A Revealing Analysis of Mr. Bruene's 'R_S

The following are four items of concern pertaining to errors in the Bruene *QEX* article of May/Jun 2002.

1) Analysis shows why his assertion that R_S is the source resistance of RF power amplifiers is untrue.
2) His assertion that measuring network output resistance with the load-variation method is useless, thus impugning my data appearing in *QEX* [1] and *Reflections II.* [2]
3) Why his test-amplifier measurement failed to determine the value of R_S.
4) Why his computer method for determining network output resistance failed by an order of magnitude.

1) Analysis of R_S

For more than a decade Warren Bruene, W5OLY, has asserted that R_S is the source resistance of RF power amplifiers. His article, "On Measuring R_S," appearing in May/June 2002 *QEX*, describes another attempt to measure it. Did he measure it? No. His test amplifier incorrectly models a realistic RF amplifier. Is R_S really the source resistance? I don't think so.

Although R_S exists as a dynamic, non-dissipative resistance, I will show that R_S is **not** the source resistance of an RF power amplifier as Bruene claims. To appreciate why it's not the source resistance we must first understand the nature of R_S. Contrary to Bruene's assertion, the ironic reality is that instead of being the source of power, the effect of R_S actually **opposes** the delivery of power, a phenomenon that Sabin explains brilliantly in *QEX*[3], from which I will paraphrase:

For background, we know that DC power is converted to RF power by the changing plate current flowing into the tank circuit. Bruene defines R_S as the ratio of the change in plate voltage to the resulting change in plate current, with constant grid voltage.[4] Therefore, $R_S = \Delta E/\Delta I$. Note that this expression for R_S is precisely the handbook definition of plate resistance R_P. R_S **cannot** be the source resistance as Bruene claims, because its value is as much as five to ten times greater than the load resistance R_L and therefore impossible to deliver all the available power if it were the source. The high value of R_S is because the variation in plate current with plate voltage is very small due to the small slope of the constant-current curves of tetrode and pentode amplifier tubes. Bruene maintains incorrectly that the large difference between R_S and R_L prohibits the existence of a conjugate match in RF power amplifier operation. On the contrary, I have shown that this is not true, as explained in References 1 and 2.

According to Ohm's Law, when plate voltage increases plate current increases. Thus, plate current is **in phase** with voltage with changes in **plate voltage**. However, with changes in **grid voltage** plate voltage and current are 180° **out of phase,** due to the voltage drop across plate load resistance R_L. Thus, as plate current increases with increasing grid voltage, plate voltage decreases. Consequently, when plate voltage decreases due to increasing grid voltage, dynamic resistance R_S simultaneously tends to **decrease** the plate current. In effect, the small decrease in current due to R_S, compared to the larger increase due to grid voltage, is a form of negative feedback, the greater the value of R_S the less the effect.

Continuing, to gain perspective, we know that in triodes, the plate current responsible for delivering power varies significantly in proportion to plate voltage. Because R_S is relatively low in triodes, its effect results in substantial opposition to any change in plate current in response to a change in grid voltage. However, in contrast to the triode, due to the shielding effect of the screen grid, plate current in tetrodes and pentodes varies **only slightly** with changes in plate voltage, and then only because of the imperfect shielding of the screen grid. Due to the shielding the slope of the constant-current curves is small and thus the value of R_S is very high in comparison to that of triodes, from five to ten times greater. Consequently, in the normal operating range, the plate load resistance R_L is substantially lower than R_S, If R_S were the true source resistance it would have to be equal to R_L to obtain delivery of all the available power. Thus, we have a vital clue in proving that R_S is not the source resistance, while in fact it is a insignificant parameter in the operation of RF power amplifiers.

Therefore, it is ironic that instead of being a source resistance, R_S is really a non-dissipative, dynamic, **anti**-source resistance, because it causes a small **decrease** in delivered power relative to that which would be delivered if R_S didn't exist. Quoting Sabin[3], *"The power loss due to the dynamic resistance is compensated by an increase in the drive level."* Thus R_S is a relatively **insignificant** parameter in the performance of an RF power amplifier, because the power delivered by output tube to the pi-network of the amplifier results principally from the change in plate current due to the change in **grid** voltage, **not due the change in plate** voltage.

If the source is considered as a constant-current source, R_S can be viewed as an insignificantly-high resistance in parallel with the true non-linear input source resistance obtained by a Chaffee-analysis calculation that determines load resistance R_L. The true source resistance delivering power to the network input is the average value of the dynamic resistance occurring during the period of plate-current conduction, which is a function of the total integrated energy contained in the current pulses entering the pi-network. The average source resistance thus equals R_L when all available power is being delivered to the network.

