IN-20
19758
P. 40

NASA Technical Memorandum 106657

Evaluation of a Multi-Kw, High Frequency Transformer for Space Applications

Mary Ellen Roth
Lewis Research Center
Cleveland, Ohio

August 1994

National Aeronautics and
Space Administration

Evaluation of a Multi-Kw, High Frequency Transformer for Space Applications

Mary Ellen Roth
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

INTRODUCTION

Various NASA studies have shown that high power (multi-kW and higher) electrical systems for various aerospace applications favor high frequency distribution systems, due to the improved safety and weight factors associated with those systems. Other favorable characteristics include low EMI, minimal wiring and ease of system parameter sensing and control of a single phase system.[1] In aerospace power systems, as in terrestial AC distribution systems, transformers are needed to provide voltage changes, isolation and the resetting of ground. Under NASA contract NAS3-21948 a multi-kW high frequency transformer was designed, fabricated and tested by Thermal Technology Lab, Inc. of Buffalo, New York. "The goals of this program included the determination of the relationships between transformer weight, efficiency and operating frequency; low internal temperatures and reduced specific weight; and the validation of these new design concepts through experimentation and the fabrication and testing of transformers and their insulation systems."[2] The transformer was delivered to NASA-Lewis, where an evaluation program was conducted in Lewis' High Power High Frequency Component Test Facility. The transformer was tested in both atmosphere and under vacuum conditions. This paper will discuss the design of the transformer, the evaluation program and test results, the failures experienced and conclusions.

TRANSFORMER DESIGN DESCRIPTION

A multi-kW high frequency transformer was developed for long duration space applications under NASA contract NAS3-21948. The transformer, shown in Figure 1, was developed by Thermal Technology Lab, Inc. to be lightweight, have a low thermal internal resistance, and be cooled by metallic conduction means. Pie windings for both the secondary and primary windings were selected as being the best suited for conduction cooling. The windings are mounted on vertical aluminum support plates which are bolted to the baseplate of the transformer. The insulator, Kapton, was used to provide a thermal path and electrical isolation between the coils and the aluminum plates. The baseplate is mounted on a cooled heatsink and is thereby maintained at a design temperature of 50° C. Tape wound "C" cores of Supermalloy with 0.001 inch thick laminations were used to reduce core loss at high frequencies. The design specifications for the transformer are listed in Table 1.[2] A more detailed description of the transformer can be found in the contractor report (NASA CR 168082) "Design and Development of Multi-kW Power Electronic Transformers".

TABLE 1: TRANSFORMER DESIGN SPECIFICATIONS

Output power	25kVA
Input Voltage	200V
Output Voltage	1500V
Input Voltage Waveform	Square Wave
Efficiency	99% or greater
Leakage inductance	10×10^{-6} H relative to primary
Operating Environment	Zero g, 1.33×10^{-4} N/m^2 or less
Materials outgassing	Maximum mass loss of 1%, a maximum of 0.1% volatile materials
Operating Baseplate temperature	50° C
Storage Temperature	-20° C to operating temp
Shield	Grounded electrostatic shield between primary & secondary
Duty cycle	Continuous
Life	10 years
Operating Frequency	20 kHz
Operating temperature	85° C ±2° C

Transformer Evaluation Program

The transformer was delivered to NASA Lewis upon completion of the contract. The transformer then underwent a series of tests in the Lewis High Power High Frequency Component Test Facility. Short circuit, open circuit, power and efficiency tests were conducted. Power testing was conducted under both atmosphere and vacuum conditions. Voltage, current and power measurements were made at timed intervals throughout each test condition. The temperature rise of the transformer was monitored throughout all the tests. Once the temperature reached equilibrium, the test was terminated. Thermocouples were mounted on four of the aluminum support plates, the aluminum baseplate and the heatsink. The baseplate was maintained at the design temperature of 50° C. Figure 2 shows the placement of the thermocouples.

Short Circuit tests

A series of short circuit tests were conducted at several frequencies to determine the effects of frequency on the operation of the transformer. Tests were run at 60, 400, 10,000 and 20,000 Hz. I^2R losses were determined for each test case. The same basic test procedure was followed in each case.

Voltage was applied to the secondary so as to produce rated current in the shorted primary. The results from these tests can be found in Table 2.

