For many of you, the name Sunfire is synonymous with subwoofers – and for good reason. Bob Carver's innovative designs in the early 1990's are what created the small box, high power subwoofer category that you know (and probably love). These concepts have become commonplace nowadays, but 10+ years ago it was a much different story. Before then, conventional "wisdom" told us that in order to have high-impact, low frequency bass, a large cabinet was required. It took an innovative company to think outside the (big) box and an industry rebel to be the champion for this new technology. That rebel was Bob Carver. That company is Sunfire.

ALL ABOUT AIR – AN OVERVIEW

It seems simple – to have lots of bass, you must move lots of air. The measure of air movement is called "displacement", which is typically measured in cubic inches. If we want to shake the walls and rattle the rafters in a normal sized listening room, as a rule of thumb we need 135 cubic inches of air displacement. It's a matter of raw power, and the air moved by a woofer is the surface area of its cone, πr^2, multiplied by movement in and out (think of a cylinder of air). For example, a very high quality 15" woofer that can move in and out ½" (its "excursion" or "throw") can displace approximately 66 cubic inches of air. That's a lot, but as mentioned earlier it still isn't quite enough to shake the walls and rattle the rafters.

According to Dolby Laboratories, for Dolby Digital the air displacement required is at least 265 cubic inches of air movement. Using our above example of a 15" woofer with a ½" excursion, to reach 265 cubic inches of displacement would require *four* 15" drivers! That may not be a problem for a commercial cinema, but needless to say early home theater subwoofers fell well short of this mark.

WHY THERE'S A "CAR" IN "CARVER"

Here's where innovative thinking takes over. Bob Carver looked at this obvious dilemma (who wants a refrigerator-sized subwoofer?) and thought about the hot rod automobiles that were popular when he was growing up. Any auto-phile has heard folks talk about an engine's "bore and stroke", which equates to engine displacement (sound familiar?). Not coincidentally, these are key metrics used to determine the output power of an engine.

Bob took this knowledge and adapted it to create the voice coil for his subwoofer design. In order to get lots of air displacement he needed a very large stroke (long throw) woofer, but unlike the car analogy above, a large bore was not the answer. In order to increase the number of windings on the woofer's voice coil, he used a small bore instead – much more on this later. *Small bore, very large stroke*. The effective diameter of this new 10" driver design was about 8.0", with an unprecedented excursion of two and a half inches!

$$\pi(4.0)^2 \text{ (area of piston) x 2.5" (excursion of woofer) x 2 (two drivers in the box) = 251 cubic inches}$$

251 cubic inches of air displacement is about the same as three or four (depending on their excursion) “classic” 15” drivers operating in a cabinet the size of a small refrigerator. In practice, it's somewhat less because the excursion limiter is set to prevent bottoming, and the maximum possible displacement occurs one half octave above the tuning frequency of 18 Hz.

GRAVEYARDS AND EFFICIENCY

A two and a half inch woofer movement required a whole new technology. Early lab tests yielded a veritable graveyard of woofer parts – blown surrounds, dust caps, suspensions and distorted cones – they all fell victim to this new way of thinking. In the end after much research and trial and error a new and original driver design was created – the suspension, adhesives, surround, magnetic structure, and even the voice coil were all industry firsts and unique to this design.

Having a large volume displacement is only half the battle – *efficiency* is another critical variable in subwoofer and amplifier design. The reason is that the efficiency of a woofer is proportional to the volume of the box it is mounted in. For example, let’s say we have several woofers mounted in a 10 cubic foot box that works fine with a 200 watt amplifier. If we were to reduce that box from 10 cubic feet to 1 cubic foot, in order to achieve the same performance the power requirement would go up by a factor of 10 – meaning we would need a 2,000 watt amplifier! The original Sunfire True Subwoofer was an 11” cube, and a cube 11” square made of wood ¾” thick has an internal volume of half a cubic foot. When the necessary drivers and amplifiers are added to the box, the total box volume came in at only 0.4 cubic feet!

Knowing this, Bob realized he would need a very high power, efficient amplifier to reach his final goal of “little, low, and loud.” It just so happened that several years prior he had perfected his innovative Tracking Downconverter (TDC) amplifier that was specifically designed to be extremely high power, yet very efficient – it was an obvious fit! In the end a 2,700 watt amplifier was designed and produced for the True Subwoofer. TDC’s efficiency meant there would be high power, but in a compact design – as we saw above there isn’t much room to spare![1]

As we’ve seen there are two major parts to this subwoofer system:

1) An innovative woofer design that could undergo two and a half inches of excursion – five times the linear displacement of a conventional, large 15” driver.

