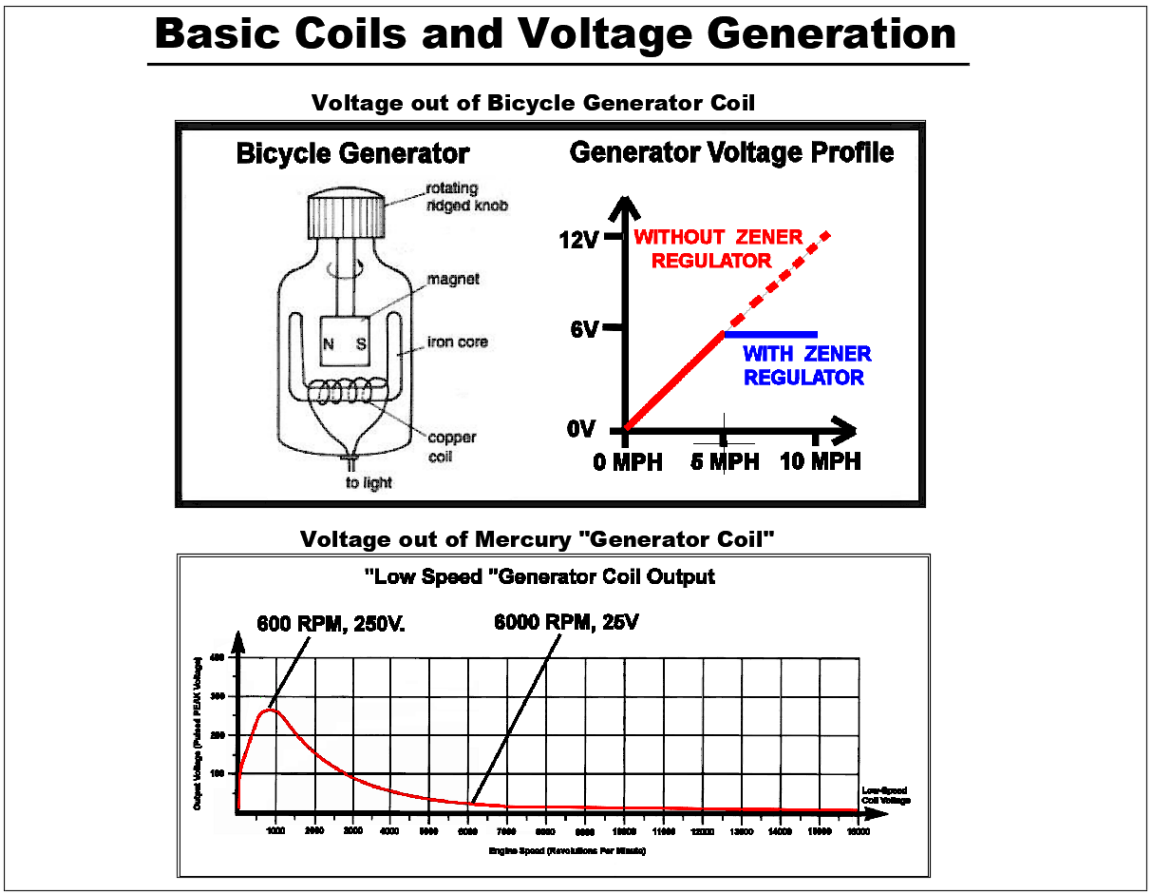
Generator Coils Explained: A "Piping Analogy"

Generator_Coils Explained.DOC W. Mohat Rev. 1.0 Dec. 19, 2020

In a recently published article on the early Mercury "Phase Maker" CDI ignition, I attempted to explain how Mercury's "generator coils" could produce their own voltage regulation, without any external parts. Apparently, my explanation was inadequate, as I have received considerable feedback indicating that this idea just doesn't make any sense.

To anyone that ever had a generator on their bicycle, they KNOW that the output voltage increases the faster you spin the generator. Without some kind of voltage regulator (bicycles usually use a zener diode), the voltage would continue to rise, until it blows your bicycle lights out....(red trace). WITH the zener voltage regulator, the voltage is clamped at 6V, protecting your light bulbs. See below for details:

