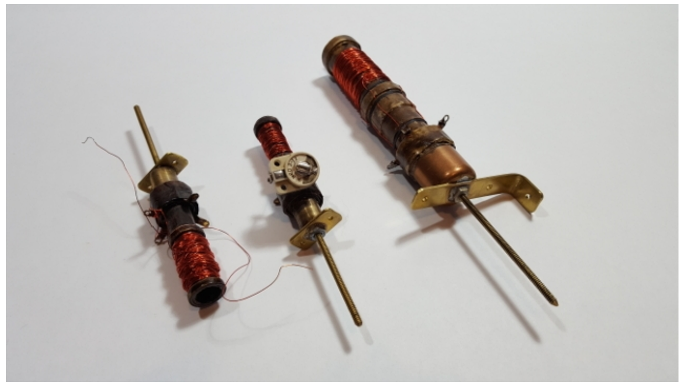


Figure 11e: Several different home-built loop-sticks scramble-wound with magnet wire.

The terminal portion of the loop-stick consists of still more glue-saturated paper. Using ribbons of paper, I wound a number of turns to thicken the tube where the terminals were be installed. This creates a cylindrical feature. When the cylinder was sufficiently large, I laid four serrated ring terminals around the periphery of the cylinder, and then continue winding glue-wetted paper over them. A little squeezing and coercion with the fingertips molds the wet paper cylinder into a homogeneous solid, and when dry, and the terminals are locked into place.

The commercial loop-sticks I’m used to playing with are usually brown, due to the phenolic polymers used to impregnate the tube material. I dipped my finished loop-stick tubes in brown wood stain, though purely for aesthetic reasons. When dry, I then submerged them in polyurethane varnish. The polyurethane soaks into the paper and when dry, “plasticizes” it, making it even more durable and impervious to humidity.

Commercial loop-sticks usually feature a stamped sheet-metal end-cap, which was fitted to one end of the paper tube. It served two purposes:

First, it provided a hole into which the slug’s brass stem was threaded. It acted as a fixed “nut” that the stem threads could work against.

Second, the cap usually featured short “ears” of some sort--a contrivance to allow the loop-stick to be snapped into, and retained in, a mounting hole drilled into a chassis or front panel plate.

Figure 11f: Loop-sticks can easily be fashioned in any size. The cap at the head of this loop-stick is a ¾-inch copper fitting.

My loop-stick caps are made from brass and copper scrap. As my first loop-stick was very large, the cap was fashioned from a copper pipe cap. I drilled a hole in the cap and soldered a 6-32 nut over the hole to provide threads for the slug’s stem to screw into. I also added two mounting “ears,” fashioned from brass.

The construction of the caps for my smaller loop-sticks is similar, though instead of a pipe cap, I employed a short section of brass hobby tubing.

The best wire to use on coils like this is Litz wire, but I've had reasonable success with ordinary enameled magnet wire. Scramble winding seems to reduce coil self-capacitance, but I think it would be ideal to lay down some nice basket-weave windings with David Gingery's Universal Coil Winding Machine, or a similar homebuilt machine.

12.0 An Experimental Current-controlled Inductor

Voltage-controlled capacitors, otherwise known as varicaps, are routinely found in contemporary radio receiving equipment. Varicaps function by exploiting the change in the junction capacitance of a back-biased PN junction. In essence, they're just diodes that have been optimized to produce this voltage-dependent change in capacitance.

As it turns out, there is a complement to the varicap, a current-controlled inductor. I first noticed a reference to such an animal in an electronic product announcement that appeared in a late 1950's or early 60's tech journal. (By the way, I'm not THAT old. Rather, decades of old electronics hobby magazines and technical journals can be found scanned, in PDF format, on the Internet, free for download, if one is willing to invest a little time with their favorite search engine.)

Figure 12a: A cast core for an experimental current-controlled inductor.

As I'd never run across reference to a current controlled inductor before then, and had never observed one in the wild, I had assumed it might be one of those ideas that was big on promise, short on delivery, and predestined to wither on the vine.

For that reason reason, after having acquired an EICO 369 TV-FM Sweep/Marker Generator (circa 1964), and having studied its manual, I was quite surprised to find a working example of the current-controlled inductor employed in a real product. In the case of the EICO 369, the controlled inductor is used to sweep the signal oscillator.

My EICO 369 is intact; I didn't want to risk damaging it by taking it apart far enough to study the controlled inductor. However, the schematic at the back of its manual suggested to me that the controlled inductor might work through a kind of purposeful saturation.

I envisioned a control coil, wound on the same core as an oscillator coil, driven by a control current. Given a core with limited ability to carry flux, the higher the control current, the less flux-carrying capability available for the oscillator coil. As the control current increased, I reasoned, the oscillator coil would essentially be flux-"starved" and its inductance should decrease.

A big problem with coincident coils—oscillator and control windings wound on top of each other—would be the unintended and undesirable coupling that would occur between them. In researching this idea, I learned of a physical arrangement that allows control flux to be introduced into the oscillator coil core area, without coupling to it. I set out to cast an example of this shape in magnetite sand and resin. The mold was made from clay. The result can be seen in Figure 12a.

The ring-shaped horizontal portion of the casting is the part upon which an oscillator coil is wound. Extending perpendicular from the wall of that torus (essentially bisecting it) is a horseshoe-shaped extension upon which the control winding is wound.

Figure 12b: Here, the control winding (left) is being added to the cast core. Supply wire is stored on a long, narrow, plastic shuttle (right). The shuttle is sufficiently narrow to allow it to pass through the bore of the casting.

To wind the control winding, I first wrapped the core with Teflon™ tape. It seemed intuitive that the success of the control winding would hinge on achieving a high number of turns, so I endeavored to add as many to the core as practical.

As winding any closed structure with wire is tedious proposition, I aided my effort by creating a small, plastic "shuttle," (scissor-cut from clear packaging plastic) which not only held the wire intended for transfer to the core, but facilitated the wire's repeated insertion through the core opening. Figure 12b shows the control winding nearing completion, along with the wire shuttle.

Regrettably, I can no longer find my records of the precise wire gauge or the number of turns laid down. As I'll explain in a moment, it's probably irrelevant anyway.

The oscillator coil contained a comparatively few turns of heavier wire. Rather than build another oscillator, I connected this coil to my LCR meter. The completed current-controlled inductor, with control and oscillator windings, appears in Figure 12c.

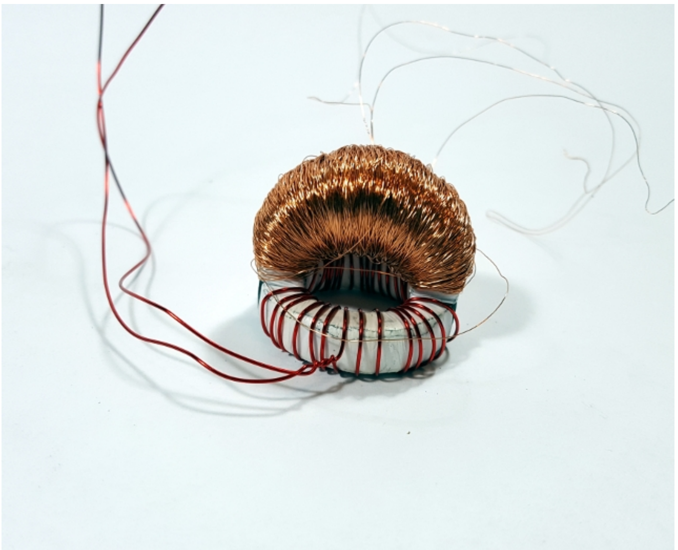


Figure 12c: The completed current-controlled inductor. The control winding occupies the arch (on top), the oscillator winding, with comparatively fewer turns, occupies the toroidal area at the bottom.

I drove the control winding with a variable D.C. power supply and varied the control current with the power supply's current limiter.

How did it work out? I'll cut to the chase: the experiment was an utter failure. In retrospect, it was probably naive to expect that a core of this size, based on material comprised of discrete (loosely-coupled) grains, could be driven sufficiently hard to modulate its permeability.

Perhaps if the cross section of the oscillator coil portion was greatly reduced, it might facilitate control. Also, it might be beneficial to vary the magnetic materials used in the slurry mix… perhaps employ the magnetite sand in the oscillator coil portion of the casting, and use something with a higher mu in the control coil portion. Or...my materials and process are intrinsically unsuitable for fabricating saturable inductors, and that’s the end of it.

In the end, the experiment was not without useful take-aways. First, the ability to cast the shape this project required inspired me to attempt casting more complex shapes. And, if the sand-resin mix is resistant to saturation, that bodes well for the many inductor applications where core saturation would be a bad thing...like chokes and baluns, for example.

13.0 A Pot Core Transformer

Ferrite pot cores are magnetic components from which one can built high-Q, low-loss, and shelf-shielding inductors and transformers. A typical pot core is a cylinder with a cylindrical column of ferrite at the center of the cavity.

Pot cores are typically shipped with form-fitting bobbins, on which a coil or coils can be wound. The loaded bobbin is placed inside of the pot core, and a cover of some sort—made from the same material as pot core—closes the cylinder and completes the internal magnetic circuit.

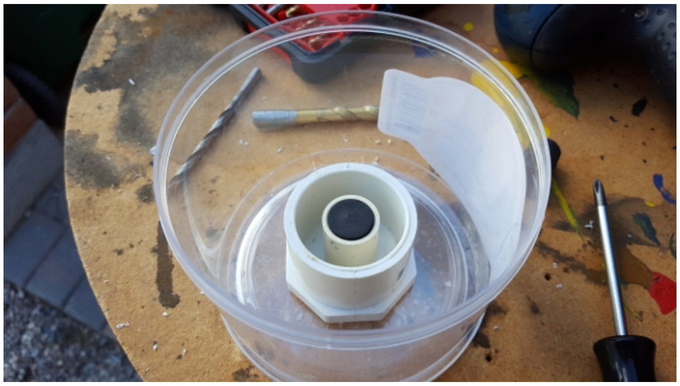


Figure 13a: Creation of the mold "positive."

Being a magnetic component manufactured from "gray stuff," I thought I'd take a stab at fashioning a pot core using my magnetite-sand-and-resin mix. This would require the fabrication of an appropriate mold.

Figure 13b: Plaster of Paris is poured onto the "positive."

Using a couple of PVC fittings and a rubber stopper, I glued together a geometric form representative of the pot core I hoped to cast. This comprised my model, my mold "positive." The "positive" was anchored to the bottom of an empty CDROM container with a screw. See figure 13a.

I sprayed the model with silicone lubricant (hoping this might act as a mold-release) and then filled the CDROM container with plaster of paris (Figure 13b).

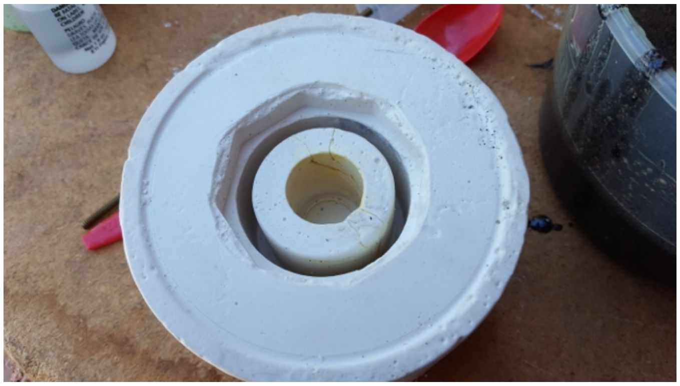


Figure 13c: When the "positive" is removed, the mold is created. Parts of the mold that broke during extraction of the positive were reinstalled and secured with carpenter's glue.

Once the plaster was set, it was time to remove the "positive." This did not occur without difficulty, and without some damage to the mold itself. After significant rapping, tapping, twisting, prying, and a few salty exhortations, the "positive" was freed from the plaster. I reattached broken pieces of the mold with ordinary carpenter's glue, and when it had dried thoroughly, I sprayed the interior of the mold with more silicone lubricant. The resulting mold can be seen in Figure 13c.

I mixed a batch of sand and resin and spooned it into the mold. Excess sand-and-resin mix was dumped into a shallow plastic lid. The disk formed by the solidified mix in the lid would later be used as the base for a pot core transformer. The loaded mold appears in Figure 13d.

