This page is all about
where the energy really goes in an antenna system.
Will a high SWR blow up my transmitter?
(No, it will not, but POOR TUNING can.)

---The Reflection Section---
The purpose of this section is to explain what happens when un-used energy comes back down the coax from the antenna.

"RF MOVES BOTH WAYS IN A COAX"
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? I just couldn't help it. At the time, I thought it was cute. ?

Here are some simple truths that you probably knew before you got here, but when they are all put together, you will have 7 different things happening.

It is a little difficult to keep track of all 7 things that are happening, but this section will try to help you do that. Please go slow here. Take breaks if you would like to.

It helped me to draw diagrams of all this. Please feel free to stop and grab some paper to draw a diagram or two, or more.

This page is the most difficult page to understand of all the pages in this site. It uses high school algebra but I show you every move. Please feel free to skip all the math stuff, but please read the discussion parts so you can learn what is really going on.

The simple truths start here.

- Your SWR meter reads the reverse energy in a coax, and converts that number into a value called the "Standing Wave Ratio". That number has very little meaning. The value is when you convert that number back into what it measured in the first place, which is the percent of returning energy. That is why you need a SWR meter.
- You should always use an antenna tuner. It goes near your rig, in the shack. Its duty is to match your antenna and coax to the impedance of your rig, not to change the SWR in the coax that goes from the antenna down to the antenna tuner. Many radios have tuners built in. Some tuners are automatic.
- Electrical energy moves forward and backward in a coaxial cable and in ladder line. (Everything I tell you about Coax is also true for ladder line, except that ladder line has far less loss.)
- Electrical energy moves forward because the generator (your rig) pushes it toward the antenna.
- It moves backwards because the antenna can not absorb all the energy, so the un-absorbed energy goes back down the coax. (The absorbed energy is converted into Electro-Magnetic energy and is transmitted out into space.)
- The reflected energy will be re-reflected when it reaches the tuner or the tuned circuit in the output stage of the transmitter. NO LOSSES happen at the reflection points, and your rig will not blow up because reflected energy got into the tuned circuit.
  OK, nothing is perfect, and there will be a very very small amount of resistance in the coil

and capacitor in the tuner which will create a very small loss, but it is truly tiny. (0.01 dB is a good estimate) This is absolutely true, Honest!

- There are usually two coaxial cables between the transmitter and the antenna.

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                           |SWR | |Antenna|
|Transmitter|   Coax #1    |meter| |  tuner  |      Coax #2      |Antenna|
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Coax #1 is usually quite short, and coax #2 is far longer because it goes from your desk up to the antenna.

Controversy ahead

The following information is absolutely correct, no matter what you have heard from your engineering professors or your favorite ham radio magazine.
I know you can read many articles that disagree with what I have written here, but I have some important people who agree with me.

The two most important people who agree with me are L. B. Cebik, W4RNL who has written many articles for the ARRL on transmission lines and antenna tuners.
http://www.cebik.com and M. Walt Maxwell, W2DU who has written the book "Reflections: Transmission Lines and Antennas". This book was published by the ARRL,

and while not a person, just as important. . . .

The ARRL Antenna Book, published by the ARRL.

Note from the author: This statement is not to imply that L. B. Cebik, W4RNL and M. Walt Maxwell, W2DU have read this web site and sent me a message telling me that they approve of what is written here. What it does mean is that nearly 100% of what is here comes from what they have written in books or on the internet. I did not create these thoughts, but I report them in as simple a manner as I can. Naturally, I agree with them and believe them to be absolutely correct.

The reason this is controversial is because so many people have been told a different story. When you hear any story over and over again, it becomes part of the "common knowledge" of the culture, and it tends to be considered the truth, even when it is clearly not true at all. That is what has happened here.

This is the last, but long, simple truth.