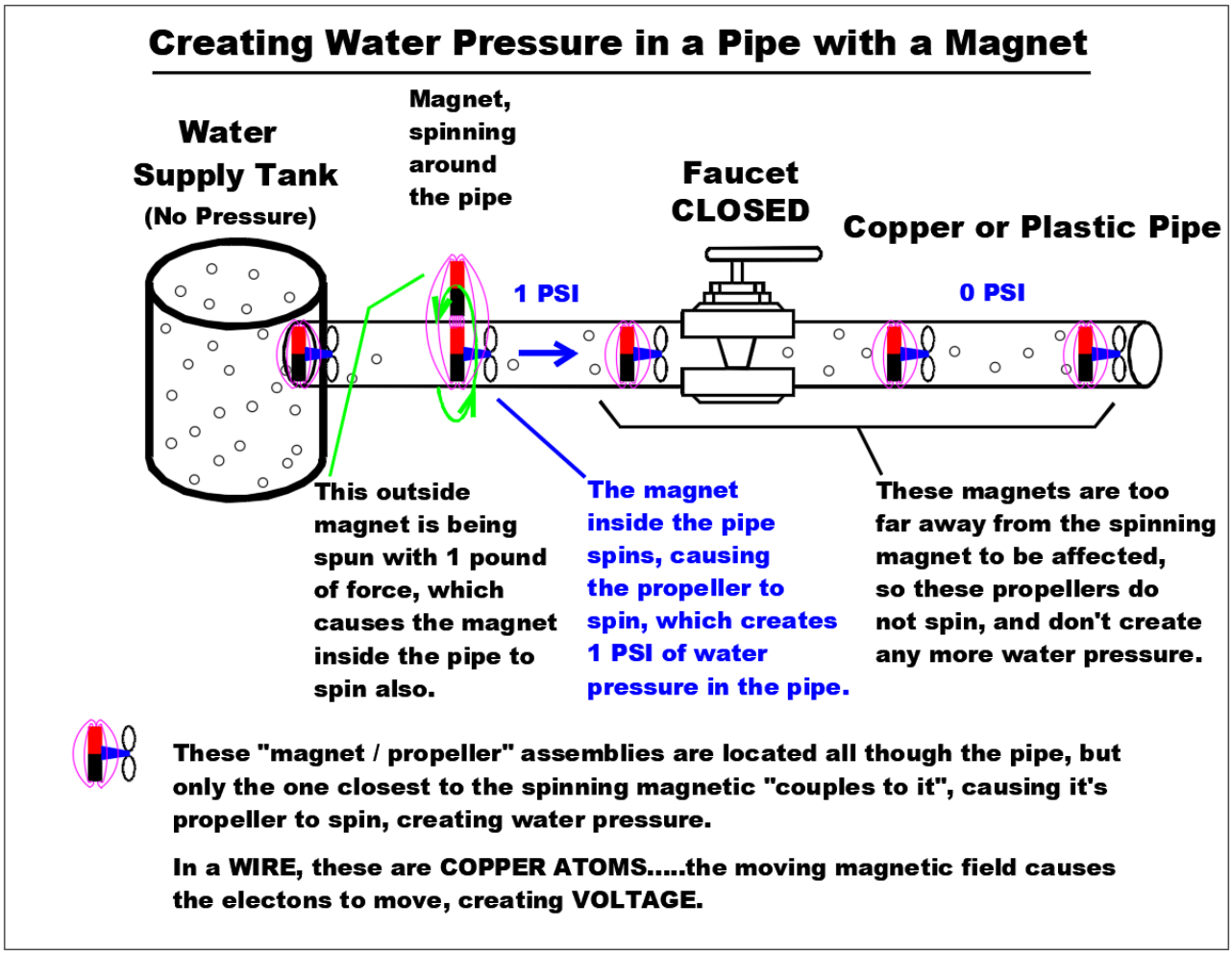


Then, along comes Mercury, claiming that the coils in their generators rise up to a peak at a specified RPM, then automatically limit (then reduce) their output voltage, without any external circuitry whatsoever. (See the lower diagram, above)

This is OBVIOUS bullshit from Mercury. Or.....is it? Is it possible to build a coil such that it's output self-regulates? Is there some kind of tricks or "conditions" Mercury is exploiting, to get this behavior? It turns out there IS.

However, (as I have learned), trying to explain electrical engineering terms to non-engineers is a bit of a challenge. It's often better to use a "mechanical analogy" of some sort, to explain concepts in terms that our "backyard mechanics" find more familiar. So, with that in mind, let's start by trying to explain how you can get a spinning magnet (in a flywheel) to create PRESSURE in water inside a water pipe. (Screwy, but stick with me here.)

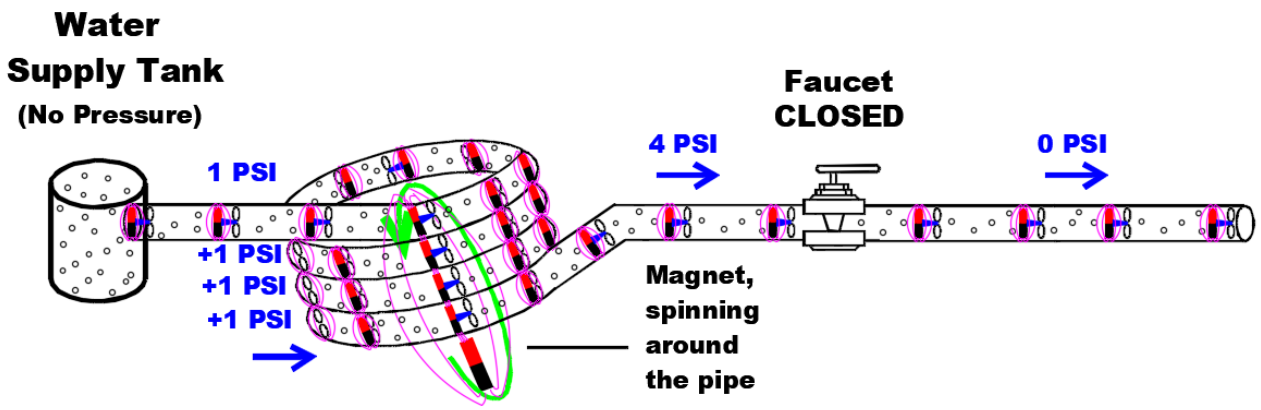
Let's begin by imagining that inside this water pipe (made of brass or plastic, so it doesn't block magnetic fields).....inside the pipe we have tiny propellers, positioned every inch or so inside the pipe. These propellers are connected to tiny magnets, and will spin if the magnet spins. We then add a spinning magnet **outside** the pipe.....and....(See the picture below for details): Note that the note that the EXTERNAL MAGNET'S field only affects the magnet / propeller assembly right next to it, and does NOT affect the other assemblies further away. Again, see below for details!



Magnets push electrons around in a wire....here we have magnets pushing water around in a pipe**. Note that the faster you spin the magnet, the more water pressure you get.....just like you get more voltage in a wire when a magnet spins by faster.**

Now, (you say)....this is a straight pipe. Mercury is talking about COILS....and we all know that COILS produce more voltage**. And, the more WINDINGS (turns) you have in a coil, the more voltage output it produces.** How does my "plumbing" analogy hold up to this? Well, see below!

Increasing Pressure in our "Water Generator"



To increase our output pressure (in P.S.I.), we can either:

1) Increase the number of loops in our generator coil

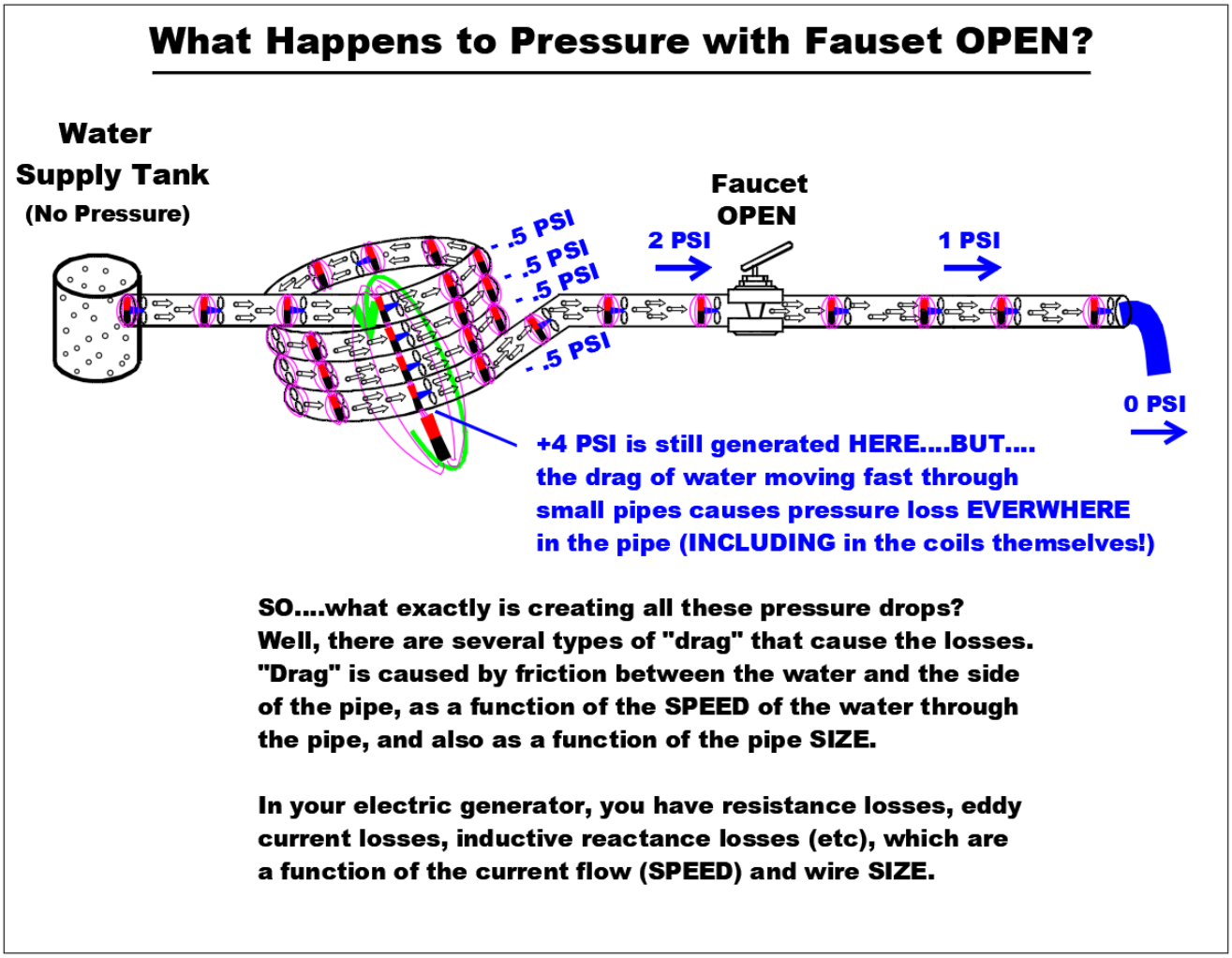
OR:

2) Spin the magnet faster. (OR, do BOTH !)

Note that in an electrical generator, increasing the number of "turns" in the coil, or spinning the magnet faster ALSO increases output VOLTAGE.

Here, the more "turns" we have, the more pressure we create in the pipe. Double the number of "turns", and you double the pressure. Follow me so far?

NOW NOTE: our "faucet" is closed here, ...there's no water moving. UPSTREAM of the faucet, we see pressure.....but DOWNSTREAM of the faucet, we don't. What happens when that faucet opens, and water starts to flow in the pipes? See the next page for details!



Here, we see that when water flows quickly, that "drag" causes pressure losses through the pipe. The longer the pipe, the more the losses. And, (a KEY CONCEPT here)**....there's a LOT OF PIPE in that "coil".** Before the faucet was opened, the COIL was producing 4 PSI (with NO LOSSES IN THE COIL.) But**, if the water is flowing FAST, the DRAG inside the coil drops half of the pressure, even before it gets out of the coil.** Further down the pipe, the "drag" created addition losses.

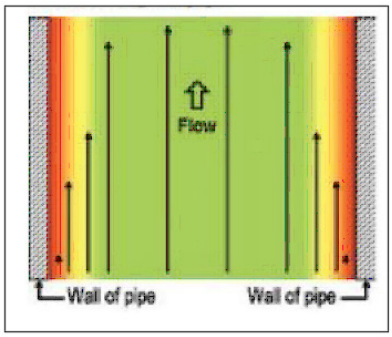
We instinctively understand this. The longer a pipe in our house, the more the water pressure drops when we try to get a high flow rate. (Or, if you're in the shower, and someone flushes a toilet, increasing the flow in the COLD WATER PIPE, increasing the DRAG, and reducing the cold water PRESSURE.....resulting in you getting scalded with hot water. I'm sure we have all personally experienced this!

So, "drag increases with flow" in a pipe. But.....there are some KEY IDEAS about "DRAG" and "PRESSURE LOSS" that we need to understand a bit better.

See the next page for details on "drag" in pipes, and key issues involved in that area.

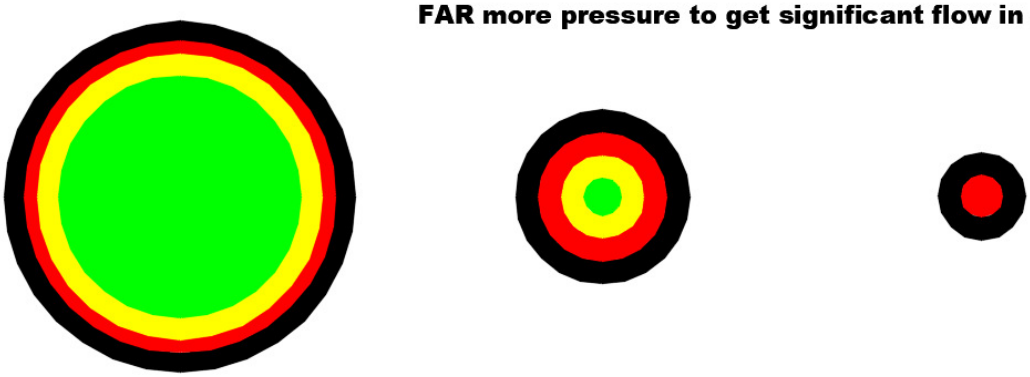
As stated on the prior page, PRESSURE LOSS is a function of FLOW RATE, and the SIZE of the pipe. (Obviously, a tiny pipe will have a lot more "pressure loss" than a large pipe, at the same flow rate.) But, let's look at that closer:

Looking Closer at Drag (and Pressure Losses)



Water flowing in the center of the pipe flows freely. Water flowing next to the wall of the pipe encounters friction, creating turbulence that greatly slows down the flow. The closer to the side of the pipe, the more drag, and the slower the flow.

Large pipes have a lot of area for water to flow quickly. Smaller pipes are far more restricted, and tiny pipes have very little capability for water flow. It takes FAR more pressure to get significant flow in a tiny pipe.