[1] For more information on Tracking Downconverter (TDC) technology, please refer to the Sunfire amplifier whitepaper. It explains how so much power is obtained in such a small volume and with little heat. Without this special amplifier, the True Subwoofer would not have been possible.

2) A small box, which means lots and lots of power. Remember that the efficiency of the system depends only on the volume of the box — all other things being equal. *It does not depend on the size of the driver.*

To give you a better idea of the forces at work within this small, unassuming cabinet, let's examine what's going on inside. The woofers are bipole (both drivers move out simultaneously and both drivers move in simultaneously). They are mounted on opposite sides of a single 11" box so that the pressure wave is positive when they both move out and negative when they both move in. The giant magnet that drives this system can produce 150 pounds of force! This means if you put the woofer on the floor and you weigh 150 pounds or less and stand on it and drive it with a signal, you can be bounced up and down two and a half inches. At maximum output the air velocity in the pressure relief hole on the back of the driver exceeds mach 1.2. That's faster than the speed of sound, and you guessed it – generates a small sonic boom. Special measures were required to eliminate this "baby boom."

So you may be asking yourself – *"How can it have all this power and output and not let the proverbial "blue smoke" out. How is it possible that it doesn't melt down?"* In home theater, special effects with low frequencies are very loud, but they come and go quickly (like thunder, explosions, or the bass drum kick in a music video). All these events produce tremendous low frequency energy but they never last very long. Even though the amplifier may be putting out enormous power, it never gets hot because it's never sustained. The average power is usually under 200 to 300 watts. The professional industry has been routinely making voice coils that can handle 600 watts continuously – well in excess of what is rationally needed in a residential application.

Just the same, it would appear that 2,700 watts is a destructive amount of power going into such a small box, so there must be another reason it doesn't "let the blue smoke out." There are several very important factors that make this possible, which will be addressed shortly.

HOFFMAN'S IRON LAW

Hoffman's Iron Law details the relationship between a loudspeaker's efficiency, its box size, and its low frequency cut-off.[2] It imposes the most frustrating and maddening constraints on loudspeaker designers, all but ensuring powerful woofers will come in giant boxes. In a nutshell it tells us what economists already know – TANSTAFL – "there ain't no such thing as a free lunch." We cannot have our cake and eat it too; we cannot have big bass in small boxes.

[2] Developed in the 1960's by Anthony Hoffman, this mathematical formula was later adapted by A.N. Thiele and Richard H. Small to create the Thiel-Small parameters widely used in the speaker industry today.

For example, a loudspeaker designer can choose two of three variables arbitrarily and at will, but ultimately will be stuck with the third.

According to this law, if we choose:	+ Great low frequency response
	+ High efficiency
… then we're left with:	– *Large box size*
Or we could choose:	+ Small box size
	+ High efficiency
… then we're left with:	– *Poor low frequency response*
Or we could choose:	+ Great low frequency response
	+ Small box size
… then we're left with:	– *Low efficiency*

In short, Hoffman's Iron Law tells us it's not possible to choose all three at once. However, with the new design approaches and technologies developed for the Sunfire True Subwoofer, we can choose all three at will – small size, lots of low bass, AND high efficiency. In the end, Hoffman's Iron Law falls (actually it doesn't fall, but it must be interpreted in a way different from the classical interpretation).

THOUGHT EXPERIMENT #1 – SUPERCONDUCTING SUBWOOFERS

A woofer is "driven" by an electric motor that consists of a magnet and a voice coil. Let's imagine for a minute that a voice coil can be constructed out of super conductive wire that has zero resistance. Since we know that most of the input power is lost in the voice coil as heat (*joules*), such a voice coil would not generate heat because, in this case, heat is equal to the current squared times resistance: $J=i^2R$. Therefore, if the resistance is zero the heat is zero. If the heat is zero that means instead of one, two or three percent of the input power becoming useful, the speaker suddenly becomes majestically efficient. A super conductive voice coil is clearly not practical, but this thought experiment teaches us that it is possible (at least in theory) that fundamental laws of the universe do not prevent us from making a very small, very efficient woofer.