Consequently, I have provided concrete and conclusive evidence that R_S is **not** the source resistance as Bruene claims.

2) Why His Assertion that the Load-Variation Method is 'Useless' is Unfounded.

In this section Bruene attempted to measure the output resistance of a pi-network using the load-variation method, but failed due to the use of inappropriate measuring equipment. Because of the failure he asserts that the load-variation method is "useless".

Bruene's data was unreliable because he attempted to measure changes in **power** with a Bird wattmeter instead of measuring changes in **voltage** to determine the change in load voltage resulting from the small change in load resistance. The wattmeter only indicates power, not voltage. He apparently overlooked the fact that when the change in load resistance is small, load voltage and current change in approximately equal amounts with change in load resistance, but **in opposite directions**. Consequently, the voltage-current product (power) changes so imperceptably it is undetectable with the Bird wattmeter.

Using Bruene's 50- and 45-ohm load resistances in an example, I'll prove why a wattmeter delivers data unacceptable for determining the small differential current $I_1 - I_2$ of his Eq. 1. Assume the output resistance of a source is 50 ohms, to be either determined or verified. Also assume all of its available power delivered into the initial 50-ohm load is 100 watts. In this condition, the load voltage and current are 70.71 v. and 1.414 a., respectively. Using the load-variation method to determine the output resistance we change the load from 50 to 45 ohms and attempt to read the change in power with which to calculate the change in the load voltage and current for use in his Eq. 1. The SWR into the 45-ohm load is 1.1111:1, and the power delivered is 99.723 watts, a decrease of only 0.286 w. (0.012 dB). **The Bird wattmeter cannot detect this small change.** On the other hand, the load **voltage** and **current** with the 45-ohm load are 66.989 v. and 1.4886 a., respectively. Note that although the product of the new voltage and current also is 99.732 watts, a decrease of only 0.286 watts, the voltage has **decreased** by 3.72 v. (0.4695 dB) and the current has **increased** by 0.0746 a. (0.4466 dB). The crucial point is that the voltage and current changed by approximately the same amount, but in **opposite directions**, resulting in a practically undetectable change in the voltage-current product, the power. This is why Bruene's attempt to determine output resistance failed using the load-variation method.

On the other hand, using digital RF voltmeters for measuring the differential load voltage, I have found that the load-variation method yields values of **output resistance** of RF power amplifiers that are right on target. The data resulting from my measurements reported in References 1 and 2, are described below. The range of scatter in my data seldom exceeded 10 percent error, with averages never exceeding 2 percent error. The scatter was due almost entirely to minor instability of the output power during the measurements. Note in both *QEX* [2], and in *Reflections II* [3], Page 19-17, Table 19.1, of the six measurements shown, the **maximum** scatter (47.4 ohms) is only a 7 percent error, and the average, 50.3 ohms, is less than 2 percent from the reference load resistance of 51.2 ohms. Many more measurements were taken with the same degree of accuracy, but the six shown were considered sufficient for publication to prove the load-variation method of measuring network output resistance is valid.

Some people say my data can't be valid because what I consider a source resistance is actually a magnitude of impedance, due to reactance introduced into the network by the 45-ohm resistance, while resonant with the 50-ohm load. It is true that reactance is introduced into the network, which appears at the input if the phase delay in the network is other than a multiple of 90°. However, the reactance is zero at the load, the measuring point, because the 45-ohm load resistance is non-reactive. Thus the measured resistance is resistance, not a magnitude of impedance.

To provide insight into why this is so, consider a transmission line terminated with a pure resistance unequal to its characteristic impedance Z_0. In this condition, except for points on the line at multiples of $\lambda/4$ from the load, impedances appearing all along the line contain reactance. However, when the termination is a pure resistance, the angle of the voltage reflection coefficient at the termination is 0° with resistance greater than Z_0 and 180° when less than Z_0. Thus, the impedance at the load is purely resistive. The same is true when the load terminating the network in the RF power amplifier is resistive. Conclusion--Bruene's claim that the load-variation method 'useless' has no foundation, and my data are valid despite his claim to the contrary.

3) Why His Reflected Power Measurement Failed to Measure R_S

Now we come to Bruene's Reflected Power method of measurement, in which he delivers a large test signal into the output of the test amplifier, delivered by a 200-watt transceiver. The test amplifier, with a π-L network, was initially adjusted to deliver 130 watts into a 50-ohm dummy load, with a computed 2100-ohm plate load resistance R_L at the input of the network. Thus, the impedance transfer ratio of the network is 45:1. Approximately 850 volts dc is applied to the plates with 22 ma idling plate current, with 18.7 watts dissipated. With the transceiver delivering power to the test amplifier, a Bird directional wattmeter showed 50 watts forward and 26.5 watts reflected power, indicating a 6.35:1 SWR, thus an input resistance at the output of the test amplifier of $50 \times$ SWR = 317.5 ohms. Now, neglecting network losses, 317.5 x 42 = 13,335 ohms are loading the network input of the test amplifier, the resistance Bruene believes is R_S, but which I'll show is not true.