Figure 13d: Black sand and resin slurry is spooned into the mold.

While the plaster mold produced a faithful casting (seen in Figure 13e), it was necessary to destroy the mold to successfully extract it. Thus, I do not recommend plaster for this kind of work.

At one point I did secure a small quantity of silicone rubber mix, a formulation intended for use in potting electronics to render it waterproof. A mold made of that material turned out to be ideal because it was rigid enough to assure dimensional stability, but flexible enough to allow for easy extraction of the finished and hardened part. I've suggested the use of silicone rubber as a mold material earlier in this paper.

Figure 13e: A beautiful magnetite pot core emerged from the mold.

My next step was the fabrication of a custom bobbin. Using a piece of metal tubing as a mandrel, I created a tube fashioned from index-card cardboard and glue. From the same material I cut a set of flanges for the bobbin, and glued them to the tube with carpenter's glue. Once the completed bobbin had dried, I dipped it in polyurethane varnish and then suspended it by a wire hook so that it could drip and thoroughly dry.

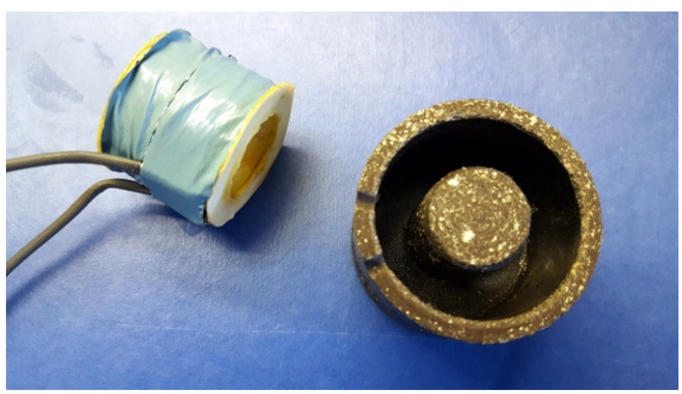


Figure 13f: The coil assembly, ready for installation in the core. Note the notches in the rim of the core to allow egress of the coil's leads.

The completed bobbin was wound with wire (specifications to follow), taped, and installed in the pot core. See Figures 13f and 13g. Note that I filed a couple of notches in the rim of the pot core cylinder to provide for an exit path for the coil's leads.

To close the pot core, I mixed a small quantity of sand and resin and applied it to the open mouth of the pot core. The mix was applied liberally, not only to the rim of the pot, but to the cylindrical column at the center of the bobbin. When I'd finished, I pressed the pot core against the base disk (the component I'd cast in the plastic lid with the mix left-overs). This permanently bonded the two structures together.

Finally, I installed a small terminal strip to the base of the transformer to provide a termination point for the coil wires. The completed transformer can be seen in Figure 13h.

Does it work? Yes, surprisingly well. The electrical specifications for the resulting transformer have been summarized in Figure 13i.

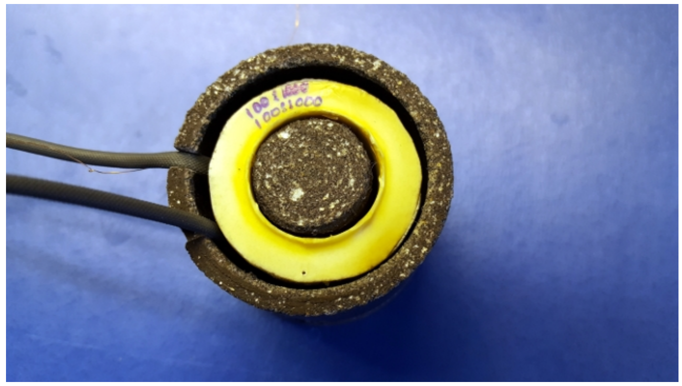


Figure 13g: The cardboard coil bobbin is sized to fit perfectly in the core.

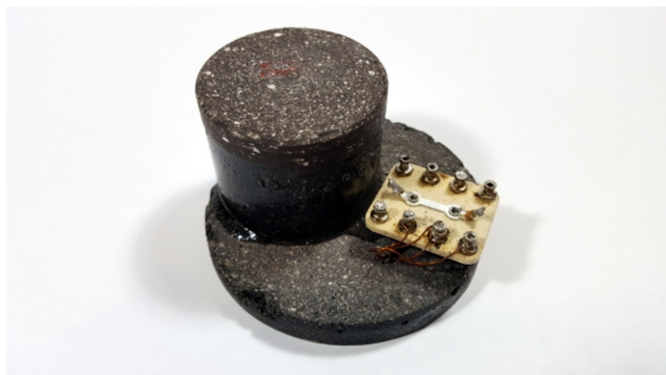
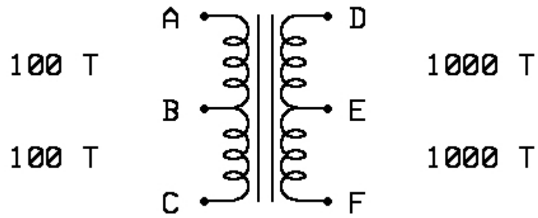


Figure 13h: The completed pot-core transformer. Note how the core is bonded permanently to the pre-cast disk-shaped base.



	L	R
A-B	66.52 mH	98.27 Ohm
B-C	66.41 mH	89.48 Ohm
A-C	174.1 mH	187.75 Ohm
D-E	41.48 uH	1.85 Ohm
E-F	17.19 uH	1.37 Ohm
D-F	110.2 uH	3.22 Ohm

LI	174.1 mH	
LS	10.99 mH	

COUPLING FACTOR

$$K = \sqrt{\left(1 - \frac{LS}{LI}\right)}$$

Calculated K= 0.97

Figure 13i: Electrical characteristics of the transformer.

14.0 Cast Transformers

I like the idea of casting transformer cores, and my experience with the pot core project suggested that useful electronic components could be fabricated. Still, preparing elaborate molds takes care, attention, and a fair amount of time. Some of the material needed to create reusable molds (silicone rubber, for example) can be expensive. I'm always open to consideration of ideas to optimize or simplify a process.

In contemplating the physical geometry of the pot core—a cast component in which a coil is installed—it occurred to me that an alternative approach would be to start will the coil assembly and to literally cast the core around it!

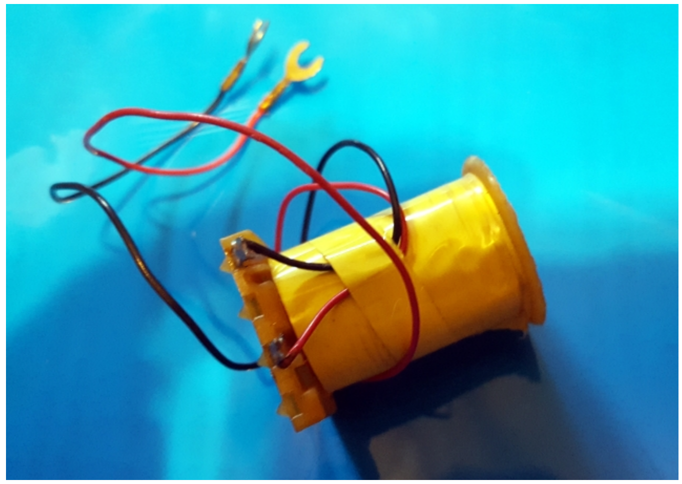


Figure 14a: A telephone ringer coil.

In theory, a transformer constructed this way:

- Does not require pre-fabrication of the core.
- Does not require careful dimensioning to assure a fit between the core and coil assembly.
- Does not require any mold more elaborate than a simple cylindrical container, yet,
- As in the case of the pot core, the core completely encloses the coil assuring minimal flux leakage and a high degree of self-shielding.

You can't effect a robust "wrap-around" of the core simply by tossing the coil into a container and dumping mix on it. The trick to making this work, it seemed, was to identify some method by which the coil assembly could be suspended in the center of the black-sand-and-resin mass and held there as it hardened.

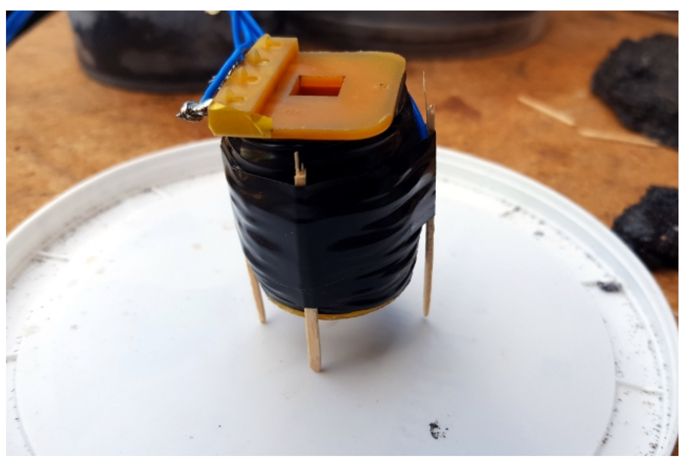


Figure 14b: The ringer coil, modified. A secondary coil has been added, as well as a set of toothpick "legs." The latter will support the structure while being cast in the black-sand-and-resin mix.

I decided to attempt the construction of a simple step-down transformer. A transformer of this type might be useful in an amplifier, for example, as an matching device between the comparatively high impedance of a transistor or vacuum tube and a low-impedance loudspeaker.

To test my fabrication idea (and avoid having to fabricate bobbins and wind coils for the this experiment), I dug through a junk box and found a “ringer” coil previously extracted from an old telephone (Figure 14a). This is a simply a two-terminal electromagnet used to actuate the bell-ringer armature in an older-style desk telephone. Ringer voltage on U.S. land-line telephone networks can be 75 VAC or higher, so the ringer coil has a fairly high impedance. This would function as the primary of my transformer.

Figure 14c: A vitamin pill bottle is a practical mold in which to cast this transformer.

Around the coil’s exterior I wound a second coil, comprised of some scrap magnet wire. The precise number of turns is lost to history, and is not necessarily relevant to present the idea here.

The coil assembly was wrapped in vinyl electrical tape to solidify the assembly and to render it sufficiently liquid-tight to preclude the intrusion of resin or sand into the windings themselves.

The coil assembly was fitted with a set of toothpick “legs” and then inserted in a plastic vitamin bottle, the top of which had been cut off with some metal shears (Figure 14b). The coil assembly was centered in the bottle, and the black-sand-and-resin mix was poured in. The container was rattled and vibrated to drive any bubbles or entrapped air from the structure.

Figure 14c shows the slurry hardening in the vitamin pill container. The resin did not bond with the plastic from which the vitamin pill bottle was made, so extraction of the transformer was easy. One of the nice things about the cylindrical form and size of the resulting transformer was that standard electrolytic capacitor mounting hardware can be used to mount the transformer to a base or chassis (Figure 14d).

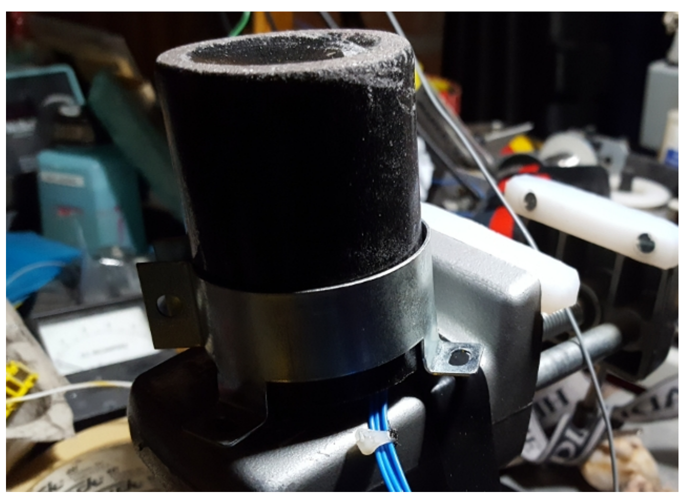


Figure 14d: Standard brackets, of the type used to mount large electrolytic capacitors, can be used to anchor this transformer to a base or chassis.