"STALL MODE" & BACK ELECTROMOTIVE FORCE

Electric motors can be marvelously efficient, well over 80%; however, electric motors will also be terribly inefficient when operated close to their "stall mode." *The stall mode is characterized by very little output power and lots of current running through the coils of the motor making the motor* *very hot*. For a variety of technical reasons, most woofers available on the market operate extremely close to their stall modes (not Sunfire's, of course). Hence, the conversion efficiency of most high-fidelity speakers rarely exceeds several percent – not even close to 80%.

Now that the foundation has been laid, we can examine the conceptual explanation that provides this woofer with much, much more efficiency than a woofer this size would normally possess. The secret to making the True Subwoofer efficient in spite of its small size and high output is to operate its electric motor – the voice coil and magnetic system – far away from stall. As it turns out, when a motor is operating there is a voltage generated inside the motor by virtue of its own motion – thank you Mother Nature! This voltage is referred to as the back electromotive force, or "back emf." If the motor is turning fast (which means it is far from stall), the back emf is large, meaning it will operate very efficiently and will therefore run cool.

TRAINS, MOUNTAINS AND MAGNETS

Let's look at an example from outside our industry. Diesel electric locomotives have a minimum operating speed below which the motors come too close to the stall mode and burn up. For passenger trains it's about 12 mph, for freight trains about 9 mph. Imagine that the freight train is going up a mountain, pulling a string of loaded containers behind it. If it goes up the mountain fast, the train is putting out lots of power because the energy of going up the mountain is delivered in a short time. Since power is work per time, a scientist would say $Power = mgh/t_{short}$, where m is the mass of the train, g is gravity, h is the height of the mountain, and t_{short} is the short time it takes to get up the mountain. The power output is large, and the electric motors run cool. If the train goes very slow it will not be putting out very much power because $Power = mgh/t_{long}$, where t_{long} is the long time it takes to go up the mountain. When t is small, power output is high, when t is large, power output is low. What's worse is the motors get very hot and overheat. In this case the motors are operating in stall mode.

Now back to the woofer. Because this woofer moves has high excursion and many windings in its voice coil, it is cutting many, many lines of magnetic flux in the magnet structure. It's the rate of flux change that generates back emf. The large in and out stroke of this woofer is good for making lots of air move but it's even better for generating a large back emf. If the voice coil didn't move very far, it wouldn't generate very much back emf. Without a large back emf too much current would flow through the windings and the woofer would overheat. To have a large back emf, lots of voice coil motion is required.

Another requirement for lots of back emf is a very high magnetic flux. To have that requires a huge magnet. The magnet in the True Subwoofer is woofer is 225 ounces and that compares to around 20-28 ounces for a "conventional" woofer – that's almost an order of magnitude larger! A potential problem with this increased woofer travel is that due to the large back emf (which is created by the large stroke cutting many of lines of force), if the woofer were driven by an

ordinary amplifier, most of the driving force would go away and the woofer would have very little output. Because the back emf is so large, the applied electromotive force to the woofer must be even greater than the back emf in order to overcome it.
These findings present themselves in the following relationship:

Efficiency ≈ B (magnetic field strength) x l (length of wire passing through field)

This critical finding means that the efficiency of the woofer is proportional to the *Bl* of the motor structure (magnet plus voice coil). This was the “ah-ha” moment when all the planets were in alignment and there was world peace – well, peace in the lab at least.

Having a high *Bl* requires an incredibly powerful amplifier to overcome its natural “push-back”; an amplifier that can swing over 100 volts RMS. Since the DC resistance of the voice coil is 3.3 ohms (nominally 4 ohms), 100 volts RMS into 4 ohms is well over 2,000 watts. The woofer will not burn up because when it's moving, the back emf prevents the damaging stall mode current that would normally flow if it were simply a resistive load. Only a small fraction of that current flows in the voice coil, but since the magnet is so huge, and because the driving force is equal to the magnetic field strength times the current, the force on the voice coil to drive the woofer and move the air is immense, even though not much current is flowing. An alternate way to get drive force on the woofer cone is to increase the current, the normal way of doing it, but that makes the voice coil overheat because of the high current. Or we use a very large magnet as outline above. The problem is that if we use a large magnet, the back emf causes us to run out of volts and therefore we need a very special amplifier to overcome the loss of volts. Fortunately for Sunfire, the Tracking Downconverter amplifier is perfectly suited for this task.

