APPENDIX 12 – ADDITIONAL MEASUREMENTS PROVING THE EXISTENCE OF A CONJUGATE MATCH AT THE OUTPUT OF RF POWER AMPLIFIERS

The purpose of this experiment is to provide proof in addition to that presented in Sec 19.8, that a conjugate match exists at the output of an RF power amplifier when it is delivering all of its available power into its optimum load resistance R_L. It will be proved by showing that the power delivered by the amplifier into a mismatched load impedance decreases in accordance with the universally-known function of conjugate mismatch loss (return loss) versus load mismatch. The legend of the parameters measured during this experiment that are pertinent to the proof are as follows:

(1) Optimum Load resistance R_L
(2) Impedance Z_{Lin} at input of pi-network tank
(3) Mismatch between R_L and Z_{Lin}
(4) Mismatch loss between R_L and Z_{Lin} at input of pi-network tank circuit
(5) Output impedance of amplifier R_{OUT}
(6) Load resistance R_{LOAD}
(7) Conjugate-mismatch loss at junction of R_{OUT} and R_{LOAD} at output of pi-network

Experiment 1:

The measurement procedure used during this experiment is as follows:

1. The RF power amplifier, a Heathkit HW-100 transceiver, was tuned to resonance at 3.8 MHz and loaded with the drive level adjusted to deliver maximum available power of 114 watts into R_{LOAD}, a 52-ohm Bird 1500-watt dummy load terminating the pi-network.

2. Using a Hewlett-Packard HP-4815A RF Vector Impedance Meter, optimum load resistance R_L was then measured at the input of the pi-network tank circuit, and found to be 1350 + j0 ohms.

3. Nine resistors of different values of R_{LOAD} from 240 ohms down to 17.5 ohms were then used separately to terminate the output of the pi-network to obtain the corresponding transformed values of Z_{Lin} at the input of the pi-network with each separate value of R_{LOAD}.

4. After measuring each of the separate values of Z_{Lin} the data resulting from the measurements appear in tabular form below:

TABLE 1

R_{LOAD} ohms	MISMATCH R_{LOAD} vs 52 ohms	Z_{Lin} (polar)	Z_{Lin} (R + jX)	MISMATCH Z_{Lin} vs R_L = 1350ohm at input of pi-network	CONJUGATE MISMATCH LOSS At Load	CONJUGATE MISMATCH LOSS At Input of Pi-Network†
240	4.6:1	950 @ 58°	503.4 + j805.6	3.74:1	–2.3 dB	–1.77 dB
160	3.17	980 @ 48°	655.7 + j728.3	2.78	–1.37	–1.09
100	1.92	1060 @ 32°	898.9 + j561.7	1.90	–0.45	–0.44
83	1.6	1150 @ 20°	1080 + j393.3	1.48	–0.24	–0.16
52	1.0	1350 @ 0°	1350 + j0	1.0	0.0	0.0
41	1.22	1580 @ –14°	1533 – j382.2	1.34	–0.04	–0.09
34.2	1.52	1630 @ –18°	1550 – j503.7	1.45	–0.19	–0.15
26.0	2.0	1780 @ –32°	1509 – j943.3	1.93	–0.51	–0.46
20.6	2.52	1900 @ –41°	1433 – j1245	2.39	–0.90	–0.80
17.5	2.97	2000 @ –48°	1338 – j1486	2.88	–1.23	–1.16

† The numbers in the column 'At the Input of Pi-network' are not intended to imply a conjugate match exists at the input, but only to indicate the decrease of the RF pulsed energy delivered to the pi-network when the network input impedance is other than R_L = 1350 ohms.

The output loading of the amplifier was initially adjusted for delivery of all the available power into a 52-ohm load to provide a reference from which to evaluate the mismatch loss encountered with various mismatched loads relative to *conjugate* mismatch loss. Accordingly, observe in Table 1 that the amplifier output is shown to be matched to R_{LOAD} = 52 ohms with zero loss showing in the Conjugate Mismatch Loss column. Note also that resistance R_{LOAD} = 52 ohms is transformed upstream through the network to R_L = 1350 ohms at the input of the network.

Now note particularly that magnitudes of the mismatches occurring between R_L = 1350 and the various values of complex impedances Z_{Lin} appearing at the input of the network are nearly the same as those at the output of the network between R_{LOAD} = 52 ohms and the corresponding mismatched values of R_{LOAD}. The differences between the corresponding mismatch values at the network input relative to those at the output are principally due to losses in the real-world network, and partially to limitations of measurement accuracy. However, because the mismatches appearing at the network input and output are correspondingly similar, the reduction in the amount of average integrated pulsed energy delivered to the pi-network tank with the various input impedances also corresponds to the mismatch losses appearing at the output of the network.

Experiment 2:

For this experiment we set a maximum reference level of output power delivered to R_{LOAD} = 52 ohms at each of five different power levels. The values of R_{Lin} appearing at the input of the network were measured at each reference power level for each of the three loads shown in Table 2. Leaving the tuning and loading controls of the amplifier undisturbed after setting the reference level at each power level, R_{LOAD} is changed to provide separate mismatches of 2:1 and 3:1 at the output. Then the network input impedance Z_{Lin}, and the output power delivered to each mismatched load, respectively, were measured.