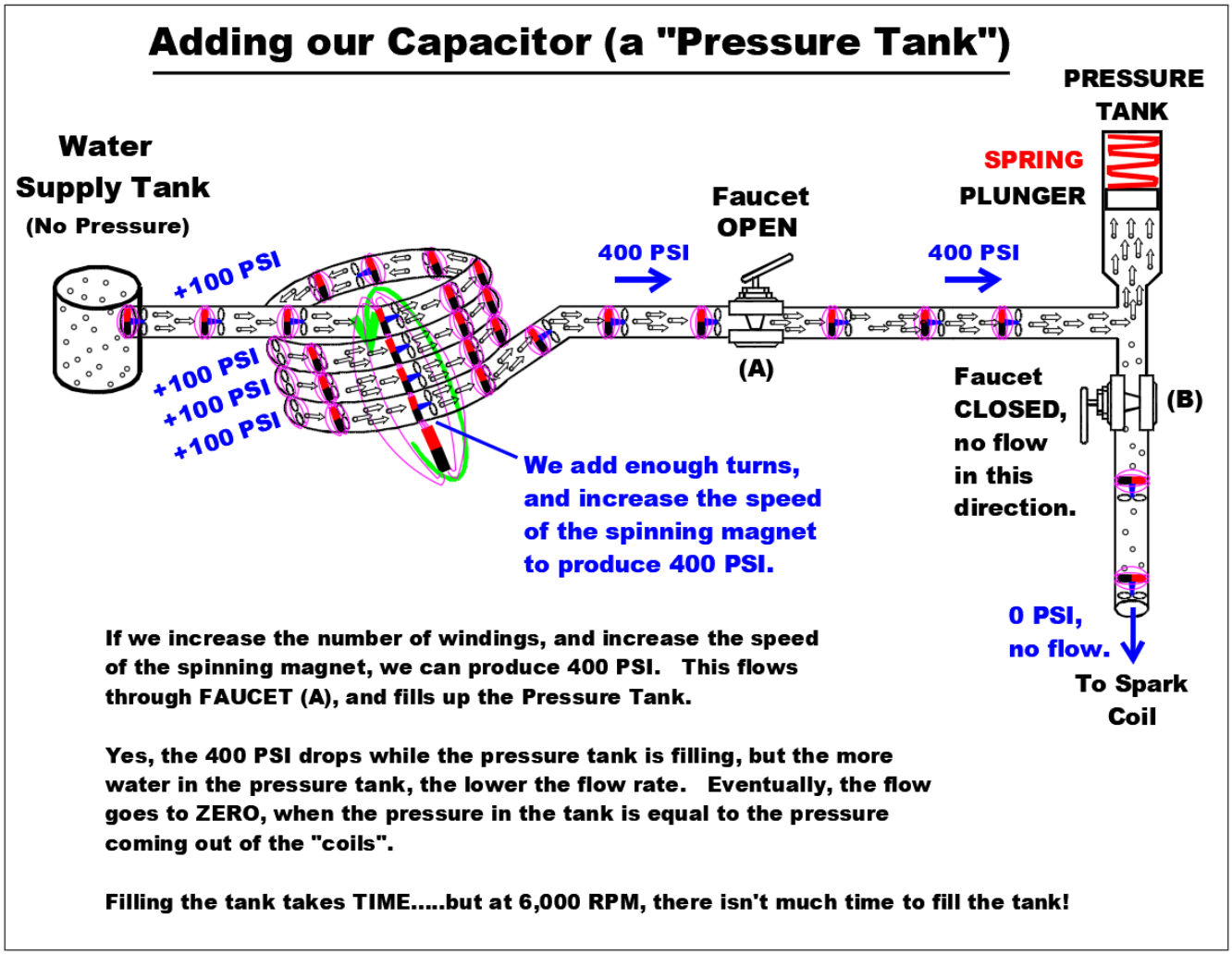


NOTE: For a given size (NOT changing the diameter).....DRAG increases as the SQUARE of the FLOW RATE. If you try to increase the flow by a factor of 10, your DRAG increases by a factor of 100.....so you have to PUSH 100 times as hard to only get 10 times the flow rate.

As this picture describes, DRAG increases as the SQUARE of the flow rate. To increase the flow by a factor of 10, you have to increase the PRESSURE by a factor of 100....(to overcome the increase in the drag.) This is a KEY CONCEPT, that Mercury took advantage of!

Now, in the "Phase Maker" CDI ignition, the "flow" of electrons was used to QUICKLY FILL a capacitor to a high voltage, in a short amount of time. Can our "plumbing analogy" handle this?

Recall from my earlier discussion that a "anti-hammer tube", or "pressure tank", can simulate the behavior of a capacitor. So, let's add a capacitor (i.e. "pressure tank") to our drawing, and see how this changes things.



In the picture above, we have added our PRESSURE TANK (to simulate the capacitor in the Phase Maker ignition. And, we have added another pipe, that will allow the "capacitor" to empty out to our spark coil.....when faucet "B" is closed.

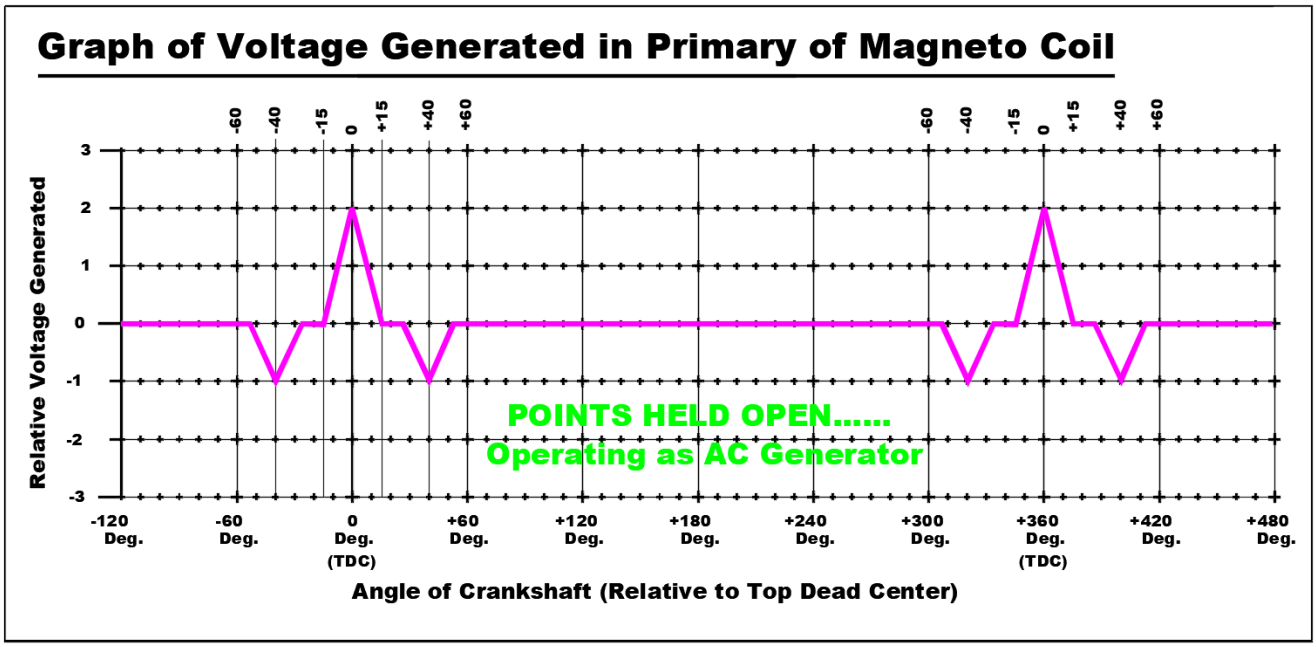
SO.....when running, Faucet "A" opens....then the magnet spins around our "coil", creating pressure in the pipe. With faucet "A" open, and faucet "B" closed, the only place for the water to go is inside the "pressure tank". As water is forced into the tank, the "plunger" rises, compressing the spring. The more water we force in, the higher the pressure in the pressure tank.