When all is said and done, the effective input power to the woofer is not 2,700 watts, even though the amplifier has to be capable of delivering 2,700 watts into a 4 ohm load. When it's actually operating into the loudspeaker, the effective power is far, far less than that. And Hoffman's Iron Law suddenly tumbles. To put numbers to this, even though this woofer is one tenth the box volume of a normal woofer, when driven to full output at the same volume level and same low frequency as a giant woofer in a big cabinet, by all the laws of the universe and all the rules that woofer engineers and designers have been taught, the input power should be at least 10 times greater than the input power for the big woofer. But that's not the case. The input power is more, but only slightly more.

THOUGH EXPERIMENT #2 – THE VARIABLE MAGNET WOOFER

Suppose we wanted to build a woofer, and we had a 200 watt amp to do it with; an amp that could only deliver 28 volts RMS to our 4 ohm speaker. Now imagine we mount our driver into a box. Imagine also that our driver has a "variable magnet", so we have a dial outside of the box that we can turn to change the strength of the magnet. The dial is calibrated continuously from zero magnetic strength to super magnetic strength. Next we drive the system with some bass. Of course, with the dial set at zero, there is no output from the woofer. We begin advancing the dial and the bass comes up. As we advance the dial further, the bass gets louder and louder. However, as we advance the dial beyond a certain magnetic field strength, the woofer output begins to drop. The point of maximum output defines the optimum magnet size for our woofer. See Figure 1.

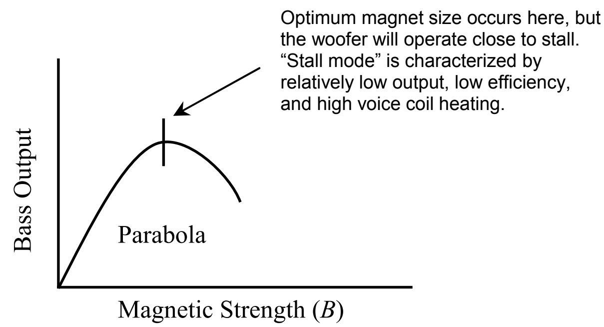


Figure 1

We know that as we advance our magnet from zero, the product of the current (i) and magnetic field strength (B) produces a force on the voice coil. As B increases, the force increases and the bass increases. However, no sooner than the woofer starts to move, it produces a back emf that begins to reduce the current through its voice coil. As the magnet becomes ever larger, the current becomes ever smaller, until by and by the ever increasing magnetic force cannot overcome the loss of current due to the increasing back emf.

Using the example described at the beginning of this section, if the back emf is 13 volts that leaves only (28-13) = 15 volts to run the woofer. If we wish to have more bass output we must have a larger amplifier, one that can deliver more volts in order to overcome the back emf. Now if we had in our possession an amplifier that had virtually unlimited output voltage, say one that could deliver 104 volts rms into 4 ohms with ease, then we could increase the magnet strength and not worry about the back emf rising since we would know that we have almost unlimited drive to overcome it. See Figure 2.

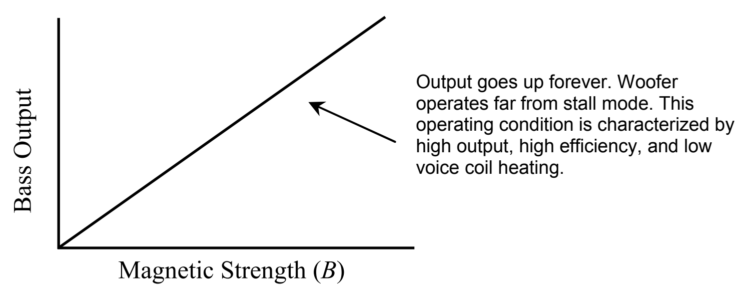


Figure 2

THE PROOF IS IN THE PUDDING

During the R&D phase of the original True Subwoofer, several telling experiments were conducted to verify the physics and mathematics behind these designs – after all, this is meaningful only if it does what it should in the real world! Using several well-known and highly revered large-cabinet subwoofers, one-by-one, tests were performed to measure both the input power from the wall (watts) and the output sound pressure level (dB). In one test, "the Big One", a woofer with a cabinet volume of 4.3 cubic feet, was selected and driven to its maximum output (where its limiter activated) with a warble tone centered at 28 Hz. The input power from the wall was measured at 240 watts; the SPL was 112 dB. It sounded great!

Next it was time for the Sunfire True Subwoofer to show what it could do. It was driven using the same signal until the same SPL was achieved – 112 dB. It too sounded awesome. The big difference, though, was in its power consumption. As we would expect, for the True Subwoofer the input power from the wall was actually 40 watts less – 200 watts! Since the limiter had not yet activated, the True Subwoofer was turned it up until its limiter finally activated at a staggering 115 dB! That's double the output of the Big One. At this level, the input power from the wall was still only 360 watts.