The antenna tuner adjusts the electrical length of the antenna and coax #2 so that the reflected energy has the exactly correct phase to be re-reflected at the antenna tuner. When the tuner is correctly tuned, no energy gets back into coax #1. An SWR meter is usually placed into coax #1 as a tuning aid, to measure the reflected energy. That meter will show an SWR of 1:1 when the reflected energy has been 100% re-reflected.

Coax #2 still has reflected waves because of the mis-match between coax #2 and the antenna, but those reflections will be re-reflected at the tuner and they will add to the transmitter energy output.

It may seem strange that the system is resonant and still has reflections due to mismatched impedance, but the coax and antenna are not the same impedance.

Actually, except for the losses in the coax, 100% of the energy that leaves the transmitter will be radiated out of the antenna, no matter how high the SWR, because of the re-reflection. A high SWR will create a higher loss in the coax because a higher amount of energy travels backwards in the coax. This energy going backwards is subject to the same losses as the forward moving energy.

The tuner provides a conjugate match (equal magnitude but opposite reactance) for the system from the antenna tuner, through coax #2, to the tip of the antenna ends. This makes the antenna appear to be resonant, and coax #2 becomes the correct electrical length for re-reflections to happen.

Many authors have stated that an antenna tuner tunes coax #1, but has no effect on coax #2 or the antenna. That is not a good explanation. A much better explanation is that when the antenna and coax #2 are tuned, the tuner can re-reflect the reflected energy from the antenna. That is one important reason reflected energy does not get into coax #1. The other reason is that since coax #2 is now without reactance at the matching point, the impedance of coax #1 (50 O) exactly matches the impedance of coax #2 (50 O) so no reflections happen at the front end of the tuner and all the transmitter energy gets through to the tuner and into coax #2.

This is a very sticky point. According to M. Walter Maxwell in his book Reflections: Transmission Lines and Antennas, published by the ARRL, on Page 13 - 4, he says " **The antenna tuner really does tune the antenna to resonance, in spite of opinions to the contrary of those who are unaware of the principles of conjugate matching. The tuner obtains a match, by which all reactance's throughout the entire antenna system are canceled, including that of the off-resonant antenna, thereby tuning it to resonance."**

An even better way to describe what happens is to point out that the specific spot called the "matching point" is where the impedance is 50 Ohms with zero reactance and it exactly matches the impedance of coax #1 at that point. There is really no need to claim that coax #1 or coax #2 have been tuned, because it is the "matching point" that is connected to coax #1, not the complete length of coax #2.

Please be patient here. This explanation has lots of steps, and each one is critical to understanding what really happens in the coax of an antenna system that is not perfectly matched.

This is the end of the simple truths. The explanations are below.

The antenna tuner can not change the SWR of your antenna, or its coax, so you will need to follow these 7 steps to see what actually happens with a higher SWR than the SWR meter in coax #1 says is there. The SWR meter is reporting on that very short connection between the tuner and the rig, **not the coax that goes between the tuner and the antenna**, but that is "where the action is."

There are 7 things you need to know. First, I will list the 7 things, and then each one will be explained in detail. The reason this following information is not well known is because most people do not take the time to understand each step that follows.

Each step is easy if you go slow and draw things out on paper. You will gain quite a lot of understanding of what really happens to a signal in a coax if you go slow, and have patience. Do not read quickly. Do not continue on if even one little thing is not clear to you. You will be proud of yourself if you learn this.

1. Reflections happen at the coax - antenna connection and **<u>they also happen at the coax - tuner connection.</u>** The last part of this statement seems to be missing from most discussions of SWR and mis-matched conditions.
   This is why a lot of people think that reflected power gets into the radio and does damage. **That does not happen!**