The first prototype, unfortunately, did not work as well as expected. The comparatively low mu of the black sand combined with the narrow bore of the coil resulted in what I’d presumed to be fairly high reluctance. In retrospect, it might have been advantageous to make use of the straight silicon-steel core laminations that came with the coil. This could have been cast into slurry with the coil, the magnetite sand completing the external magnetic circuit.

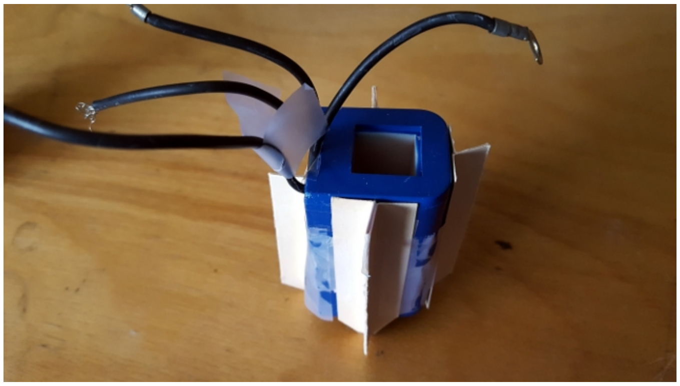


Figure 14e: Two contactor actuator coils form the basis of this 1:1 transformer. Cardboard fins, added to the coil assembly, will center it when inserted into its mold container.

Still, there was evidence of transformer function, the fabrication process was quick and easy, and the end product was very nice. I decided to try again.

Another trip to the junk box yielded an identical pair of actuator coils, previously part of a set of three-phase contactors. The coils were wound for 120 VAC. Their bores were considerably larger, they were more squat (meaning the external magnetic path would be shorter) and a pair of them stacked together should yield a 1:1 isolation transformer.

Because of the high density of the casting slurry, one of the problems encountered in casting the phone-ringer coil was buoyancy—the coil assembly wanted to rise out of the mix. I ended up using a piece of stiff wire to keep it pinned down and submerged until the mix had set.

In the case of the contactor coils, I attached index-card “fins” to their exterior with cellophane tape (Figure 14e). The fins not only center the coils in the vitamin-pill bottle, but act to wedge it in place so that it can’t easily move (Figure 14f). Problem solved.

The 1:1 isolation transformer, with slurry in place, is visible in Figure 14g. This transformer functioned much better than the previous device, though still not as well as I would have liked.

An interesting experiment I tried was to *energize* the transformer windings with a fairly substantial DC current while the slurry was setting. I presume this had the effect of aligning the magnetic particles in the casting slurry, as it greatly improved the coupling in the finished transformer. Figure 14h shows a small sample of the family of transformers I produced through the casting process I’ve just described.

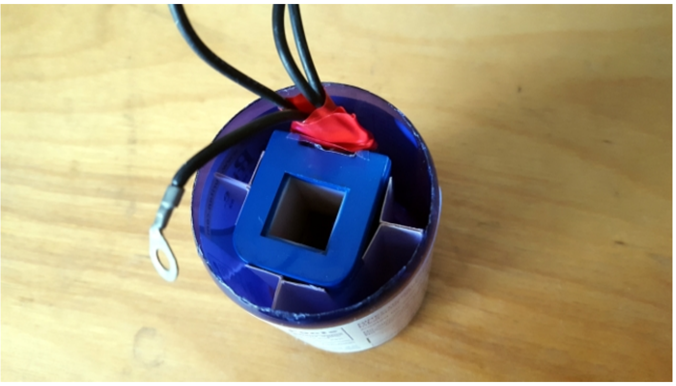


Figure 14f: The coil assembly has been inserted into a vitamin pill bottle and awaits the casting process.

In the end, I decided that this was an application where magnetite sand really doesn’t measure up. I began contemplating other options for magnetic materials. When I revisited these devices some time later, using milled cast iron brake drum turnings in lieu of magnetite sand (see section 16.0), the improvement was so great as to move these transformers into the realm of practicality.

Figure 14g: Casting the 1:1 transformer. Plastic-tape-coated cardboard is used here to allow for some over-fill.

Figure 14h: This photo is representative of the family of experimental transformers created with the process described here.

15.0 A Compact Transmit Antenna

Nature is remarkably unyielding in its enforcement of the “no-such-thing-as-a-free-lunch” rule. One of the many arts in which this is readily apparent is in transmitting antenna design. Stated crudely, big waves like big antennas.

This fact has not discouraged ham radio operators from seeking short-cuts and work-arounds. After all, full-sized antennas can be expensive, complex, situationally impractical, and often (where zoning or regulatory restrictions exist) impossible to erect. Luckily, if one is willing to accept the limitations of alternative designs, it is sometimes possible to trade a barrier for a concession. It’s been said that the antenna you have is always better than the antenna you’d like, but can’t have.

A compact antenna design that has become increasingly popular in recent times is the so-called magnetic loop antenna. The magnetic loop is an electrically small antenna, a loop with a circumference between one-eighth and one-quarter of its operating wavelength. The loop is resonated with large capacitor, and is usually (but not always) driven with a smaller loop, about 1/5 the diameter of the main loop. Reasonable performance (some claim comparable to a half-wave dipole at half-wavelength height) can be achieved without the need for a ground plane and without having to significantly elevate the antenna.

Whether these claims are true or not can be debated. What cannot be debated are the concessions for this claimed performance. The mag-loop is a resonant, high-Q structure. As a result:

- The mag-loop can generate extremely high voltages. If you want to run at any reasonable transmit power, construction of the loop requires careful attention to insulation and the use of expensive and fragile vacuum variable capacitors for tuning.
- The radiation resistance is very, very low. This means that even milliohm resistance in the antenna material, in joints, and in connections (inconsequential in other antenna designs) will result here in substantial and debilitating parasitic losses.
- The mag-loop is a narrow bandwidth device. Any changes to the transmitter operating frequency beyond a couple of kilohertz usually requires retuning of the loop.

A cousin to this device is the ferrite bar antenna, an example of which was introduced in section 8.0. Fitted with a coil (a magnetic loop with more than one turn, if you will) and a capacitor, it becomes a resonant antenna structure, too. The big difference between the mag loop I’ve just described and the bar antenna is that while the mag loop is used for both receiving and transmitting, the bar antenna is only seen only in receiver applications.

Over the years several hams have dared to ask why this should be the case, and have conducted experiments to see if some configuration of ferrite-based antenna might offer another compact transmitting antenna option.

More than 20 years ago, Richard Marris, call sign G2BZQ, penned a fascinating article in the March, 1999 issue of *73 magazine* concerning his use of ferrite bars in the construction of ultra-compact transmitting antennas. There is no need to reproduce the content of that article here; it is readily available for download from the Internet Archive.

https://archive.org//

The key takeaway is that after experimentation spanning several decades, he had arrived at configurations that he described as “quite encouraging.”

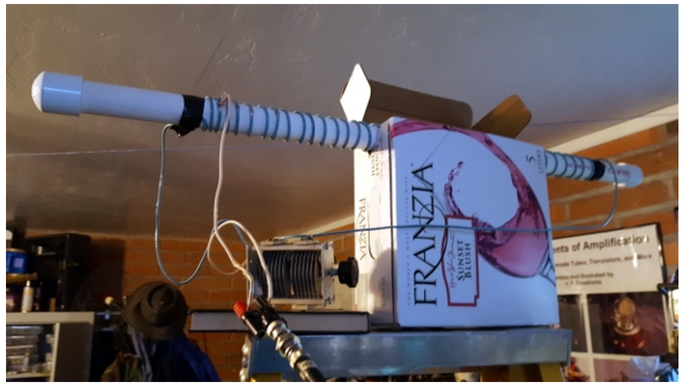


Figure 15a: A “ferrite” bar transmitting antenna implemented with magnetite sand; the sand is contained in the capped PVC tube.

It occurred to me that some of the challenges that ‘BZQ faced in developing his antenna might be addressed through the application of magnetite sand in lieu of the ferrite bars he had employed.

For example, ‘BZQ remarks on the relative expense of ferrite bar material, and the expectation from certain manufacturers for absurdly-high minimum-purchase quantities. In contrast, magnetite sand is abundant and quite literally “dirt cheap.”

Richard commented on the difficulty he had obtaining *large* ferrite bars. The biggest bars he could obtain were no more than a half-inch in diameter and 8 inches in length. To render a composite bar sized large enough for his transmitting experiments, it was necessary to glue the smaller bars together end-to-end to achieve the desired length, and then bundle the glued sub-assemblies so as to achieve girth.

On the other hand, there is no apparent limit to the size one could cast a black-sand bar, provided enough refined sand and enough resin was available. A cast bar many inches in diameter and many feet in length seems perfectly feasible.

It should be mentioned that the chemical reaction behind the hardening of polyester resin is exothermic—it throws heat. There may in fact be a recommended limit to the volume of resin one can cast in one sitting, so as to assure that the reaction can rid itself of its own heat fast enough. If so, large bars could alternately be constructing by packing the interior of PVC drainpipe with magnetite sand and then capping it. Imagine a “ferrite” rod 4 inches in diameter and 8 feet long!

Figure 15b: The core of this transmitting antenna contains three PVC tubes and three times the volume of magnetite as the antenna in Figure 15a.

Richard observed that antenna gain and directivity increases with the size of the ferrite bars used. Once again, the relative ease with which large magnetic bars can be crafted with magnetite sand, would appear beneficial.

In his experiments, ‘BZQ observed and grappled with instances of saturation and overheating. As recounted in Section 5.0, my magnetite sand samples did not heat up in any significant way, despite exposure to the comparatively high-power, high-frequency RF field in my microwave oven. This implies low loss. In section 12.0, where I described my experimental current-controlled inductor, its failure was connected with the black-sand-resin mixture’s apparent predisposition *not* to saturate. In short, a magnetite-sand-based bar might be precisely the material ‘BZQ was looking for.

My own experimentation in this topic to date has been no more than brief and superficial, but worth mentioning. My “ferrite” bars were similar to what I just proposed in the prior paragraphs—in this case lengths of 2-inch PVC tubing, 2 or three feet in length, filled with refined magnetite sand and capped at each end. Basically, I used the materials I had on hand.

Before driving on the last cap on each tube, I stuffed in a chunk of foam rubber packing material. The intent of this was to apply and maintain pressure on the column of magnetite sand in the tube, so as to prevent the formation of voids.

One of my antennas consisted of a single sand-filled PVC tube wound with 12 AWG solid copper wire (Figure 15a). Another consisted of three such tubes bundled together (Figure 15b). The coil was tapped at the “cold” end to provide a near-50-ohm feed-point for my transmitter, and the coil was resonated with a transmitter-type variable capacitor.

In each case the antenna structure was balanced on an empty wine box (consumed in the name of science!) and set upon the top rung of a fiberglass ladder.

After tuning each antenna to resonance (tuning was quite sharp, implying an expected high-Q condition) I made a few attempts to establish radio contact at QRP levels. I heard several distant stations, but was not successful in soliciting a response.

The reasons could be many. Band conditions were very poor, the transmit power level was low, and the antenna was located indoors. Mag loops (and presumably bar antennas) don't like metallic objects in their immediate proximity, and the aluminum top step of the ladder probably qualifies.

I consider it premature to regard these single-test results a failure. To the contrary, given G2BZQ's success, I think my idea worthy of further experimentation, including the construction of the four-inch by eight foot bar I fantasized about. Next time, my bar antenna will be properly located out-of-doors, away from metallic objects in the near-field, I will wind it with copper tubing, and drive it to the 100-watt levels my transceiver can produce.

For the record, there are others who tinker with ferrite bar antennas and report some success. Roger, G3XBM has a web page devoted to this:

https://sites.google.com/site/g3xbmqrp3/antennas/ferrite_tx

His site contains links to other experimenters, to published papers, and to the Richard Marris' article in *73 Magazine*.

16.0 <u>Cast Iron as a Magnetic Material</u>

16.1 In Search of Alternative Magnetic Materials

While black magnetite sand seemed to be a suitable material from which to fabricate certain kinds of inductors, it is clear there are applications for which it is completely unsuitable. This became most evident in my transformer-fabrication experiments, and led me to contemplate possible alternative materials.