FINDINGS OF THESE EXPERIMENTS

"Big One" woofer operating in stall	*True Subwoofer operating far from stall*
240 watts input, standard amplifier 60% efficient at maximum output means (240) x (.6) = 144 watts into voice coil	*200 watts input, tracking down converter amplifier approximately 88% efficient means approx. (200) x (.88) = 176 watts into voice coil*
Big one has 4.3 cubic feet box volume	*Sunfire has 0.38 cubic feet box volume*

If we were simply to compare the two cabinets using *Thiel-Small* parameters and the assumptions of Hoffman's Iron Law:

4.3 (box volume #1) ÷ 0.38 (box volume #2) x 144 (power of box #1) = 1,629 watts (power of box #2)

Sending this much power through the voice coil would cause a fireworks display – not good. Obviously that is not the case; it is actually only 176 watts – an order of magnitude less! Is it magic? Has Sunfire sold their soul to the devil? No and no. It is proof that the theory we've examined to this point is not theory, but *fact*. To take this a step further, according to the formula above at its 115 dB full output, the True Subwoofer should need

2 (represents 3 dB increase to 115 dB) x 1,629 (power at 112 dB) = 3,258 watts

As measured during the experiments it only requires 360 watts to reach 115 dB!

So that's the secret of how this woofer can be so small, put out so much bass yet not burn itself up, and also not draw tons of power from the wall. As a matter of fact, in spite of all the bass it can output, it uses only a six amp slow-blow fuse.

The following are commonly asked questions:

Q) With these huge motions and large inertial forces, what prevents the woofer from hopping around the room when driven to full output?

A) The two drivers are quasi balanced and reduce the vibration to a rational amount. In fact, the vibration is just enough to help shake the floor and provide a tactile sensation to your toes, feet, or body if you're sitting on the floor, but not so much vibration that the woofer bounces around the room.

Q) Is back emf good or bad?

A) It's a double edged sword. On one hand, it's bad because it makes bass go away. On the other hand, it's good because the diminished bass is being produced at a higher efficiency, waiting only for a giant amplifier to bring it back – enter TDC.

Q) If the woofer uses only several hundred watts, why must the amplifier have several thousand watts?

A) A woofer has an impedance that engineers calls “complex.” It's made up of two parts. A real (resistive) part, and an imaginary (reactive) part. Consider this example: suppose the amplifier is delivering 104 volts and 10 amperes of real and imaginary current to the loudspeaker. From the amplifier's point of view, it thinks $Power = V\ i = 10 \times 104 = 1{,}040W$. The speaker thinks $Power = iR = 10^2 \times 3.3 = 330\ watts$.

Imaginary currents cause sorts of engineering complications. For instance a dirty little secret of power companies is that the watt meter installed on the side of your house cannot detect imaginary current, but it costs the power company money and water over the dam to generate it! In woofers, a giant magnet means giant reactive currents, which the amplifier must accommodate. These currents impose large stresses on the amplifier, as much stress as if it were operating at several thousand watts into a regular speaker. Strictly speaking, it's more complex (pardon the pun) than this illustration, but hopefully this is enough to give you the big picture.

A NOTE ON COMPUTER-AIDED DESIGN

All computer-aided speaker design software programs in use at the time of this writing use Thiel-Small parameters. A.N. Thiel[3] told the world in a footnote to his original paper years ago that his equations were only approximations and would be valid only if the efficiencies were very low. If a modern speaker designer sits down at his computer and asks it to build a woofer flat to 18 Hz in a 0.38 ft^3 box that can do 110 dB SPL, the computer will politely inform him that he will need an amp with more than 5,000 watts. As we've seen, nothing could be further from the truth!

HOW THE DRIVERS MOVE

Both drivers in the Sunfire True Subwoofer are driven by a common electric motor and magnetic structure. One driver is driven by a voice coil, the other by a 1.7 lb weight. Both drivers move inward together and both move outward together. The voice coil driven driver is moved by a force, $J = Bli$, where B is the magnetic field, l is the length of wire on the voice coil, and i is the current through the coil. The mass driven driver is moved by the force (*mass x acceleration*) of a 1.7 lb weight. The two forces are exactly equal and opposite. The mass driven driver is often called "passive" because it lacks a voice coil. It is anything but passive, and contributes equally to the output in its chosen operating band.