   ** What does kill radios is explained at the very bottom of this page. **
2. These reflections do not cause energy loss. **<u>All losses are due to the coax itself.</u>**
3. Energy moving backwards in the coax is subject to the exact same losses as energy moving in the forward direction.
4. The amount of energy reflected at the coax - antenna connection depends on the amount of impedance mis-match (read SWR) between the antenna and the coax. The greater the mis-match, the greater the reflection.
5. The amount of energy re-reflected at the coax - tuner connection is 100% of the energy that gets there, but not all the energy that was originally reflected gets back to the coax - tuner connection. **There will be losses in the coax.** All the reflected energy that reaches the coax - tuner connection is re-reflected back into the coax headed for the antenna. (Yup, another lossy trip in the coax.)
6. The re-reflected energy will be in phase with the generator so the two signals will add. This can create <u>more</u> forward power in the coax than the transmitter is actually producing. It is possible to measure 125 Watts forward power from a 100 Watt transmitter because the re-reflected power <u>adds</u> to the transmitter power.
7. Coax losses are the only losses in the whole system. These losses can be significant, but they are the ONLY losses in the antenna system. If you have been paying attention, you know that this last step is just a re-statement of other steps above.

Here come the details! Do not skip this section. It is full of math, but you can do it. Use a calculator that has X^2 and v X.

1. Reflections happen at the coax - antenna connection, and again at the coax - tuner connection. This means that energy will zoom up the coax between the antenna and the tuner and some of it will return down the coax. The "lost" energy is both lost in the coax, and radiated out into space by the antenna.

   Another detail must be introduced here. Every time the signal is reflected (or re-reflected) a 180 degree phase shift happens to the current. This means that the current turns around and goes the other way, <u>and it also turns upside down.</u> Both things happen at the reflection points.

   Let me say this again. In the case where the impedance of the antenna is greater than the impedance of the coax, [$Z_{Antenna} > Z_{coax}$] the reflected voltage will just turn around and go in the other direction, but the reflected current will become upside down as it also travels in reverse. This means that the forward voltage and reverse voltage are in phase with each other, but the forward current and reflected current are 180 degrees out of phase with each other. When the reverse (and upside down) current reaches the tuner, another 180 degree phase reversal and direction change will happen.

Now the re-reflected current is back in phase with the generator current, and the forward and reverse voltage are also in phase. This phase reversal is a good thing because it allows the forward and reverse current to ADD together when the re-reflection happens at the tuner.

Try drawing a picture of this. Be patient. Go slow.

2. These reflections do not cause energy loss. Energy losses are caused by heating (I^2 * R) or radiation, but not by reflection. The law of conservation of energy tells us that what ever goes into a reflection will come out if there is no radiation and no heating.
3. Energy moving in a coax will have losses due to leakage and (I^2 * R) heating. These losses are well documented by the companies that make the coax. One of my favorite places to find the losses in different kinds of coax is **http://www.ocarc.ca/coax.htm** they have a calculator that will help you convert the dB losses into actual Watts for a better understanding of what is happening.
Follow the zig - zag path of power!

Here is an example of a typical coax with its typical loss in an antenna system with a SWR of 1.4 to 1. Go to the web site listed directly above and scroll down to the calculator. Press the little "down arrow" and pick Belden 9913 (RG-8). It is a high quality coax used by many amateurs. Do not change anything else yet. When you have chosen the Belden 9913 coax, press the "calculate" button.

Do it now.

If you have done this correctly, the calculator will tell you that Belden 9913 has a dB loss of only 0.388 dB and that calculates out to 91.461 Watts output from the coax if you put 100 Watts in to it.
Where did the rest of that power go?

It was lost to leakage inside the coax and to (I2 * R) heating.

How much of that 91.461 Watts will be used by the antenna and how much will be reflected?
The reflection coefficient is a number that tells you the percentage of reflection at the antenna - coax connection. The symbol "p" is used to represent this reflection coefficient. The math is easy to do.

$$p = (SWR - 1) / (SWR + 1)$$

We started by assuming that the SWR is 1.4 to 1. Use that 1.4 value to fill in the formula.