TABLE 2: SHORT CIRCUIT TEST DATA

Parameter	60Hz run	400Hz run	10kHz run	20kHz run
E_s	10.26 v	11.17 v	55.3 v	90 v
I_s	16.7 a	16.66 a	16.7 a	16.7 a
I_p	119.2 a*	125.8 a	129 a	127.6 a
O_s**	8.6^o	17.3^o	59.4^o	61.2^o
High Temperature	163^o F	173^o F	267^o F	335^o F
Losses	180 w	178 w	470 W	724 w

* could not reach rated current of 125 A at 60Hz
** Phase angle between E_s and I_s

At 60 Hz, the copper losses were 180 watts. All the temperatures were within the design specs, the maximum temperature was 163^o F at TC #3. However, rated current was not achieved on the primary due to saturation of the core at this low frequency. At 400 Hz, the copper losses equaled 178 watts. Again, all temperatures were within the specs, the maximum temperature was 173^o F at TC #3. At 10kHz, the losses were 470w. All temperatures were above the designed operating temperaure with the maxiumum temperature being 267^o F at TC #3. At 20kHz, the design frequency of the transformer, the losses equalled 724W. All temperatures were above the design rating, with the maximum temperaure being 340^o F. It should be noted that the losses measured exceeded the predicted short circuit losses(136W) as stated in the design report.[2]

Open Circuit tests

For the open circuit test, power was applied to the primary until rated voltage (200v) was reached on the primary. This test was conducted only at 20kHz. Open cicuit losses (the coreloss) equalled 90 watts. The calculated core loss, as stated in the contractor design report, was 60 watts.

POWER TESTS

Atmosphere tests

A series of power tests at 20 kHz were conducted at the following power levels; 1, 5, 10, 15, 17, and 20 kw. Various power equipment was used for the different tests. However, the same basic instrumentation and measurement techniques were used for all the tests. Appendix A includes all the test set-ups for the individual power tests conducted.

For all tests, power was applied to the transformer through a dual feed of the primary bus bars. Voltage measurements were made with a Fluke true RMS voltmeter. Current measurements were made with Pearson coils and the Fluke voltmeters. All waveforms were monitored on a Tektronix analog scope. The baseplate of the transformer was maintained at the design temperature of 122° F. The temperature rise of the transformer was monitored through the thermocouples mounted on the aluminum support plates. See Figure 3 for placement of thermocouples. Testing was terminated once the transformer temperature reached a steady state condition.

The data recorded from the various power tests can be found in Table 3.

It should be noted that because of the nature of the power supply used for the 5 kW and above power tests, there was some distortion in the waveforms. Examples can be found in Appendix B.

TABLE 3: ATMOSPHERE POWER TEST DATA

Input Pwr	E_p	I_p	TC 1	TC 2	TC 3	TC 4
1050 w	200 v	5.4 A	113°F	114	122	119
4600 w	180 v	25.8 A	121	125	132	129
11,000 w	198 v	60.7 A	91	167	174	78
*16,000 w	200 v	84.7 A	96	216	228	83
**15,800 w	160 v	101.7 A	251	271	277	227
17,400 w	160 v	109.6 A	258	283	286	244
***20,000 w	160 v	130 A	317	350	356	295

* First failure experienced
** Core tests revealed the core was saturating, input voltage reduced to 160v, power rating reduced to 20kVA.
*** Second failure of the transformer occurred during this test run.

Failures

The first failure occurred during testing at 16 kW. There was a problem with distortion of the waveforms. These waveforms are depicted in Figure B.1 of the Appendix. The failure occurred 45 minutes into the test procedure. The maximum temperature at the time was 228° F. The transformer was disassembled and examined to determine the cause of the failure. Examination of the transformer revealed a hole in the two 5 mil sections of Kapton insulation located between the secondary bus bar and the aluminum support plate #8. Figure 3 shows the location and nature of the failure. It was concluded that the breakdown of the Kapton was due to increased electric field strength along the sharp edges of the aluminum support plates. The damaged Kapton was removed and replaced with two 6 mil strips of Mica tape. The sharp edges of plates 7 and 8 were rounded.

While repairs were underway, a core test was conducted. These tests revealed that the core was beginning to saturate at the design operating voltage. It was recommended that the primary input voltage be reduced to 160 v for the remainder of the test program. The reduced input voltage did improve waveform quality for the next two power levels.

The transformer evaluation continued with a 20 kVA (derated) maximum power test. The waveforms were again distorted (especially on the secondary) at this power level. See Figure B.2 in the Appendix, for waveforms. There was a considerable increase in temperature as compared to the previous test at 17.5 kW. A second failure occurred about 45 minutes into the test run. The highest temperature recorded was 350^{o} F, which is almost double the design rating of the transformer.

The transformer was disassembled and examined. This time the failure occurred on the second to last coil of the secondary winding. The first failure took place at the last secondary coil. The secondary is composed of eight coils in series. Again, the two 5 mil section of Kapton separating the secondary coil from the aluminum support plate broke down. See Figure 3 for placement and description of the failure.