Eventually, the pressure in the tank becomes the same as the pressure coming out of our "generator coil", and the flow stops. If the magnet stops causing the propellers to spin, the pressure in the coil would drop to zero....and the pressure in the "pressure tank" would then force all the water BACKWARDS through the coil, and back into the supply tank. So, we have to time the opening and closing of the faucet with the spinning of the external magnet.

In our actual ELECTRICAL system, the flywheel magnet spins past these "generator coils" very quickly, producing voltage for only a SMALL fraction of a second. For the rest of the flywheel rotation, the magnet is NOT NEAR THE COIL, and no voltage is being produced.

SO.....in the REAL system, the magnet "spins past" the coil periodically, producing narrow pulses of high voltage. And, when the magnet is NOT moving past the coil, the coil produces NO voltage. This creates a series of narrow high-voltage "spikes", that repeat periodically.

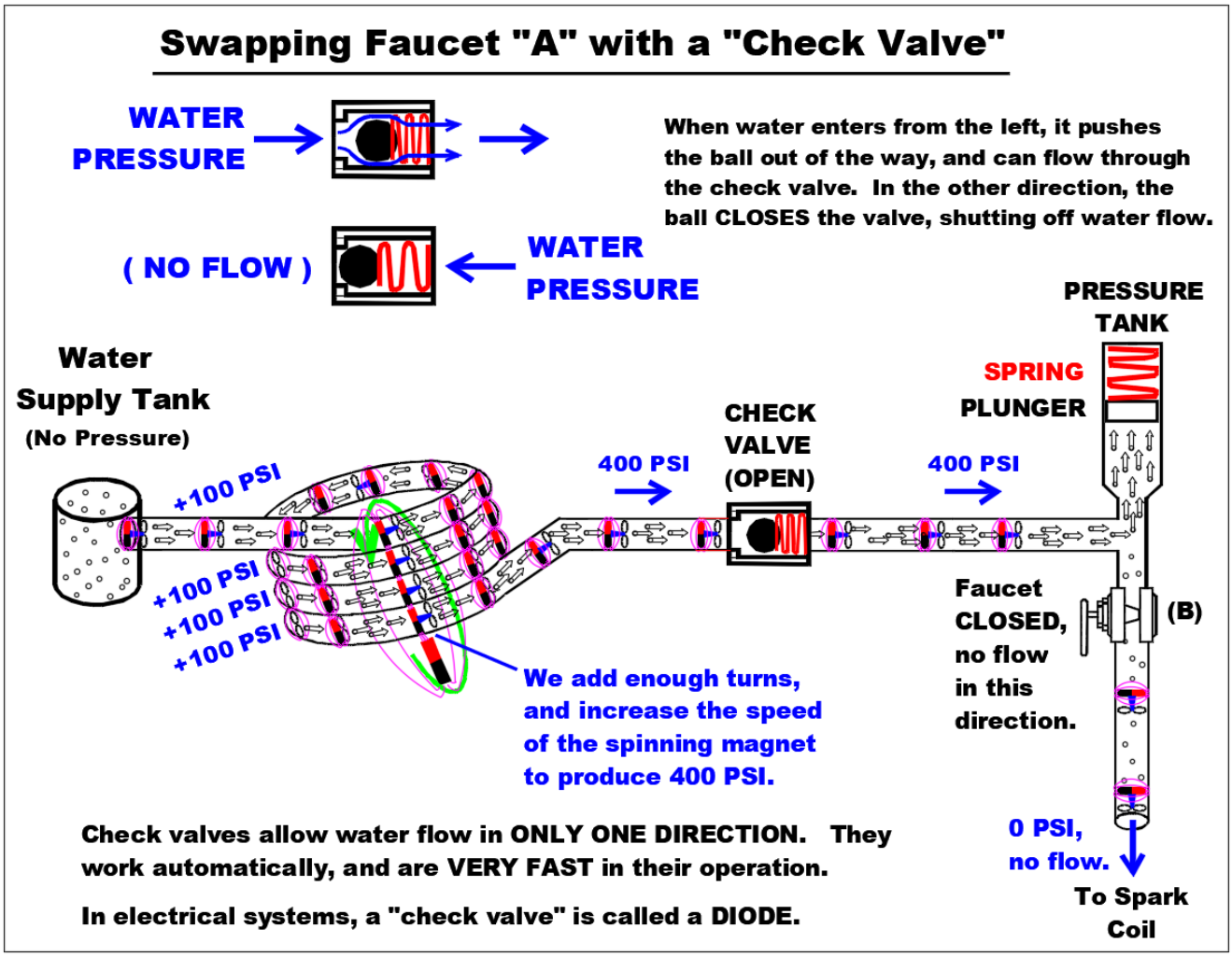
In a real coil, the voltages look like this:



In our old-fashioned MAGNETOs, the "faucets" (breaker points) were operated by a cam on the crankshaft. The "faucets" were TIMED to open and close, synchronously to the voltage generation waveforms (above), so that current flowed in the spark coil at the appropriate time**. These "contact points" were being used as MECHANICAL RECTIFIERS.**

In our CDI system, "faucet A" is right next to the coil. Mechanically trying to get this to operate fast enough to catch all of the coil pressure and water flow would be impossible with a "cam" and mechanical points. Can we find a way to do this in our "plumbing analogy", such that the "faucet A" operates by itself, and VERY QUICLY, completely automatically, such that it will allow ALL WATER to flow TOWARD the Pressure Tank, and will BLOCK ALL water flow in the other direction?

Hmmmm....if this sounds like a "check valve" to you, then you're getting the idea!



The picture above shows how "check valves" work. I think we all are familiar with these, right? **Well, ELECTRICAL terms, these are known as DIODES.** (In the Phase Maker schematic, I show where these are located in that early CDI ignition system).

In our drawing (above), the "check value" replaces "faucet A". Now, any pulse of pressure from the coil that is HIGHER than the pressure in the "pressure tank" will cause some amount of water to flow INTO the pressure tank, "charging it up". Even tiny pulses of high water pressure at the coil will get water stored in our tank. Our "check value" is VERY FAST. (Funny thing, behaving JUST LIKE a "diode" in our electrical system).