Commercial transformer cores are typically assembled with “E” and “I” laminations stamped from sheet metal, comprised of a special grade of silicon steel. My first thought was that the ideal cast-core alternative to magnetite sand would be a powdered form of that metal alloy. Unfortunately, if transformer steel exists in powder or granular from, I wasn’t able to find a source. This means that if I wanted to experiment with that material, I would have to develop a process or build some type of machinery to produce it from transformer scrap.

My next thought was to see if some form of powered steel—of any kind—was in fact available, even if said powder was intended for other applications. Granulated steel is sold for use in sand-blasting applications. It checks the important boxes of being inexpensive and readily available. Yet in researching its physical properties, I noted that the grains were comprised of a comparatively hard grade of steel. Experience with similar metals suggested that that it might suffer from magnetic hysteresis and retentivity, the last things I’d want in a transformer core material.

I recalled that vintage induction coils were often fabricated with magnetic cores comprised of bundles of soft iron wire. Why not try iron filings in the resin mix? I began to look for sources of powdered iron.

Powdered iron is readily available from suppliers of chemical reagents. Their commitment to chemical purity, however, raises the cost of what should otherwise be a very cheap material. A seller on Ebay, for example, was asking more than $25 dollars for a 500g bottle of reagent-grade iron powder. In rough numbers, this is $25 bucks a pound.

Then it came to me: Brake drums… fabricated from cast iron (with a small percentage of copper to improve wear characteristics). Every brake shop has a lathe, which is used to turn and true the drums when automobile brakes are being serviced. With dozens of vehicles passing through each day, they should produce many pounds of metal shavings.

A visit to a local brake shop proved this to be the case. I asked for the manager. We had a friendly chat wherein I explained the nature of my science experiments and why I was interested in his lathe turnings. When we parted, he had a few extra bucks in his pocket—sufficient for lunch at the burger joint next door—and I walked away with a pail containing at least 15 pounds of brake drum turnings. The second time I showed up, he gave me the turnings for free.

Progress in experiments like this are often chaotic in nature--two steps forward and one step back. Test bars cast with the brake drum turnings were initially disappointing. The material did not pack very well, and closer examination of the turnings revealed why.

Despite its brittleness, lathe chips shaved from a cast iron body have a pronounced curve to them, not unlike the curled chips produced by a carpenter's plane when driven down the length of a piece of wood. Grain-like particles of iron can pack fairly densely, but curved and curled shavings discourage intimate contact, leaving numerous voids and reducing the overall density of an iron-and-resin mix. Somehow, I needed to break up these microscopic curls.

My first thought was to grind the particles between counter-rotating metal plates. I judged this overkill and too much trouble to implement. I applied a mortar and pestle to the problem, and the results were encouraging, but tedious work for the small volume of filings that I could process. I then recalled that ball mills had been used in the preparation of ore for smelting, and smaller mills were used to pulverize ingredients for the production of ammunition propellants. I decided that a ball mill might answer my needs and I set out to build one.

16.2 Construction and use of Ball Mill

A ball mill is a sealed rotating cylinder or drum-like container, into which the material to be processed has been loaded. Added to the drum are numerous metal spheres—the "balls" of the ball mill—which tumble with the material as the drum rotates.

As the balls move, they strike each other. Process material trapped between opposing balls is crushed and pulverized. Where the balls are not striking each other, they are sliding past one another. The sliding movement of the balls serves to grind material caught between them. Thus, two distinct effects work to break down the process material, impact and grinding.

Figure 16a: The base of my ball mill is a framed plywood deck, reinforced with ribs. The underside of the base is visible here.

The quantity, size, and composition of the balls is selected based upon the material being processed. For breaking ore, large iron spheres were used. The propellant mills likely used brass or lead balls, so as to avoid producing an accidental spark.

Construction of my ball mill began with a wooden base comprised of a deck of plywood and a skirt of some re-purposed lumber. See Figure 16a. I installed ribs beneath the deck to stiffen it and discourage the tendency of the deck to act like a sounding board. Mills like this can be noisy as it is.

A quick check of my junk stock yielded some 12-mm polished steel shaft, probably harvested from a discarded printer or similar piece of office equipment. I cut the shaft into two lengths, and then fitted each shaft with a series of one-hole rubber stoppers. The steel comprises my roller shaft, the rubber stoppers, my rollers. The rubber rollers would ultimately support and rotate the drum in which my iron shavings could be milled.

I purchased a set of pillow-block-style ball bearings. The bearings were fitted to the roller shafts and secured to wooden pedestal blocks with quarter-inch hardware-store bolts and tee-nuts (Figure 16b).

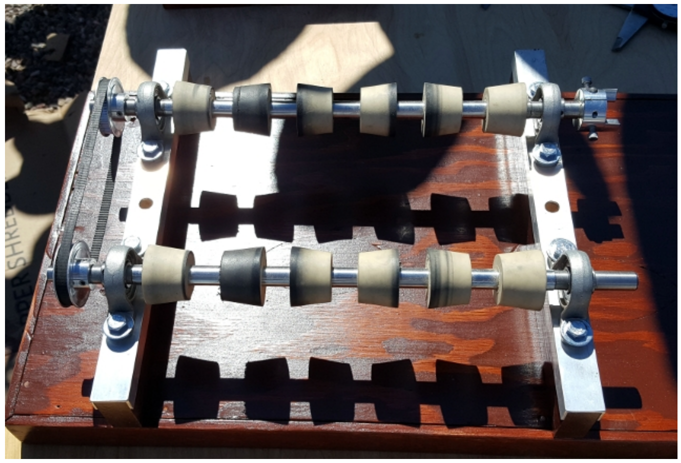


Figure 16b: The ball mill, partially assembled. Visible here are the roller shafts fitted with their rubber (stopper) rollers. The shafts ride on four ball-bearings in pillow blocks. To the left are two pulleys and a belt that synchronizes the rotation of both shafts.

I fitted each roller shaft with a timing pulley and linked the shafts together with a narrow, toothed belt. I created a simple spring-loaded mechanism to force an idler pulley against the exterior of the belt. This offers some shock protection to the belt and maintains tension, despite inevitable wear (Figure 16c).

In my travels I happened to come upon a nice gear-head motor and an accompanying control box. The motor had been intended for use with a set of peristaltic pump heads, but it proved to be ideal for my mill. It produced ample torque, and its top speed was a bit higher than what I expected to need. With the control box, speed was infinitely adjustable, a feature which turned out to be very useful, later. I fashioned a mounting pad on the ball mill's deck to accept the motor's base and secured the motor to the pad with a large stainless steel hose clamp. Near the front of the deck, I prepared a place to accept the motor's control box (Figure 16d).

The gear-head motor was coupled to the rear roller shaft with a “jaw” style shaft coupler. This can be seen in Figure 16e. A polymer “spider,” that resides between the jaws of the coupler, allow for minor misalignment and provides some shock absorption to protect the gear train in the motor.

Figure 16c: Detail of the pulleys and belt that link the roller shafts. Beneath the left pulley lies a tensioning mechanism. A compression spring applies downward force to the left side of a pivoting arm. On the right side, the arm is fitted with an idler wheel which applies pressure to the exterior of the belt. Tension in the belt is adjustable by manipulating the nut above compression spring.

None of the mechanical components I've mentioned should be construed to be exotic or difficult to source. The proliferation of cheap 3-d printers manufactured in Asia has resulted in a corresponding increase in the availability of cheap mechanical components like pulleys, belts, bearings, couplers, shafting and similar items. The only possible headache for North American experimenters is that these parts are universally designed to metric specifications.

I added a pair of garage-door rollers to the pedestal blocks supporting the shaft bearings. In normal application, these ball-bearing rollers are used in conjunction with a metal track or channel, and guide the movement of segmented garage doors as they're raised or lowered. In my machine, they are used to assure that the material drum stays on the rubber rollers. If the drum should wander laterally, it will eventually contact one of the garage door rollers, which will prevent further travel drum without hindering its rotation.

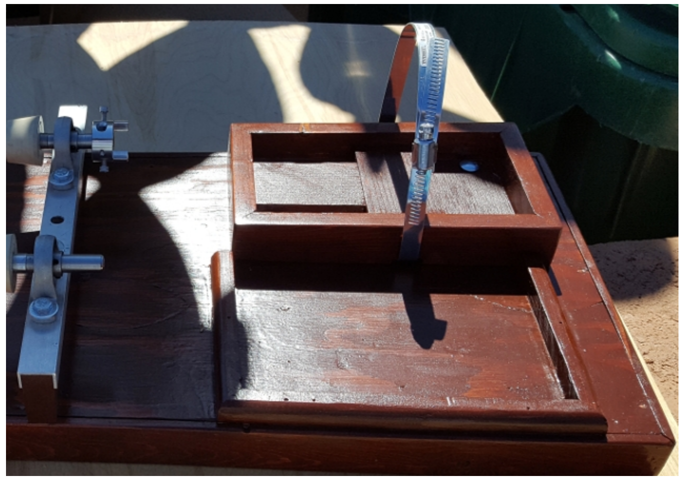


Figure 16d: At the rear, a wooden frame is ready to accept the base of the gear motor that will drive the mill. The hose clamp will secure it in place. The frame toward the front is sized to accept the base of the motor control box.

The simplest, and yet in some ways the most important, part of the machine is the drum in which material is processed. I employed a large, thick, HDPE (high-density polyethylene) screw-top jar, in which protein powder had been sold. After some initial experimentation, I force-fit the jar into a section of thick-walled cardboard tube. The tube protects the exterior of the jar from roller-induced wear-and-tear and it improves the "ride height" of the jar between the roller shafts. I applied a coat of polyurethane varnish to the cardboard, which seems to have toughened it up as well.

At this point, what I've described bears more than passing resemblance to large rock tumbler. In essence, that's what it is. The difference is the introduction of metal balls into the drum, which is what makes this a ball mill.

The balls I employed were a mixture of loose, used and surplus ball bearings of varying diameters. The smallest balls in my machine are about a quarter-inch in diameter. The largest are about three-quarters of an inch. Unprocessed brake drum turnings are scooped into the drum, the ball bearing assortment is added, and the drum is sealed. The drum is set upon the rollers and away we go.

When processing is finished, the balls can be separated from the material with a kitchen-style sieve.

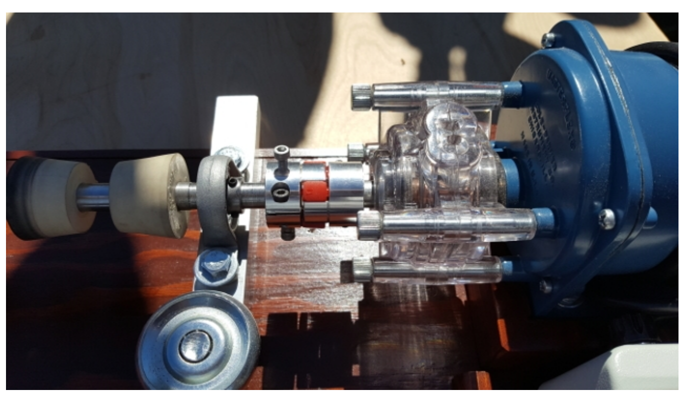


Figure 16e: At the rear of the mill, a jaw-style coupler joints the shaft of the the gear motor and the rear roller shaft. Also visible is one of the metal garage door rollers (bottom) that is used to prevent the revolving drum from wandering off the rubber drive rollers.

Through experimentation, I have determined that it is advantageous to vary the drum speed depending upon the stage of processing. Initially, I run the drum more slowly. This seems to favor tumbling and impact between the balls. The hammer-like effect of colliding balls apparently dominates the physics. Later, I increase the speed of the drum. This seems to favor rolling and sliding. The grinding effect of the balls then dominates.


Figure 16f: The interior of the ball mill's drum. Loose ball bearings of assorted sizes grind and pulverize brake drum turnings into usable form.

The milling process is surprisingly aggressive and energetic. After a few hours of operation, the beaten and ground turnings are noticeably warm to the touch. Even to the naked eye, the particles of iron are visibly reduced in size, and evidence of the potato-chip-like curves and curls in unprocessed lathe chips completely vanishes.

16.3 Comments on the Application of Milled Materials

The ability to mill my brake drum turnings rendered this otherwise unusable source of iron, usable. After having produced a quantity of the milled iron, I revisited some of the projects described in prior sections of this paper, and re-fabricated them with cast iron instead of the magnetite sand. The greater mu of the powdered iron makes some of the devices function better...or at least differently, depending upon the application.