[3] A.N. Thiel was an Australian university researcher. He wrote a paper approximately 30 years ago that put rigorous mathematics into the design of subwoofers. With that remarkable paper, and arresting insight, he taught the world how to design subwoofers (albeit in jumbo boxes).

SUMMARY

Sunfire subwoofers do the seemingly impossible – from a tiny cabinet they are able to put out as much bass as an extremely large woofer in a very large cabinet. Here's why:

1. **Custom Large Excursion Drivers**
   Its in and out movement (excursion) is approximately five times greater than a conventional woofer. Since it can move back and forth 2.5 inches, it can move lots of air.

2. **High Back Electromotive Force**
   This is generated by magnets designed specifically for this purpose, whose weight is approximately ten times greater than in a conventional driver. This increases the back emf, allowing the driver to operate away from the stall mode, and consequently at an efficiency more than ten times greater than a woofer this size would ordinarily possess.

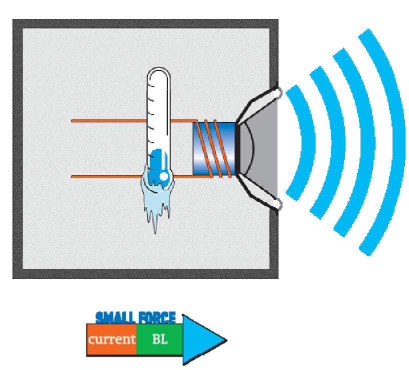
3. **Giant Amplifier**
   Since the woofer is in an extremely small box, whenever it moves back and forth, very high air pressure is generated within the box. To overcome the box pressure, a giant amp is needed. The built-in Tracking Downconverter amps can deliver as much as 2,700 watts RMS into a 3.3 ohm load.

WHY OTHER COMPANIES HAVE FAILED

As you have seen, there has been thousands of hours of engineering coupled with just as much trial and error to create Sunfire's True Subwoofers. There have been many who have tried to copy these designs, but most have reached the same dead end. To get a closer look at their processes, let's consider the following examples.

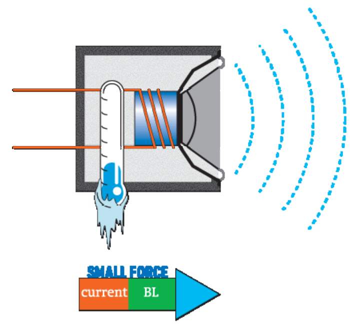
BIG BOX + LOW FORCE = BIG BASS (CONVENTIONAL METHOD)

Let's face it, large subwoofers are easy. These are the ones you've seen for years. There is lots of air in there, so it doesn't take much force (amplification) to compress it. Without much force, it doesn't take much current and therefore the voice coil remains cool. This is the low-back-EMF, low-current, low *Bl* subwoofer system that's been around for years.



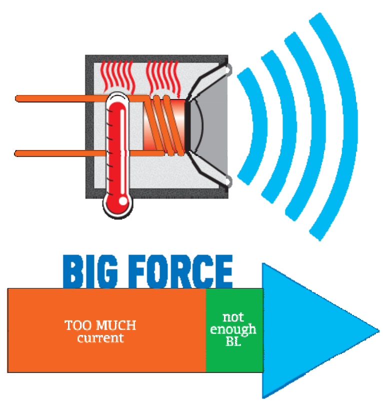
SMALL BOX + LOW FORCE = WEAK BASS (TRIAL #1, FAILED)

The next logical step for a would-be copy-cat would be to just shrink the box. If you use the same force as the big box example above, the voice coil remains cool but the since the air is hard to compress you get weak bass. This model is the low-back-EMF, low-current, low *Bl* subwoofer that doesn't perform because of the additional force required.



SMALL BOX + BIG FORCE = BIG BASS, BUT KILLS VOICE COIL (TRIAL #2, FAILED)

The next logical step for a would-be copy-cat would be to add more force by simply increasing the output power of the amplifier. Boosting the current and nothing else causes the voice coil to overheat. After a few seconds the voice coil fails.



SMALL BOX + BIG FORCE = BIG BASS (THE SUNFIRE WAY)

To pull this rabbit out of the Sunfire hat, we need a very high *Bl*. To achieve this, a custom long-throw woofer (increased stroke), a specialized, tightly wound, small bore voice coil (increased "*l*"), and an enormous magnet (high "*B*") were used. The result is high power, but not destructively-high current via the Tracking Downconverter amplifier.