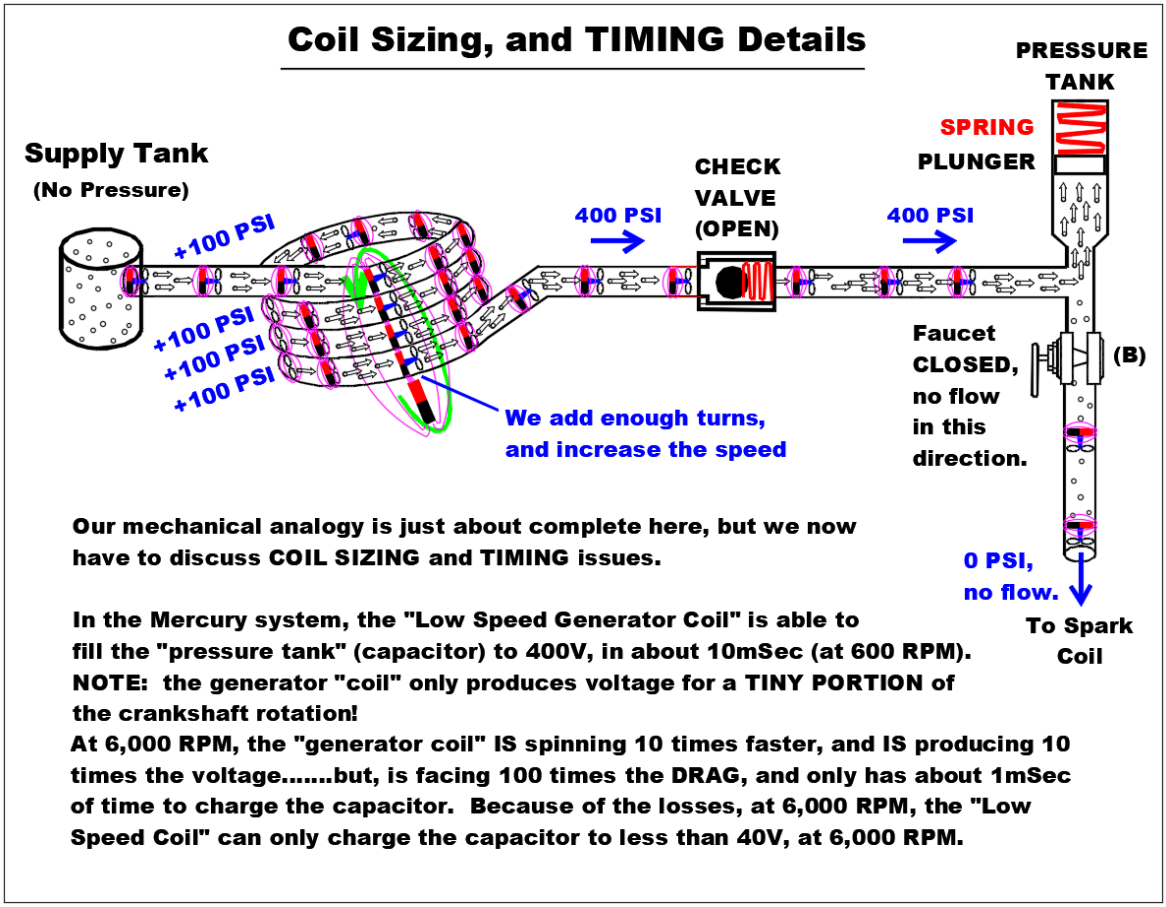
Now, one detail that's CRITICAL to understand. Because of DRAG, a SINGLE, pulse of water pressure can only completely fill the pressure tank if it's a LONG TIME DURATION pulse of water pressure. A VERY SHORT pulse of water pressure, because of the "drag" and losses in the pipes and coil, will only be able to fill the pressure tank

halfway....or even less. The shorter the pulses, the less water can be stored in the tank, for a given size of pipe. Unless the size of the pipe is increased.....HMMMM....we're now getting enough pieces to solve this puzzle!

Let's look at this "short pulse / long pulse" issue in greater detail!

The picture below shows the "low speed generator coil". In the electrical system, it's producing up to 400V at 600RPM. 600 RPM is rather slow, so the system has enough time to charge up the "pressure tank" to the entire 400V.

However, increase the speed of the motor up to 6000 RPM, and what happens? Well, the TIME you have to fill the pressure tank goes DOWN by a factor of 10, so it SOUNDS like less than a full charge of water can get stored in the tank in that much time. BUT....HEY! Spinning 10 times faster, doesn't the voltage out of the coil go UP by a factor of 10, pushing the water flow up much faster, effectively canceling out the shorter time interval? You would think so, but remember that IF YOU INCREASE THE FLOW RATE by 10 (to fill the pressure tank faster), the DRAG increases by a factor of 100, which REDUCES THE PRESSURE available. The tank now gets only a TINY portion of the pressure, compared to before.



This is where everything comes together. For the "low speed generator coil", at LOW speeds, it's only producing about 400V, and is has enough TIME to be able to get most of that voltage into the capacitor.

As the RPM increases, the VOLTAGE goes up LINEARLY, in direct proportion to the speed. The TIME available DECREASES in inverse proportion to the speed....so those two effects cancel out. What does not cancel out is the DRAG, which increases as the SQUARE of the speed increase.

From 0 RPM up to 600, the voltage increase in the low-speed generator coil wasn't opposed by any significant drag. So, as the RPM went up, the voltage increased, and most of that went into the capacitor. Voltage out seemed to be directly proportional to RPM.....as we expected from our "generator" prior experience.

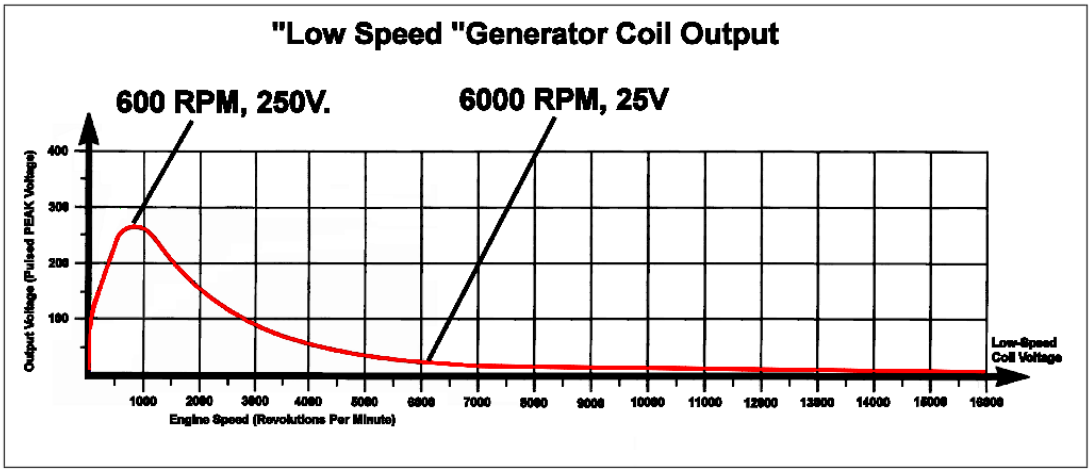
However, at about 600 RPM, the "drag" starts to become significant.....in fact so much so that at above 600 RPM, the increase in VOLTAGE is overwhelmed by the DRAG.....so much so that the voltage actually starts DROPPING as the RPMs get faster than 600. By 6000 RPM, the drag (and losses) are so great, that the low-speed coil isn't providing ANY flow into the capacitor. See the graph below for details.