TABLE 2

NOMINAL OUTPUT	R_{LOAD}	MEASURED Z_{in}	MISMATCH AT LOAD	MISMATCH AT PI INPUT	POWER OUT		CONJUGATE MISMATCH LOSS	IDEAL CONJUGATE MISMATCH LOSS ‡
100 watts	52	1500 + j0	1:1	1:1	95.9	ref	0.0 dB	0.0 dB
	26	1509.6 - j980.4	2.0	1.79	80.0		-0.78	-0.51
	17.5	1271.3 - j1412	2.97	2.7	59.2		-2.09	-1.23
75	52	2100 + j0	1:1	1:1	71.7	ref	0.0	0.0
	26	1677 - j1089	2.0	1.85	60.1		-0.77	-0.51
	17.5	1312 - j1509	2.97	2.68	45.6		-1.96	-1.23
50	52	2850 – j0	1:1	1:1	48.8	ref	0.0	0.0
	26	1951 – j1219	2.0	1.88	38.8		-1.0	-0.51
	17.5	1472 – j1635	2.97	2.72	31.2		-1.94	-1.23
25	52	5100 + j0	1:1	1:1	20.2	ref	0.0	0.0
	26	3380 – j1505	2.0	1.72	16.8		-0.80	-0.51
	17.5	2409 – j1951	2.97	2.50	14.7		-1.38	-1.23
20	52	5600 + j0	1:1	1:1	17.7	ref	0.0	0.0
	26	3472 – j1546	2.0	1.8	4.9		-0.75	-0.51
	17.5	2451 – j2057	2.97	2.65	11.1		-2.01	-1.23

‡ The ideal conjugate-mismatch loss assumes lossless components in the pi-network. The difference between 'conjugate mismatch loss' and 'ideal conjugate mismatch loss' is the result of the inherent loss in the network.

Now comes the revealing part. Examination of the tabular data in Table 2 reveals that the decrease in power delivered to R_{LOAD} is directly proportional to the loss resulting from the conjugate mismatch between loads Z_{Lin} at the input of the pi-network and the corresponding amounts of average integrated power delivered by the source at each power level.

Experiment 3:

The purpose of this experiment is to measure the decrease in power delivered by the amplifier to various *complex*-impedance loads with specific degrees of mismatch, to show again that the decrease in power due to mismatch conforms to the function of *conjugate mismatch loss* (return loss) versus load mismatch. The impedances which presented specific mismatches to the output of the amplifier were obtained using a T-network antenna tuner terminated in a load of 50 + *j*0 ohms. The network was first adjusted to obtain a one-to-one input-output ratio to yield a 50 + *j*0 ohm resistance at the input to provide a matched impedance reference. The network was then re-adjusted to provide various complex impedances at the input that yield specific desired values of load mismatch at the output of the amplifier for the measurements of power delivered through the mismatches to the 50-ohm load terminating the tuner. The power delivered to the 50-ohm load terminating the tuner was determined by measuring the load voltage with a Hewlett-Packard HP-8405A RF Vector Voltmeter, and calculating the power using the measured resistance of the load. The resistance of the load was measured with a Hewlett-Packard HP-4815A RF Vector Impedance Meter.

In Table 3, ρ is the voltage reflection coefficient corresponding to the SWR measured at the input of the antenna tuner to obtain the desired reactive mismatched load impedances to terminate the output of the amplifier. Power reflection coefficient ρ^2 represents the power *reflected* from the mismatched load impedances, and $(1 - \rho^2)$ represents the power *transmitted through* the mismatched loads and absorbed in the 50-ohm load terminating the tuner. Table 3 also shows the relationship between the SWR mismatch and conjugate mismatch loss, in relation to the decrease in power absorbed in the 50-ohm load due to the load mismatch. The reference for the 0.0 dB conjugate mismatch loss was set with the impedance at the input of the tuner adjusted to $50 + j0$ ohms, for a 1:1 SWR, and reflection coefficient $\rho = 0$. In this reference condition all power delivered is absorbed in the 50-ohm matched load at the output of the tuner. The measured power absorbed in the $50 + j0$-ohm load terminating the tuner versus the various mismatched impedances at the tuner input terminating the output of the amplifier, is based on 100 watts measured at zero conjugate mismatch loss, i.e., with the input impedance of the tuner adjusted to $50 + j0$ ohms. The tuner was then readjusted to obtain the various desired values of mismatch appearing at the input of the tuner. Power loss in the tuner network is excluded, because all measurements, including the 50-ohm reference load at the input of the tuner, were taken through the network while continuously terminated with the $50 + j0$-ohm load resistor in which the delivered power was measured.

TABLE 3

SWR	ρ	ρ^2	$(1 - \rho^2)$	Mismatch Loss dB	Relative Power Watts	Measured Power
1.0:1	0.0	0.0	1.0	0.0	100	100
1.5:1	0.200	0.040	0.960	0.177	96	96
2.0:1	0.333	0.111	0.889	0.512	88.9	89
2.5:1	0.429	0.184	0.816	0.881	81.6	80
3.0:1	0.500	0.25	0.75	1.249	75.0	74

The data in the relative power column indicates the theoretical *calculated* power that would be absorbed in the load versus the varying degrees of SWR and conjugate mismatch. The data in the *measured* power column indicates the power actually absorbed by the $50 + j0$-ohm load terminating the network. Comparison of these two columns shows that the values of measured power agree with the theoretical calculated values based on conjugate mismatch loss within the limitations of measurement accuracy. Hence, a condition of conjugate matching is proved when the measured conjugate mismatch loss is zero and the power absorbed by the mismatched loads terminating the amplifier decreases uniformly according to the standard return loss vs conjugate mismatch curve.

Thus, the data obtained from these measurements also provides additional conclusive proof that a conjugate match exists at the output of the RF power amplifier when the amplifier is delivering all of its available power.