Figure 16g: The completed ball mill in operation.

I also experimented with ball-milling magnetite sand. This might at first seem an unnecessary treatment, but the effect of milling, even on this material, was demonstrably beneficial. Two improvements in the resulting product were noted:

First, pulverizing the sand serves to further disaggregate the magnetite from caliche, quartz, and other non-magnetic minerals adhering to the individual magnetite grains. This breakdown allows for a more thorough refinement (see section 6.0) and an end-product that is much more pure.

Second, magnetite is brittle and yields well to the crushing forces in the mill. It shatters into increasingly tiny particles, some of which are so small as to appear as a black mist or “smoke” when the lid to the ball drum is opened. The variety of particle sizes in the milled magnetite allows for more efficient packing of the particles when mixed with resin, which in turn results in cast structures with a higher mu.

It would be very interesting to capture the magnetite “smoke” with a magnet and collect a sufficient quantity of it to form the basis of a special, ultra-fine-magnetite-and-resin mix. Would this further improve particle density and improve mu?

Another avenue for exploration lies in the combination of milled magnetite sand and powdered iron in various proportions. Aside from providing a potential means for varying the mu of the mix to specification, there is also the possibility that, in combining the two materials, some synergistic attribute may emerge.

17.0 Experimental Universal Motor with a Metal/Resin Cast Field

The sheer quantity of the iron powder I had rapidly processed and accumulated inspired me to consider it's application to larger castings—and to electromagnetic machinery I would have previously considered unreproducible without the use of sheet metal laminations. I decided to build an electric motor.

Rather than start from scratch—the point of this exercise was to explore the application of a novel magnetic material, not test my skills as a machinist—I decided instead to retrofit an existing motor. A discarded kitchen appliance provided an ideal test subject, a small but powerful universal motor complete with rotor, commutator, brushes, and field electromagnet.

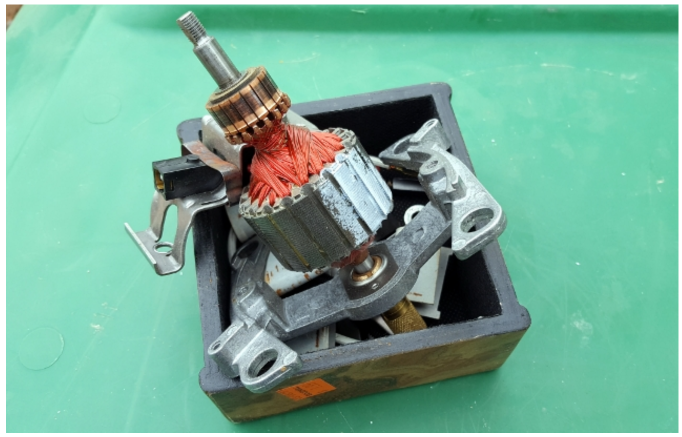


Figure 17a: The rotor, brushes, and bearing supports for a universal motor

I first considered replacing the motor's rotor with an iron-and-resin-mix equivalent. However, without knowledge of the tensile properties of my mix, I was reluctant to fabricate a high-speed rotating structure that might fail catastrophically under the stain of centrifugal force. I decided, instead, to target the much larger field magnet structure. I would replicate the whole of the lamination stack which comprised the core of the field magnets, and constituted the bulk of the motor's frame.

I began by dismantling the motor. All the parts except the field magnet were set aside (Figure 17a). The coils of the field magnet was unwound, with great care taken to count the number of turns removed and to save all the wire removed onto an empty plastic spool. The coil slots had been lined with vulcanized fiber insulator sheets; these were extracted and set aside. This left the field frame completely denuded (Figure 17b).

Figure 17b: This structure, comprised of stamped steel laminations, stacked and riveted together, comprised the physical frame and core for the field coils in the original motor.

Successful fabrication of a field structure from iron and resin would require replication of critical dimensions and shapes. The bore would have to be accurately sized and positioned, as would a set of holes, bored through the lamination stack, that provide for alignment and attachment of the bearing supports at each end of the motor.

I concluded that the best strategy would be to use the motor's original field frame as the "positive" from which to create a mold. My intention was to use silicone rubber as the mold material, which would allow for easy extraction of this complicated shape when the resin had hardened. Since silicone is flexible and "gives," my mold would contain, embedded in it, a rigid registration fixture to assure that the critical dimensions and relationship between the field's bore and mounting holes would be maintained.

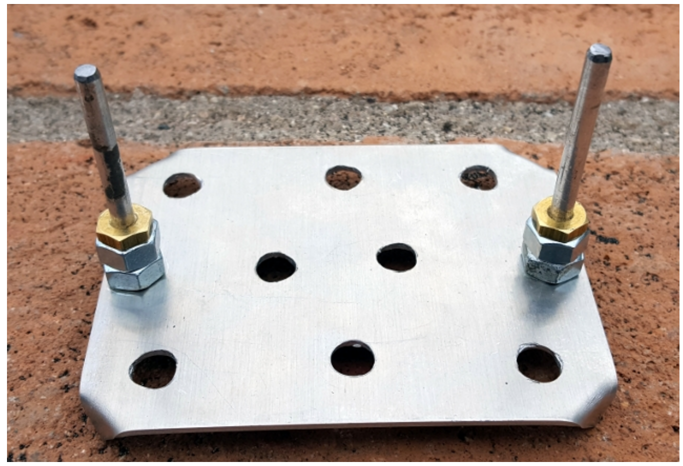


Figure 17c: The registration fixture. The metal dowels are sized and spaced to fit into the mounting holes of the original field frame.

The registration fixture was made from a small plate of scrap aluminum. The corners of the plate were bent down to form makeshift "feet," and numerous large holes were drilled in the plate to allow silicone rubber to flow through and integrate the plate into the mold structure.

I cut two locating dowels from a piece of soft steel rod, threaded one end of each dowel, and attached them to the plate with a series of nuts. The dowels were sized to fit through the mounting holes in the motor's field frame, and spaced accordingly. A stack of nuts at the lower end of each dowel assured that the motor frame, when installed on the registration fixture, would be elevated above the plate. Figure 17c depicts the registration fixture, Figure 17d shows the motor's original field frame seated on the fixture, and Figure 17e shows the field-frame and registration fixture stack seated in the bottom of the plastic container in which the mold would be created.

I have alluded several times to the relative expense of "proper" commercial silicone rubber mold-making chemicals. I'm not alone in this concern, and others have been sufficiently inspired to experiment with clever work-arounds… chemical "hacks," if you will. I stumbled upon one such idea on the Youtube channel of a young woman who made her own molds for casting small resin objects for gifts and jewelry (I was not able to relocate her specific channel for reference here, but numerous videos with comparable content are easy to find). I adopted her technique and applied it this way:

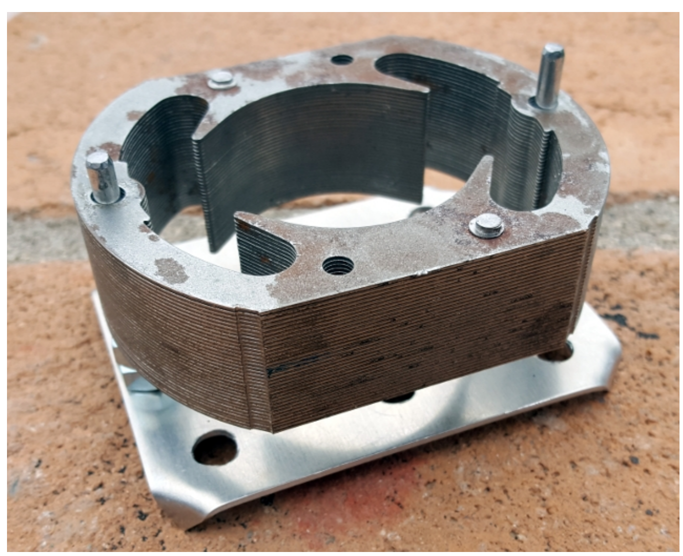


Figure 17d: The field frame resting on the registration fixture.

I started with the purchase of a large plastic mixing bowl, a set of nitrile or similar “rubber” gloves, two cartridges (sized to fit a caulking gun) of 100% silicone sealant, and some blue liquid dish soap.

I filled the bowl with clean water and then, using a caulking gun to dispense the silicone, I emptied the entire contents of the two cartridges directly into the water. Next, I added a teaspoon or two of of the dish soap. I donned the rubber gloves and began kneading the gelatinous silicone blob congealing in the water.

Within a few moments, the silicone became a very compliant putty, which I removed from the water and wadded it into the plastic container holding the registration figure and my motor’s original frame. When the silicone had been forced into every shape and crevice, I added a second, small, aluminum plate to the registration fixture, which covered the field frame and imprinted into the silicone, sharply defining the upper plane of the field frame. See figure 17f.

In 15 minutes or so, the silicone was already beginning to set and would no longer flow. It could be handled and manipulated an hour or so later, though I left my mold to cure for a full 24 hours after that.

Exactly why silicone sealant can be used in this fashion, I don’t know. It has been suggested to me that water promotes the setting process of silicone sealant, and that acetic acid (the vinegar smell associated with many silicone sealants) is actually added to the silicone to inhibit and slow the process. If so, manipulating the silicone sealant in the soap water would serve to wash out the inhibitor,

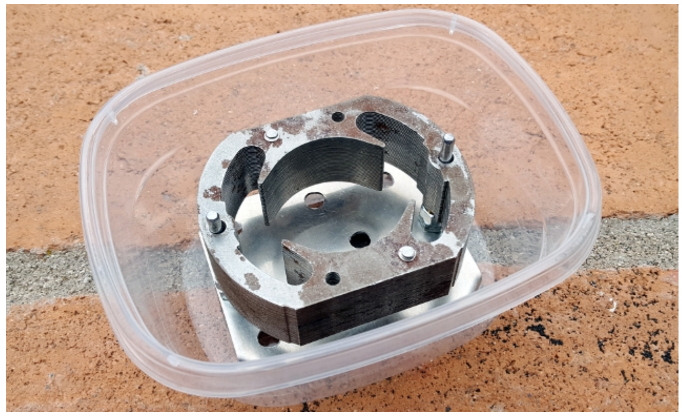


Figure 17e: The field frame and registration fixture in the mold container, awaiting the silicone rubber.

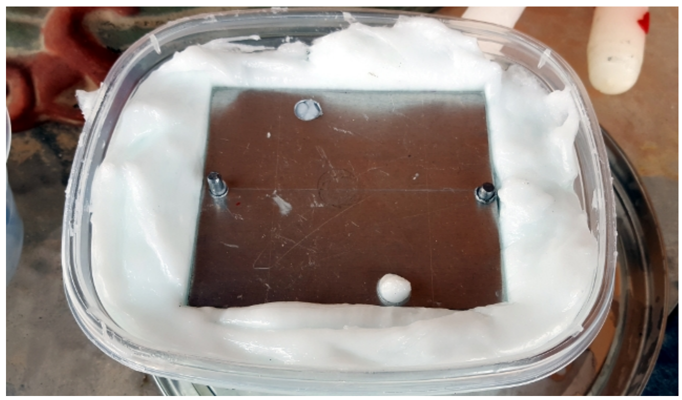


Figure 17f: Here, silicone rubber has been introduced into the container. An aluminum plate helps define the boundary of the upper face of the field frame.

Figure 17g: A newly cast field frame, hardened in the silicone mold.

while at the same time providing ample moisture. The dish soap, which is supposed to be added to the water, may act simply as a wetting agent to improve the washout of the acid, though some individuals specify Dawn™ brand dish soap by name and claim that its glycerin content plays some beneficial role in this application.

Figure 17h: A newly cast field frame, emerging from the mold.

For the record, I have not validated any of these claims or the alleged chemistry. I offer this information only as a starting point from which to conduct your own research.

When the silicone had set, I carefully removed the top aluminum plate from the registration fixture, and then pried out the motor's original field frame. I cleaned the registration dowels and then sprayed them, as well as the entire interior of the mold, with silicone lubricant. The intent of the lubricant is to act as a release agent.