$$p = (1.4 - 1) / (1.4 + 1) = 0.4 / 2.4 = 0.166$$

The reflection coefficient is used for voltage, current, and when squared, it is used for power. Since the reflection coefficient is 0.166 in this example, the voltage reflected will be 16.6% of what arrives from the generator, and the current reflected will also be 16.6% of what arrives from the generator. The power that is reflected will be the **square of the reflection coefficient.**

To find out how much power is reflected, you will need to use the following formula.

$$\text{Reflected Power} = p^2 \text{ times the Power available}$$

Reflected Power = $(.166)^2$ times 91.461 Watts.
Reflected Power = (0.02775) Times 91.461 Watts
Reflected Power = 2.54 Watts

This means that 2.54 Watts of the forward power will be reflected back down the coax toward the tuner, and the rest (91.461 W - 2.54 W = 88.921 Watts) 88.921 Watts will be used by the antenna and be radiated into space.

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Try drawing a picture of this. Be patient. Go slow.
Is it breaking time yet?
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The power that reached the coax - antenna connection was 91.461 Watts and 97.25% of that power will be radiated into space, leaving 2.75% to be reflected back down the coax. Both of these percentages come from the Reflection Coefficient that has been squared.

$(\text{Reflection Coefficient})^2 = (0.166)^2 = .0275$, which means that 2.75 % will be reflected.
Power used by the antenna = 100% - 2.75 % = 97.25%

How much power will be radiated by the antenna?
The antenna will radiate 88.921 Watts into space.
This number will get slightly larger after the reflected power is returned to the antenna, but for now, during the first cycle, only 88.921 Watts are transmitted.

How much power is headed toward the tuner?
Only 91.461 Watts was available at the antenna - coax connection, and 2.75 percent of that will be reflected back down the coax toward the tuner. (91.461 Watts times 2.75% = 2.54 Watts) 2.54 Watts will be returned to the coax to go back to the tuner.

How much power gets to the tuner? **http://www.ocarc.ca/coax.htm**
We must use the calculator again. Put 2.54 Watts in the place of the 100 Watts just above the "calculate" button. Press the "calculate" button.

Do it now please? Notice that 2.323 Watts gets to the tuner and the rest was lost to heat and leakage.

5. **How much power is re-reflected at the tuner?**
   100 % of the reflected power that gets to the tuner will be re-reflected. In this case, the power that is re-reflected is 2.323 Watts. This 2.323 Watts now starts its way back to the antenna.
6. 6) The re-reflected energy will be in phase with the generator so the two signals will add. [Note: If the two signals were not exactly in phase, the addition still happens, but the method is messy, and the result is not the same. This would be the case if the antenna was not exactly tuned to the operating frequency as it is in this example or if an antenna tuner was not correctly adjusted.]

The generator is producing 100 Watts and now it will have an additional 2.323 Watts added to it, for a total of 102.323 Watts heading for the antenna.This is the official end of the first cycle of the generator. This first cycle started with a 100 Watt signal leaving the generator, but only 88.921 Watts was transmitted. The total loss so far due to heating and leakage was

(100W - 91.46 W = 8.55W) 8.55 Watts on the trip up to the antenna, and
(2.54 W - 2.32 W = 0.217 W) 0.217 Watts loss on the way back down the coax.

This makes a total of (8.55 W + 0.217 W = 8.76 W) 8.76 Watts actually lost in the form of heat and leakage. There are still 2.32 Watts stored in the coax (and tuner) about to be added to the generator power. All the power is accounted for. This is important because it helps you realize this explanation is correct.

That's a lot of information. What is the actual result?
What's the Score?

Input Power -	100 W
Loss of power going up the Coax- - - - - - - - - - - - -	**8.55 W**
Power reaching the Antenna - - - - - - - - - - - - - - -	91.46 W
Power Radiated by the Antenna- - - - - - - - - - - - -	88.91 W
Reflected Power returned to the Coax- - - - - - - - -	2.54 W
Loss of Power going back down the Coax - - - - - - -	**0.217 W**
Power that arrives at the Tuner - - - - - - - - - - - - - -	2.32 W
Radiated power eventually evens out to? - - - - - - - -	91 W.