Coil Sizing, and TIMING Details, Part 2

The "low speed generator coil" has MANY windings, of very fine wire. This allows it to produce over 100V at 100 RPM, for a good spark even a low idle.

At 600 RPM, the coil is producing (probably) about 500V, but the losses are almost half that, reducing the output to about 250V. From this point on, the voltage increases linearly, but the LOSSES increase by the square of that. So, from that point forward, the voltage output of the "low speed coil" starts to drop as fast as it rose, and continues to fall all the way through the outboard's expected RPM range.

See the graph below for what this looks like.



SO....the "low-speed generator coil" is GREAT for providing high voltage to our capacitor at very low speeds (even slightly under 100 RPM). It's output continues to rise up to 600 RPM, where the losses match the gains. At higher RPMs, the losses GREATLY OVEWHELM the voltage gains, and the output of this coil collapses. At above 2000 RPM, this coil is basically WORTHLESS, and above 4000 RPM, the engine would be misfiring.

SOOO.....(see where this is going?) Mercury produced a SECOND coil, called their "high speed coil". This coil produces almost NOTHING at low speeds. But, at higher RPM (where the low-speed coil starts to fall apart), this "high speed" coil's output voltage starts to significantly climb. The outputs of the two coils cross at about 2,000 RPM. Above that, the "high speed coil" is able to increase it's output, PEAKING at about 6000 RPM. Above 6000 RPM, the "high speed coil" would start seeing it's DRAG overwhelm it's voltage gains, and it's output would start dropping, just like the low-speed coil's output fell apart.

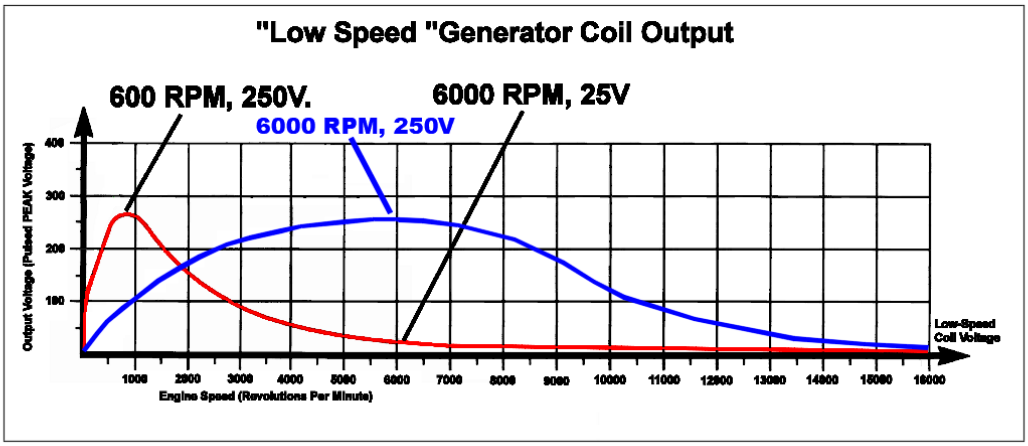
The DIFFERENCE is that the HIGH SPEED COIL has fewer windings (so it doesn't generate too much voltage at higher RPM).....and, it's WIRE DIAMETER IS MUCH LARGER (so it produces far less drag at lower RPM. You have to get to 6000 RPM until it hits it's "break even" point.)

Coil Sizing, and TIMING Details, Part 3

In contrast, the "high speed generator coil" has far fewer windings, but of much larger diameter. At 100 RPM, it's producing almost nothing. It's output peaks at about 6,000 RPM, and from that point on, the losses exceed the voltage gains, and the output voltage begins to drop, just like the low-speed coil did.

Note that the curves are identical, just stretched in scale, because the losses in the high-speed coil don't match the gains until 6,000 RPM.

See the graph below for what this looks like.



Now.....let's cut off our graph at 7,000 RPM (since our outboard can't go over 6000 RPM anyways.) And, let's add another line to the graph, showing the **voltage** on the capacitor.

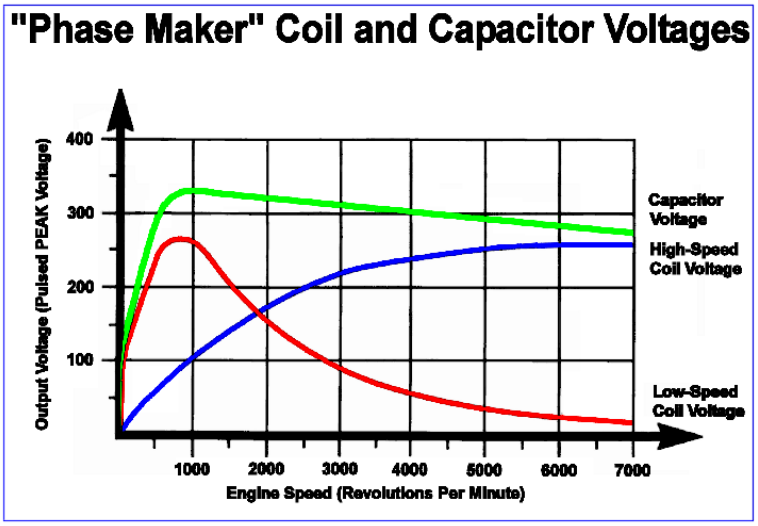
The output of the two coils go through a collection of DIODES (i.e. "check valves"), and is stored in the capacitor. It's not exactly the SUM of the coil voltages that's stored on the capacitor, but....it's close to that value. So, in the graph below, you can see that the "low speed coil" (in RED) gets the capacitor voltage up over 100V, even at less than 100 RPM. This is enough to generate spark! The low-speed coil rapidly rises to about 400V output, with more than half of this getting stored on the capacitor every cycle.

Above 600 RPM, the "low speed coil" starts to lose output voltage. However, as it's voltage is collapsing, the "high speed coil" starts to produce enough voltage to compensate.....with the coils switching over at about 2000 RPM. See below for details.