I mixed up a batch of ball-milled brake drum turnings and resin and spooned the slurry into my silicone mold. I was careful to fill the mold only to the level indicated by the impression previously left by the top aluminum plate. I waited 24 hours for the slurry to harden, and then carefully extracted the casting. See Figures 17g and 17h.

I little bit of cleanup was required. I sanded the front and rear faces of the casting with fine-grained sandpaper to remove surface imperfections and assure parallelism between them. I

Figure 17i: The new field frame, cleaned and polished.

also reamed the holes (through which the registration dowels had projected) to a final, proper diameter. The finished copy exhibits a lot of fine detail and is almost indistinguishable from the original (Figure 17i). It even exhibits signs of “laminations” that no longer exist!

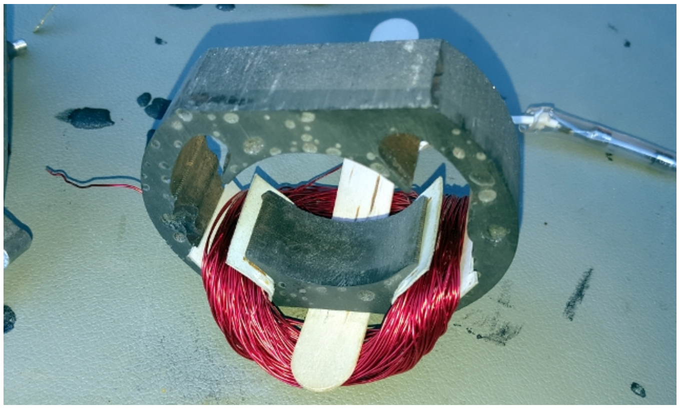


Figure 17j: Rewinding the field coils. This coil is nearing completion.

At this point it was necessary to rewind the field coils. I started by replacing the vulcanized fiber insulators into the coil slots, and then began laying down turns of wire. There is no doubt this process was originally carried out by automated machinery of some type; hand winding is time-consuming and not a task for anyone with dexterity problems.

The use of a wooden tongue-depressor helped to restrain and contour the windings as they were laid down (Figure 17j). In the end, I was able to return 150 (of the original 156) turns back to each of the field windings. I considered this close enough for proof of concept.

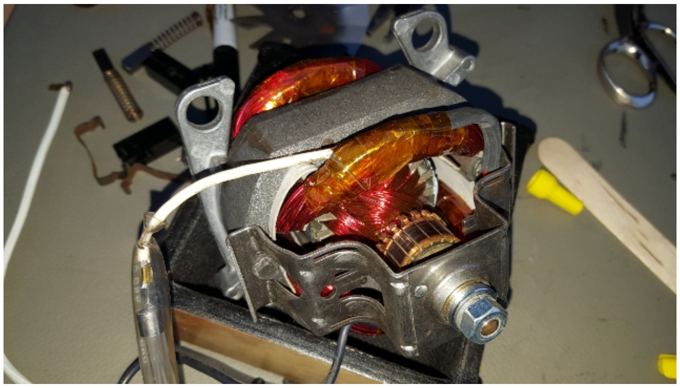


Figure 17k: The reconstructed motor, minus its cooling fan.

I reassembled the motor in its entirely. The rebuilt motor, minus its integral cooling fan, can be seen in Figure 17k.

I ended up mounting the machine to a custom “test stand” of sorts, complete with cooling duct, finger guards, proper shields and properly grounded wiring. See Figure 17l.

The modified motor runs vigorously and, when in operation, it sounds like a vicious little jet turbine.

Figure 17l: For demonstration purposes the motor was mounted to a “test stand,” complete with finger guards, shields, and properly grounded wiring.

18.0 Experimental Alternator with a Metal/Resin Cast Armature

18.1 Design and Assembly

Given the success of the iron-and-resin mix in the construction of a motor, it seemed natural to attempt the inverse—build an alternator. This machine would be built entirely from scratch.

The alternator depicted here is not based upon any preexisting design, at least none that I am consciously aware of.

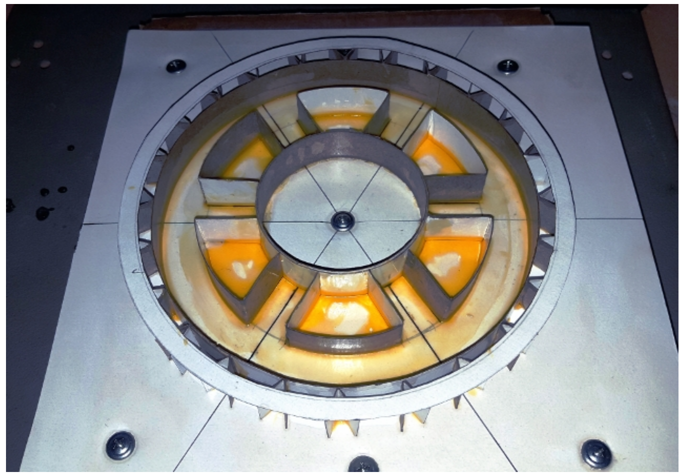


Figure 18a: A cardboard mold defines the shape of an experimental alternator's stator.

Development started with a sheet of notepaper and freehand sketches of something that “should” work. Again, because of the unexplored tensile properties of the resin mix, I designed a machine with a permanent magnet rotor and a 6-pole stator. As in the case of the motor field-frame project, the cast stator in my alternator would function not only in an electromagnetic capacity, but as a structural element for the machine itself.

The mold used to cast the stator was fabricated from cardboard and carpenter’s glue. Using sheet metal screws, I attached a clean sheet of cardboard to an old wooden cutting board (to provide structural rigidity). Using a compass and other drafting tools, I laid lines for the desired stator geometry directly onto the face of the cardboard.

Strips of cardboard were glued edge-wise to the base sheet, so as to form the mold’s walls. Numerous small V-shaped pieces of cardboard were installed to buttress and reinforce the walls. A cardboard ring was glued on top of the buttresses to further stiffen the mold structure. These details are visible in Figure 18a.

I revisited all of the seams—multiple times—to apply additional glue. This was not only to assure that the seams would be liquid-tight, but to encourage the growth of fillets. I judged that radius-ed seams would be preferable to sharp corners, and might facilitate extraction of the cast stator from the mold, later.

Figure 18b: The stator mold, filled with processed-brake-turnings-and-resin mix.

Speaking of mold-release, I painted the interior of the mold with polyurethane vanish. This, I reasoned, would prevent resin from soaking into the cardboard, and would hopefully allow for a clean extraction of the finished stator. I later decided that a urethane coating was not enough. I melted some old candles in a double boiler and painted liquid paraffin on the interior surfaces of the mold with a small brush. This turned out to be a very good idea.

The stator was cast with the usual mix of milled brake drum turnings and resin (Figure 18b). When the finished stator refused to pop free of the mold, I warmed the mold gently with a heat gun. This reduced the paraffin coating to a liquid, and the finished stator came out (Figure 18c).

Figure 18c: The finished stator, as extracted from the mold.

The next item of business to address would be the creation of electromagnets for the stator's poles. My plan was to fabricate a set of bobbins from cardboard, wind and test them separately, then install the finished coils on the stator.

The need for multiple coils and uniformity inspired the fabrication of a combination mandrel and assembly aid. This consisted of a steel bolt and three pieces of wood. One piece was sized and shaped to reflect the bore of the desired bobbin/coil, the other two were sized to define the bobbins' flanges (Figures 18d, 18e, and 18f).

For quality-control purposes, the finished bobbins were test-fitted to the stator (Figure 18g). Then they were removed, stained brown, and dipped in polyurethane varnish.

The coils were wound on the bobbins with the aid of a makeshift winding rig, cobbled together as follows: An empty bobbin was loaded onto the mandrel (just described). The mandrel was chucked in my rechargeable drill motor, and the drill motor itself was gently clamped into the jaws of a bench vise. Thus, with one hand, could pull the trigger, run the drill and moderate its speed while, with the other hand, feed wire evenly onto the bobbin (Figure 18h).

A short length of rubber refrigeration hose was used as a flexible coupler to join the rotating mandrel with a mechanical counter. By noting the start and stop figures on the counter, I could assure that the same number of

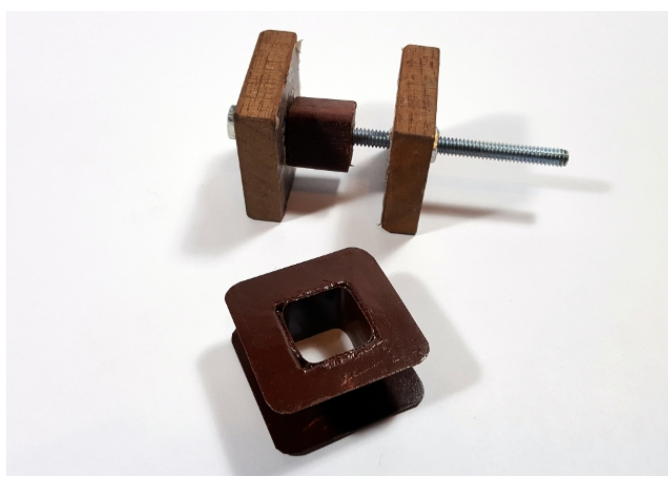


Figure 18d: Fabricated from three pieces of wood and a long steel bolt, this combination mandrel/assembly aid assists both in the production of the empty bobbins, and in the coil winding process, later.

windings would be applied to every bobbin. An example of a finished coil can be seen in Figure 18i.

The finished coils were pressed onto the stator poles and remained in place through simple friction. I later drove some thin wooden wedges into the gap between stator-pole and coil-bore which effectively locked the coils into place (Figure 18j).

The next item of business was the construction of a rotor. Its physical details are best communicated through the CAD model in Figure 18k. At the center of the rotor is a six-faced, soft-steel hub. A cubical neodymium magnet was installed at each face of the hub. The cube magnets' poles were arranged radially (one pole toward the hub, the other pole toward the periphery) and the exposed pole faces were alternated to as to present North, South, North, South, and so on (Figure 18l).

The hub and magnets were sandwiched between two aluminum end plates, and shaft flanges served to lock the rotor assembly as a whole to the alternator's drive shaft.

During assembly of the rotor, before the end plates were screwed tight to clamp the whole thing together, the cubical magnets were bonded with epoxy on three faces: To the rotor hub, and to each of end plates. It was my estimation that the shear-strength of the adhesive bond between the magnets and the flanges would be greater than the centrifugal forces likely to be encountered.

Finally, a fashioned a front and rear plate for the alternator. Each was crafted from 1/8th-inch aluminum, ventilated with a circular pattern of

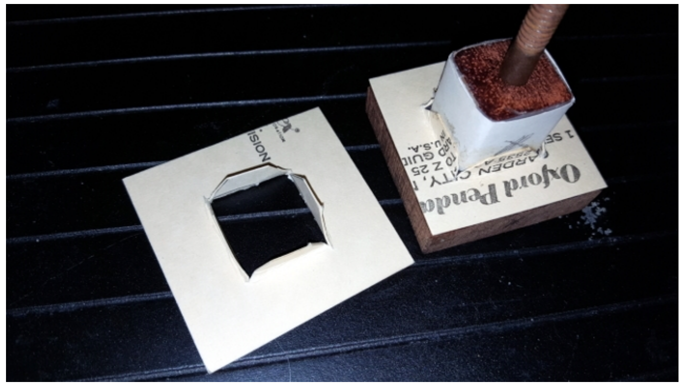


Figure 18e: A flange being added to a cardboard coil bobbin. The mandrel/assembly fixture assures proper dimensions and shape.

Figure 18f: A cardboard coil bobbin nearing completion.

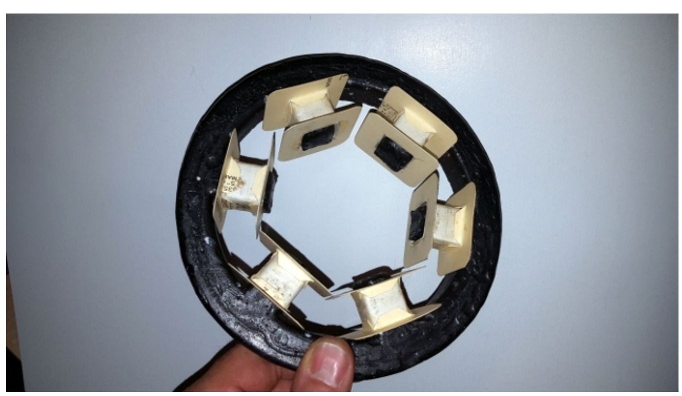


Figure 18g: A complete set of cardboard coil bobbins are temporarily installed on the stator to test for proper fit.

holes, and fitted with a flange-mount ball-bearing assembly, sized to fit the rotor shaft.