(after about 5 cycles)

This shows where the power is lost, and what is radiated. This is far too much information, but it is necessary to tell the whole story truthfully. As you know, this is only the first cycle.

Make a diagram of all this information so you can see where all these numbers fit in. That will help you understand this.

The power that is still in the coax (and tuner) will add to the generator power which will add a little to the output and add to the losses. This will continue for a few cycles until the system settles out to finally produce 91 Watts radiated power.

Finally, take a look at what happens when the SWR is high and what happens when the coax loss is great.

First, lets look at what happens when the SWR is high (SWR = 3)
this uses the same 50 O coax as before.

	SWR = 1.4	SWR = 3
Input Power -	100 W	100 W
Loss of power going up the Coax- - - - - - - - - - - - - -	**8.55 W**	**8.55 W**
Power reaching the Antenna- - - - - - - - - - - - - - - - -	91.46 W	91.46 W
Power Radiated by the Antenna - - - - - - - - - - - - - -	88.91 W	68.59 W ?
Reflected Power returned to the Coax - - - - - - - - - -	2.6 W	22.86 W ?
Loss of Power going back down the Coax - - - - - - - -	**0.217 W**	**1.95 W**
Power that arrives at the Tuner - - - - - - - - - - - - - - -	2.32 W	20.9 W
Radiated power eventually settles out at - - - - - - - - -	91.0 W	86.7 W?

Even when there is a high SWR, the final power output is nearly the same.

SWR is not a killer at all.

This is the same SWR = 1.4, but the COAX now has a loss of 2.5 dB (Belden 8216) which is Rg-174.

	Belden 9913 Coax loss = .388 dB	Belden 8216 Coax loss = 2.5 dB
Input Power- -	100 W	100 W
Loss of power going up the Coax- - - - - - - - - - - - - -	**8.55 W**	**43.7 W**
Power reaching the Antenna - - - - - - - - - - - - - - - -	91.46 W	56.2 W
Power Radiated by the Antenna- - - - - - - - - - - - - -	88.91 W	54.6 W
Reflected Power returned to the Coax- - - - - - - - - -	2.54 W	1.56 W
Loss of Power going back down the Coax- - - - - - - -	**0.217 W**	**0.68 W**
Power that arrives at the Tuner- - - - - - - - - - - - - - -	2.32 W	0 .87 W
Radiated power eventually settles out at- - - - - - - - -	91 W	**55.1 W ?**

These losses are terrible! The coax losses have ruined the output power!!

Finally we have come to the very last subject on this page.

So, why do people think they can blow up their rigs or linear amplifiers when there is a high SWR on the antenna?

Because that can happen, but it is not due to the reflected power!
There is a totally different reason. A high SWR on an antenna probably means that the antenna is not tuned to the frequency that is being used. This, in turn, means that the antenna has some inductive or capacitive reactance that is de-tuning the final amplifier. De-tuned final amplifiers draw far too much current and can burn up. The rig or linear amplifier will have to be re-tuned to avoid creating too much heat.

Many linears and nearly all tube amplifiers have some tuning knobs that allow you to "dip the plate current" or adjust the SWR by adjusting something on the front of the device. Transistor rigs usually do not have any tuning adjustments. To avoid the extra heat created when running a de-tuned amplifier, there is a protection circuit that will significantly reduce the output power if the SWR is high.

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The conclusion section.

Finally we are at the conclusion section. I hope you have seen that . . . . .

- High SWR at the transmitter can ruin that rig because the final amplifier is de-tuned. Using an antenna tuner will tune the rig back to where it should be.
- High SWR at the antenna will not significantly reduce your power (if you are using an antenna tuner) unless:
  • you are not using a tuner and
  • there is a circuit inside the rig that shuts down power when it sees a high SWR.
- High loss coax can really reduce your output power. A coax with a 3 dB loss will suck up half the power, allowing the antenna to radiate the other half.