Coil Sizing, and TIMING Details, Part 4

If the graph is cut off at 7,000 RPM (just above the peak expected RPM), we see only a portion of the "high speed coil's" output curve, so it's harder to see that it really is following the same "losses" and output voltage curve as the low-speed coil.....just higher in the RPM range.

Keep in mind that this is the voltage put on the capacitor with JUST ONE PULSE out of the coils....(just one turn of the flywheel.) If the capacitor was NOT discharged every turn of the flywheel, the coils would "pump up" a MUCH HIGHER voltage on the capacitor, likely destroying it.



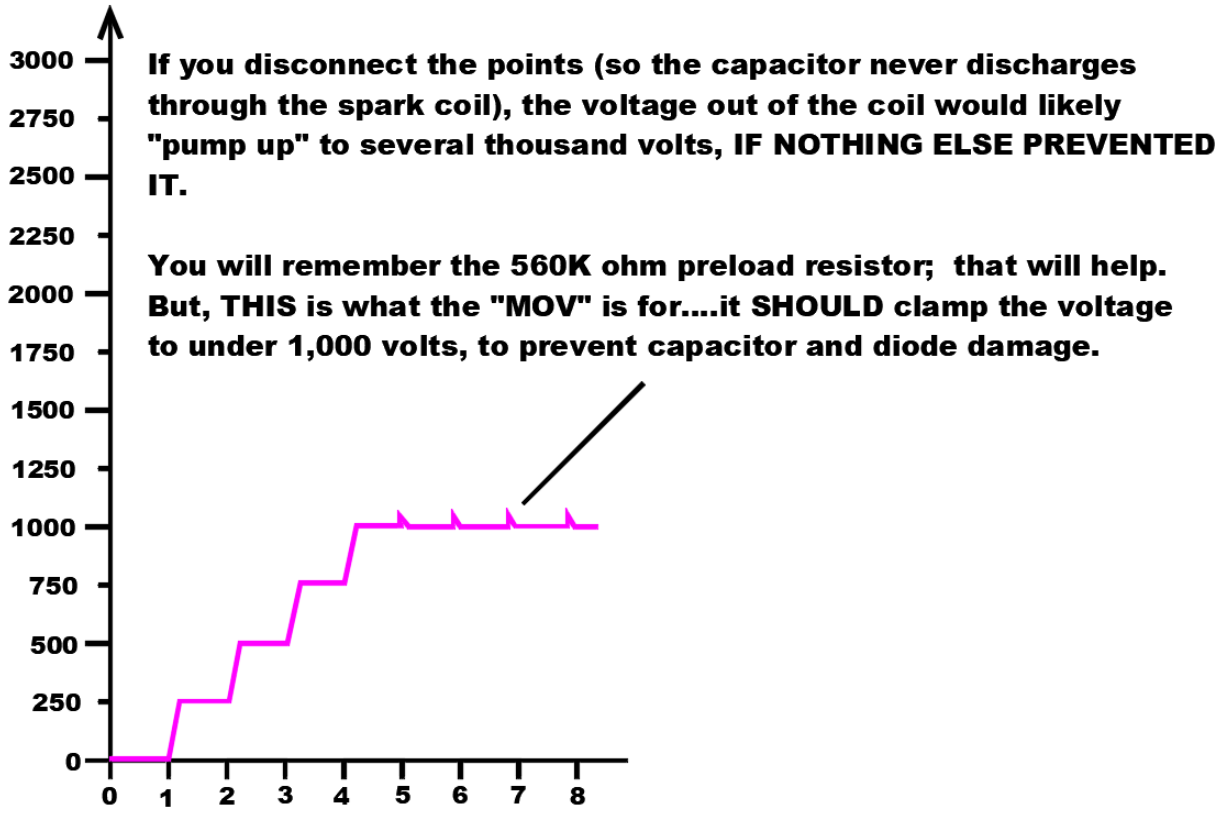
A KEY POINT TO REMEMBER is that in CDI ignition systems, the capacitor only gets the charge from ONE PULSE of the flywheel magnets moving past the generator coils. **The capacitor is then COMPLETELY DISCHARGED through the spark coil.....and the cycle repeats over and over and over**.

An interesting question would be.....**what would happen if you did NOT discharge the capacitor through the spark coil, on every turn of the crankshaft? Would the coils and diodes "pump up" the voltage in the capacitor to a much higher lever?** And YES, you would be correct here....that's exactly what would happen.

I'm not sure how high the voltage would be that the "high speed coil" is capable of, but I expect that IF ALLOWED TO, it could "pump up" the voltage to well over 3,000 or 4,000 volts, effectively incinerating the diodes and likely blowing up the capacitor....(it's a tossup which one would fail first.) But, fortunately for us, the Mercury engineers put a "transient voltage suppressor" in the design, which CLAMPS the voltage to less than 1000V, preventing damage should such a failure occur.

(Opening up the primary of your spark coil, or having a wire fail, or having the "maker points" NOT EVER CLOSE would ALL create this high overvoltage condition. Again, the "transient voltage suppressor" (likely a Metal Oxide Varistor) in the design is there to keep failure conditions like this from causing any damage to the module, should a failure happen in the points or the wiring or spark coils.

Voltage Runaway, and Overvoltage Protection



Anyhow, that's all I've got. Hopefully, this "plumbing analogy" will have given you some sense of how those "generator coils" produce those oddly-shaped output voltage waveforms.

The only difference between the two coils, is their number of turns and their wire diameter. The number of turns determines how quickly their output voltage rises with RPM, and the wire diameter determines when the DRAG kicks in, to cut the voltage back down. The "drag" is sized by the amount of current it takes to charge the capacitor in an ever-decreasing period of time, as the RPMs increase.

Simple, actually.....although I'll bet the Mercury engineers messed up a lot of coils figuring this all out.

And yes, we could build a "high speed coil" in plumbing, with fewer turns, with LARGER diameter pipe, and add the additional check valves....and it would "pump up" the pressure tank with pressure vs. RPM curves that would look similar to those of our electrical system. (However, the entire system would have to run MUCH, MUCH slower than 6000 RPM!) Electricity though a wire travels far faster than water in a pipe.*

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* (Actually, that's not true either. VOLTAGE travels through a wire at nearly the speed of light.....but individual ELECTRONS only move about 1 millimeter per second through the wires in your house wiring. Yes, you see your ceiling light turn on the split second you flip your light switch.....but electrons are NOT flying through your wires at nearly the speed of light. Instead, they are "sloshing back and forth" in your house wiring only a fraction of a millimeter, when the light switch is on.) And yes, this is really how electricity works in the electrical world.

Don't ask me to explain this in a plumbing analogy.....I think my head would explode.

--Bill Mohat / AOMCI, Western Reserve Chapter
MS/CIS, BSEET, CCNA

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