The alternator is assembled as a stack, front and rear plate at each end, and the stator sandwiched in the middle. Six sections of threaded rod pass through the stack and hold it together. Spacing between the stator and end plates is establish with washers, nuts, and aluminum stand-offs. The relationship between components can be seen in Figure 18m.

18.2 Initial Testing

Testing of the alternator required the fabrication of a test stand or fixture of some sort. I needed something physical to mount the alternator to, and I needed some source of rotational power to turn the alternator's shaft. An early version of my test stand appears in Figure 18n.

I fashioned a wooden base with two parallel aluminum mounting plates—one to which the alternator was mounted, and the other, a surface to mount an electric motor. The shafts of both machines met in the space between the mounting plates, and a jaw-type shaft coupler was used to join them. Since I had just finished the motor experiments describe in section 17.0, I thought it a clever idea to employ the motor I'd just built to drive the alternator in this series of experiments.

I immediately ran into difficulties, not with the alternator as such, but with the test stand.

First, there were endless problems with alignment and vibration. That was ultimately addressed with careful (and very time-consuming) attention to the

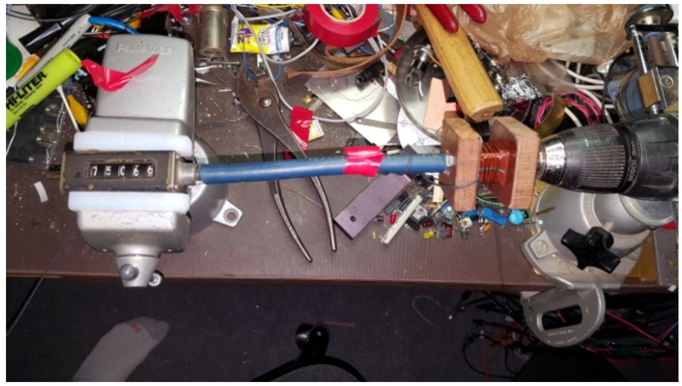


Figure 18h: The stator coils were wound on this makeshift winding machine. A rechargeable drill motor, clamped in a bench vice, rotates a bobbin held in a mandrel. A mechanical counter keeps track of the the number of turns laid down.

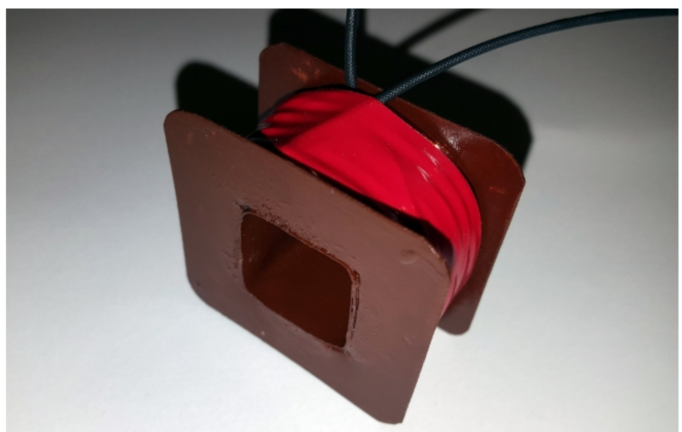


Figure 18i: An example of a finished stator coil.

Figure 18j: Finished rotor coils installed on the stator.

adjustment of the motor, alternator, and mounting plate fasteners to assure the best possible parallelism and concentricity in their respective shafts.

Next, I had motor problems. The motor I had fashioned in Section 17.0 certainly worked, but it spun far too fast for this application. I ordered a Chinese-made TRIAC-based motor speed control board, sourced from Ebay. It was cheap, and technically speaking it functioned, though the components used were woefully undersized for the power rating the sellers had claimed.

At this point I was able to spin the alternator on the test stand, and do so at a moderate speed. I observed voltage present on the the alternator's windings, so I knew it was working. Unfortunately, whenever I applied a load to the alternator (a bank of incandescent lamps), the whole affair would bog down. The motor was clearly undersized for the task at hand.

Coincidentally, I had purchased a new "wet/dry" vacuum cleaner to replace an aged one that was slowly going to pieces. I rescued the old one from the trash, dismantled it, and extracted its motor. It was substantially larger than the modified appliance motor I'd been trying to use. I modified the test stand and installed the larger motor.

18.3 Catastrophic Disaster and Recovery

With the new motor in place, I set out to resume testing of the alternator. Now the marginally-designed Chinese speed controller was giving me problems. The undersized TRIAC with undersized heat sink was apparently getting too hot.

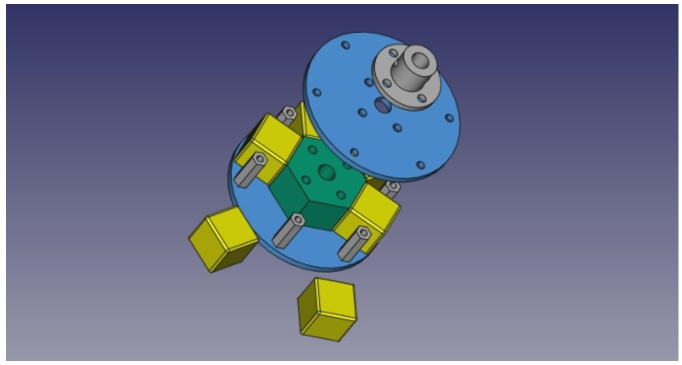


Figure 18k: The rotor is comprised of six rare-earth magnets and steel hub sandwiched between two end plates. Flanges couple the rotor assembly the rotor shaft.

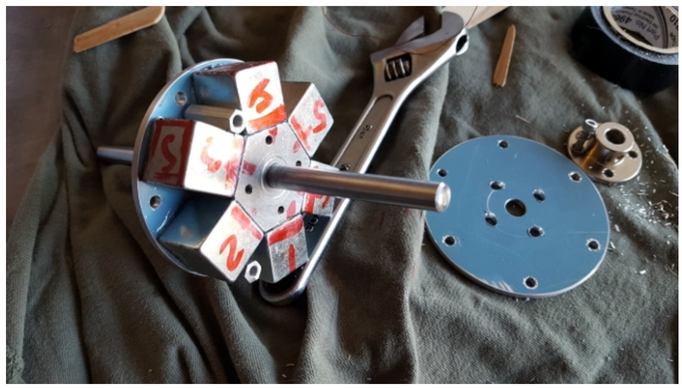


Figure 18l: A photo of the rotor being assembled.

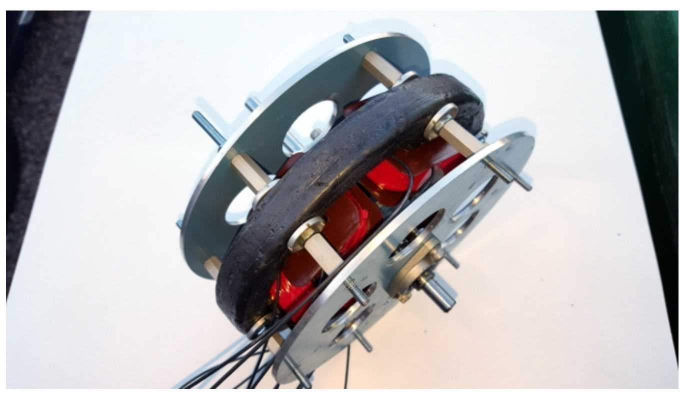


Figure 18m: The alternator nearing completion. Visible is the stator with its coils, the end plates with shaft bearings, and the threaded rods and spacers that hold everything together.

Since I've never had occasion to overheat a TRIAC before, I was unaware that the failure mode is full-on conductivity. One moment, the test stand was running at a reasonable speed. Then, without warning, the motor revved like a motorcycle, the alternator spooled up to a frightening speed, and before I could yank the power plug, BANG. The alternator had exploded. Debris flew everywhere.

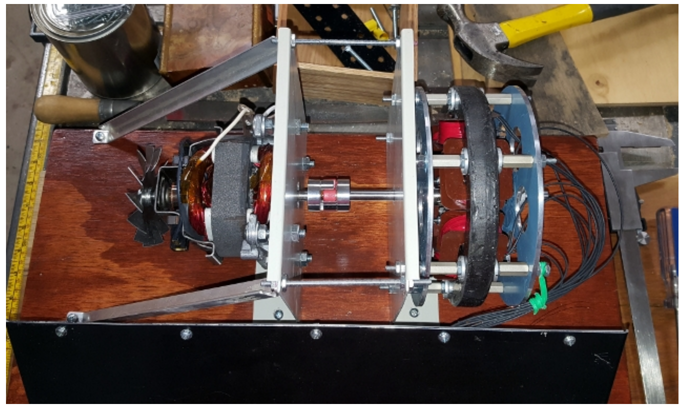


Figure 18n: The first version of the alternator test stand. On the right is the alternator, on the left is the motor described in Section 17.0. That motor ultimately proved to be too small for this application and was replaced with larger one.

A post-mortem revealed that the over-speed condition (caused by the failed TRIAC in the speed controller) had subjected the rotor magnets to severe centrifugal forces. These forces exceeded the shear-strength of the epoxy-and-flange interface. One or more magnets slipped, radially, outward, and contacted a pole face. This led to domino-like effect of shifting, jamming, and wedging components which, driven by rotor inertia, blew the whole thing apart. I was struck in the hand by a dime-sized fragment of stator. Pieces ricocheted off the ceiling and walls of my garage. One of the coil bobbins, with a streamer of copper wire flailing behind it like the tail of a comet, landed ten or fifteen feet away in the driveway. This is one of those occasions where I was glad that it's my personal policy *always* to wear safety glasses when I work. See Figures 18o and 18p.

Figure 18o: The first alternator exploded and essentially gutted itself.

Initially, this turn of events was as devastating to my motivation as it was to the hardware. I had invested a lot of time in the construction of the alternator, and now it was all in ruin. I didn't feel much like starting over, and I was about to walk away from the whole mess. I put away my tools away and started to sweep up the wreckage.

However, as I cleaned up, I found I had recovered all of the major chunks of the stator. An absurd thought came to my mind. Was this damage repairable? See Figure 18q.

Using a Dremel™ tool with a grinding bit, I attacked the broken faces of all of the stator fragments. The purpose here was to make sure that the faces were clean and free of cracked or crumbly pieces. I also wanted to remove some material to widen the gap between adjacent fragments of stator.

Next, I set up the cardboard mold again—the one used to cast the stator in the first place—and repainted the interior with a fresh coat of melted paraffin. Through trial and error, I fitted the stator fragments into the mold, reassembling the it, jigsaw-puzzle-style.

I mixed up a fresh batch of brake drum turnings and resin, and spooned the material into the gaps separating the broken fragments of stator. When the fresh resin had hardened, to my joy and amazement, the stator came out of the mold in one piece! The repair was seamless and I could not identify where fractures had previously existed.

Encouraged by this, I shifted attention to the failed rotor. It had gone to pieces. One magnet was missing, another was fractured and unusable. Luckily, four magnets were still in usable condition, and when I originally ordered the magnets, I'd had the foresight to order a couple of spares "just in case."

I reassembled the rotor, pretty much as before, but with one significant change. As visible in Figure 18r, the rotor was encircled with a belt of 3000-PSI stainless steel. The belt was cut from a section of stainless tubing I had lying about. As good stainless steel does not show much by away of magnetic behavior, it seems to have no deleterious effect on the function of the rotor. The only downside to the addition

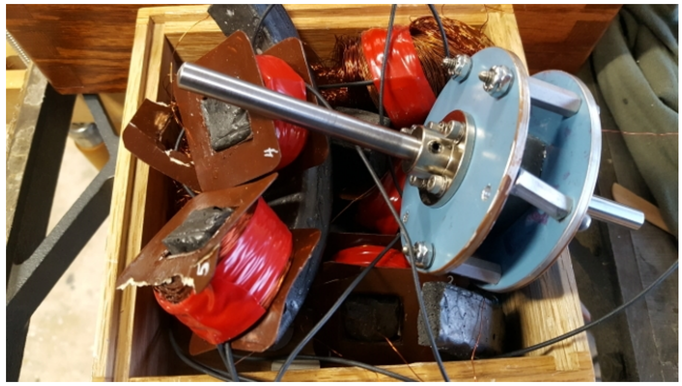


Figure 18p: Wreckage from the failed alternator. The damage was severe.