Recalling from Part 1, R_S (or R_P) = $\Delta E_P/\Delta I_P$, which equals the **change** in plate voltage divided by the resulting **change** in plate current. Observe that Bruene's measurement of reflected power gleans no data concerning a change in either plate voltage or current. Thus, there can be no determination of R_S with his measurements. So let's examine what his measurements really gleaned, where I'll show that the resistance he determined is only the dissipative resistance R_{PD} of the tube. That is, the resistance responsible for the power dissipated to heat, which is the product of instantaneous voltage and current between the cathode and plate.

To demonstrate the principle involved here, losses can be neglected, because the difference in the final numbers will be insignificant in understanding the principle. Consequently, we let the 6.35 SWR exist at both the input and output of the network of the test amplifier, indicating a dissipative load resistance R_{PD} of 13,335 ohms at the network input, as Bruene indicated. (Of course, this value will be somewhat higher when losses are considered.) The load voltage reflection coefficient at the network input (at the plates) is $\rho = 0.728$, the power reflection coefficient $\rho^2 = 0.530$, and the power transmission coefficient $(1 - \rho^2) = 0.470$. With 50 watts incident at the 6146 plates the power absorbed in the dissipative plate resistance R_{PD} is 50 watts

$\times$ 0.470 = 23.5 watts, and the power reflected at the plates is 50 $\times$ ρ^2 = 50 $\times$ 0.530 = 26.5 watts, as Bruene indicated. However, if only 26.5 watts of the incident 50 watts is reflected, the remaining 23.5 watts must be absorbed in the dissipative plate resistance R_{PD}, 50 watts $\times$ 0.470 = 23.5 watts, which simply adds to the 18.7 watts of idling power.

This is proof why Bruene has not been measured R_S with his test setup.

4) Why His Calculation of Source Resistance is in Error by an Order of Magnitude

Bruene's **computer** analysis of the load variation method resulted in data that are incorrect and misleading, because the computer-simulated amplifier model used in his analysis in no way represents the physical operating test amplifier used in the reflected-power method of measurement discussed in Part 3. For starters, the program begins using R_S as the series source resistance, as shown in his Fig 3. (Why would he expect us to believe that with an internal series resistance R_S of 20,000 ohms the 6146 amplifier could deliver 130 watts?) However, we disposed of R_S earlier as not being the source resistance of the amplifier. Consequently, in using R_S in the computer calculations, the values of Z_{OUT} in his Table 1 are far off target for an amplifier of the test-amplifier type delivering 130 watts into 50-ohm and 45-ohm loads. The maximum power deliverable (and delivered) with this amplifier is approximately 130 watts, which indicates that the π-L network was initially adjusted for delivering all the power available for the given drive level. Except for the value Z_{OUT} = 46.9–j4.82 ohms in Table 1, no other values even come close to an output impedance that would allow delivery of 130 watts into the 50- and 45-ohm loads.

The values appearing in the example in his Appendix 1 are also off target, by an order of magnitude for the amplifier under discussion. This RF test amplifier, capable of delivering 130 watts into a 50-ohm resistive load, would require an output resistance of 50 ohms to deliver that amount of power into a 45 or 50-ohm load. But with the indicated 499.99-ohm output resistance it could deliver only 42.97 watts (33.1% of 130 watts) into a 50-ohm load, because it sees a 10:1 mismatch looking into the 50-ohm load. Evidently, to obtain a computed output resistance of 499.99 ohms, ten times the value required to deliver 130 watts, the voltages computed across the 45- and 50-ohm load resistances are also in error. These discrepancies provide adequate and compelling evidence that the computer-simulated model of the RF amplifier Bruene used is not a realistic simulation of the physical RF amplifier, and that the resulting computer data is invalid.

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References:

[1] M.W. Maxwell, W2DU, "On the Nature of the Source of Power in Class B and C Amplifiers," *QEX*, May/June 2001, pp 32-44.

[2] M.W. Maxwell, W2DU, "*Reflections II--Antennas and Transmission Lines,"* Chapter 19, Sec 19.8 and Table 19.1, pp 19-15 to 19-25. (Chapter 19 is a copy of Ref 1.)
[3] W.E. Sabin, W0IYH, "Dynamic Resistance in RF Design," *QEX*, September 1995, pp 13-18.
[4] Personal Correspondence from Warren Bruene, W5OLY, dated November 25, 1992. (Copy furnished via e-mail on request.)