Figure 18q: Failure of the alternator resulted in complete destruction of the stator. Remarkably, this level of damage was still repairable.

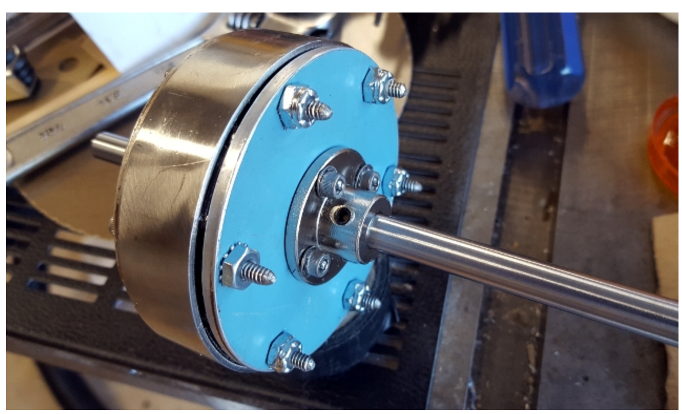


Figure 18r: An improved rotor. A belt of stainless steel contains the magnets.

of the belt is that its presence increases the effective gap between the magnets and the stator coils.

Not content merely to repair the rotor, I wanted to proof it. I temporarily reassembled the alternator (without stator coils) and set up the test stand behind a short brick wall, adjacent my garage. I covered my test stand with two sheets of old plywood, a packing blanket, and some other creative “ballistic” shielding. From the safety of the far side of the brick wall, I plugged in the test stand and ran it to full speed. The sound was disconcerting, but I left things running at that extreme rate for several minutes. The new rotor held, and I certified it as safe.

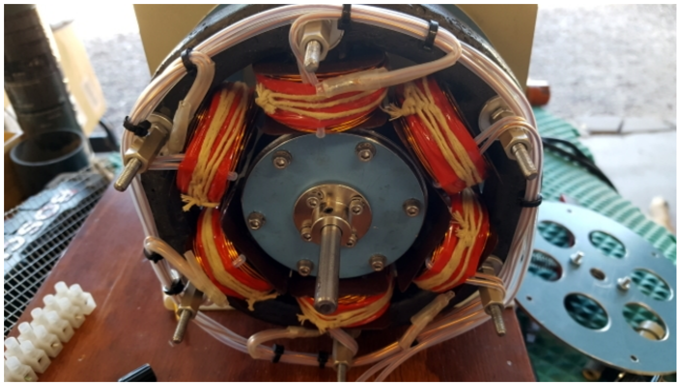


Figure 18s: The resurrected alternator takes shape. The improved rotor (center) is nestled in the repaired stator and its fresh set of coils.

It was time to replace the damaged stator coils. Luckily, in fabricating the first set, I had produced a number of spare bobbins. These were quickly stained, polyurethaned, and wound. They can be seen installed in Figure 18s.

Another modification I made in the interest of safety was to wrap the body of the alternator in quarter-inch hardware cloth. I have no reason to suspect that rotor disintegration is still a possibility, however, I thought the steel mesh was a worthwhile attempt at containment, if needed. (Figure 18t).

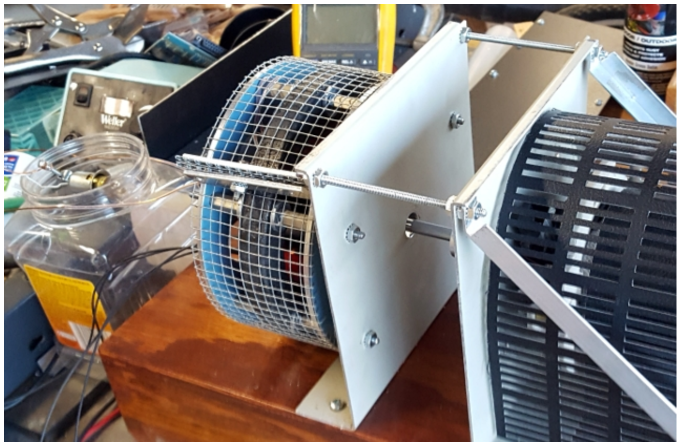


Figure 18t: Improvements to the rebuilt alternator (left) include this nod to safety: a wire-mesh containment net, intended to help confine internal parts in the event of another catastrophic mechanical failure.

The motor control board was also reworked. I removed the old TRIAC and replaced it with a part with roughly twice the the current-rating I thought I’d need. The new part was physically larger than the original, which improves its ability to transfer heat, and I have it fastened to substantial heat sink. (Figure 18u). Since this upgrade, the TRIAC runs cool and I have observed no anomalous electrical behavior in the controller, whatsoever.

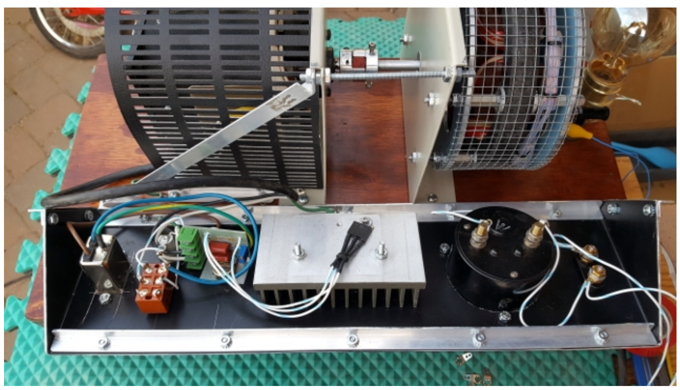


Figure 18u: The motor controller was upgraded with a better TRIAC and much larger heat-sink.

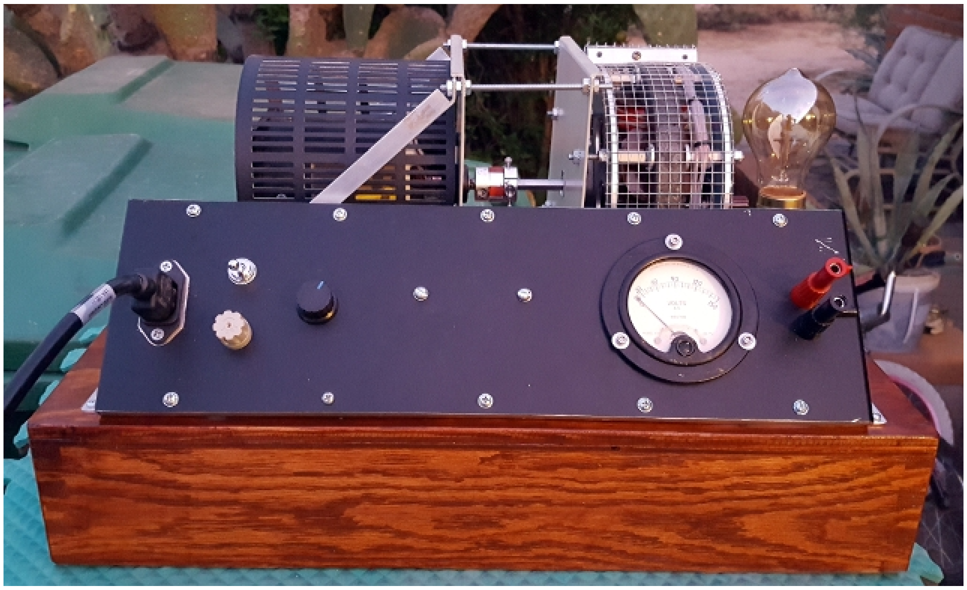


Figure 18v: The final version of the alternator test stand. At the rear (left) is the drive motor. At rear (right) is the improved alternator adjacent a 60-watt incandescent load. In the front is a control panel with a power switch, motor speed control, an AC voltmeter, and binding posts to which external loads or instrumentation can be connected.

Figure 18t shows the finished test stand with drive motor, alternator, motor speed control, and a default incandescent load of 60 watts. An on-board volt meter allows you to monitor the output of the alternator and, if necessary, tweak the motor speed to keep voltages reasonable.

At the risk of being accused of puffery, I think the performance of this model is exceptional. While the default load on the test stand is only 60 watts, at one point I had daisy-chained an additional 7 lamps, for a total of 480 watts. Half-kilowatt-class performance from a machine whose core was fashioned with discarded brake-drum turnings and resin is, in my mind, astonishing.

My only criticism of the machine could be rectified with two design changes.

First, this machine needs a more substantial rotor shaft. It was built using an 8mm shaft I happened to have on hand. Were I to repeat this build I would use nothing less than a 10mm shaft, and would prefer something more on the order of 12 mm.

Second, because the rotor and stator have the same number of poles, and the magnets are very strong, the machine exhibits some cogging at very low speeds, and a tendency for rotor lock when parked. In retrospect, a better design would have the same 6 magnets in the rotor, but 9 (or more) poles in the stator. I think this could go a long way to minimizing the cogging and eliminating the difficulty in getting a parked rotor into motion. I would connect the coils to create a 3-phase Wye.

20.0 Conclusion

In the wake of the experiments described in the preceding pages, it's worth asking what conclusions can be drawn.

First and foremost, it should be conceded that magnetite sand is not comparable to, or a direct replacement for, any commercial ferrite or powered-metal core offering. In fact, at least where permeability is concerned, it is arguably inferior. Thus the operators of Palomar, Fair-rite, Magnetics, and similar manufacturers can sleep soundly. My desert-wash-sand and liquid plastic concoctions will not disrupt the industry.

However, that does not mean that this material or the processes described in this paper are without utility or merit. To the contrary:

- Magnetite sand is plentiful at my location and is quite literally "dirt cheap." It's easy to collect and to refine to a high-degree of purity. If not found locally, experimenters can purchase it at reasonable cost through the Internet.
- The samples I played with appear to be essentially non-conductive. I expect magnetic structures fabricated from it to have negligible eddy-current losses.
- Microwave oven tests suggest low hysteresis losses.
- I did not observe saturation in the samples I tested or in the devices I fabricated.
- In many cases, the magnetite sand's comparatively low mu can be compensated for in device design by changing core dimensions or adding more turns to coils.
- Bar antenna experiments demonstrated possible application to low-power LC circuitry like receiving antennas and tuning circuits, at least through the HF range, but possibly higher.
- The Joule thief experiment demonstrated possible application to low-power switching circuitry.
- The FET oscillator experiment demonstrated possible applicability to low-power RF circuitry, at least over the HF range.
- Other experiments showed possible application to pot cores and transformers.
- Large magnetite-sand bar antennas might possibly be engineered to function as compact transmitting antennas.

The introduction of milled brake-drum turnings to the resin mix only adds to the possibilities just summarized.

- Given the higher mu of the cast-iron brake-drum turnings, toroids can be fabricated with performance approaching commercial offerings.

- Experiments with the brake-drum-turnings-and-resin mix suggest possible application to magnetic devices for use in switching power supplies or to the fabrication of audio output transformers.

- The electric motor experiment demonstrated possible application of the brake-drum material to the fabrication of electromechanical parts, like the field-frame of small motors.

- The alternator experiment demonstrated the potential application of the brake-drum resin mix to the construction of higher-power (one-half kilowatt) devices, like alternators. Conversely, the same structure might form the basis for an electronically-switched, brushless DC motor.

In general, the technique of combining a powdered or granular magnetic material with a liquid plastic resin (as described in the preceding pages) allows for the fabrication of all sorts of magnetic components, including those requiring complex shapes. I demonstrated the fabrication of bars, toroids, adjustable loop sticks, pot cores, cast transformers, electric motor components, and a 6-pole stator for a half-kilowatt alternator.

There appears to be *substantial* opportunity for additional experimentation, based upon the ideas set forth in this paper. I would be very interested in feedback from individuals who endeavor to explore these ideas furthe**r.**