Repairs were made to the tranformer, and the damaged Kapton was replaced with two 6 mil strips of Mica tape. The transformer evaluation program continued with tests under vacuum conditions.

Vacuum Tests

The repaired transformer was then tested in a vacuum chamber at the following power levels; 1, 2, 5, 8, 10, 16, 17 and 20 Kw. The objective was to test the transformer at increasing power levels and assess its performance under vacuum conditions. A belljar vacuum system was used as the test chamber for this series of tests. A Residual Gas Analyzer was used to track the outgassing of the transformer. A complete description of this equipment can be found in Reference #1.

At each power level, the transformer was placed in the vaccuum chamber with the necessary instrumentation connected. The chamber was then pumped down to a pressure of 4 to $8x10^{-}6$ Torr. Power was applied to the transformer once the chamber was down to a pressure of less than 4 x $10^{-}6$ Torr. The test was then run until the temperature of the transformer reached steady state.

The test set-ups for each of these runs can be found in Appendix A, Section 2. A listing of select data points for each of the tests can be found in Table 4.

TABLE 4: VACUUM TEST DATA

INPUT POWER	E_p	I_p	I_s	TC 1 ^oF	TC 2 ^oF	TC 3 ^oF	TC 4 ^oF
1150 W	159 V	7.4 A	0.93 A	113	112	112	115
2400 W	160 V	15 A	1.9 A	122	122	122	125
4600 W	160 V	29.5 A	3.78 A	132	135	134	135
7900 W	158 V	50.8 A	6.61 A	157	166	166	161
10200 W	155 V	67.3 A	8.6 A	182	198	198	185
15800 W	159 V	102.3 A	11.1 A	238	300	289	280
16900 W	158 V	107.4 A	14.1 A	274	300	303	269
20000 W	160 V	129 A	15.5 A	335	390	387	352

EFFICIENCY MEASUREMENTS

Due to the distorted nature of the waveforms from the power supplies used for the high power testing, it was difficult to get an accurate efficiency measurement of the transformer at full power. A management decision was made to make efficiency measurements at a lower power level - 1 kW - where the waveforms were far less distorted. The 1 kW ENI power amplifier was selected as the power source for these tests because its output had the least amount of visual distortion as compared to the other available power sources. There was also an instrumentation limit on measuring the secondary voltage of the transformer which is 1200v. In order to get an accurate measurement of the secondary voltage, the input primary voltage was reduced to 80v for these tests. Two different measurement techniques were used to make the efficiency calculations. The first method involved the use of the Fluke 8920A true RMS voltmeter, Pearson current monitors and an analog scope.

For the second method, a Yokogawa digital power meter was used to make the necessary measurements, along with Fluke and Pearson instrumentation for comparison.

The test and instrumentation set-up for both methods are depicted in Appendix A, Section 3. Parameter measurements and efficiency calculations can be found in Table 5. Both these tests were conducted under vacuum conditions.

TABLE 5: EFFICIENCY CALCULATIONS

Parameter	Method #1	#2: Yokogawa	#2: Fluke
E_p	80 v	78.9 v	80 v
I_p	12.8 a	12.67 a	12.76 a
E_s	600 v	600.5 v	603 v
I_s	1.65 a	1.65 a	1.65 a
Input Power		1003 w	
Output Power		990 w	
Primary Power factor	$\cos 0_p=0.999$	0.999	
Secondary Power factor	$\cos 0_p=0.999$	0.996	
Calculated Efficiency	96.6 %	98.7 %	97.3%

CONCLUSIONS

The transformer did not operate within its design ratings. The temperature rise of the transformer exceeded its design rating even at lower power levels. Some of the temperature rise can be attributed to the distorted waveforms that were applied to the transformer. However, design changes are required to better remove the heat from the windings and the core. Another problem was the saturation of the core even though it was designed to operate with an input voltage of 200V at 20kHz. Another concern is the higher than expected losses in the transformer. Even the open circuit and short circuit tests, which were done at low power and at design operating temperatures, yielded losses that measured greater than expected.

Increased losses may be partly attributed to eddy current losses in the aluminum used as the support plates for the primary and secondary coils. Another concern is the use of Kapton as an insulating material at this frequency and temperature. However, at lower temperatures, this may not be an issue.

It should be also noted that the test equipment, mainly the power sources used for this test program, were not ideal. A less distorted sine wave input would probably improve the operation (reduce the losses) in this transformer. Better sources and better instrumentation would also allow for more accurate efficiency measurements to be made.

Acknowledgements

Walter Krawczonek
Gene Schwarze
Jan Niedra
Irving Hansen
Ira Myers

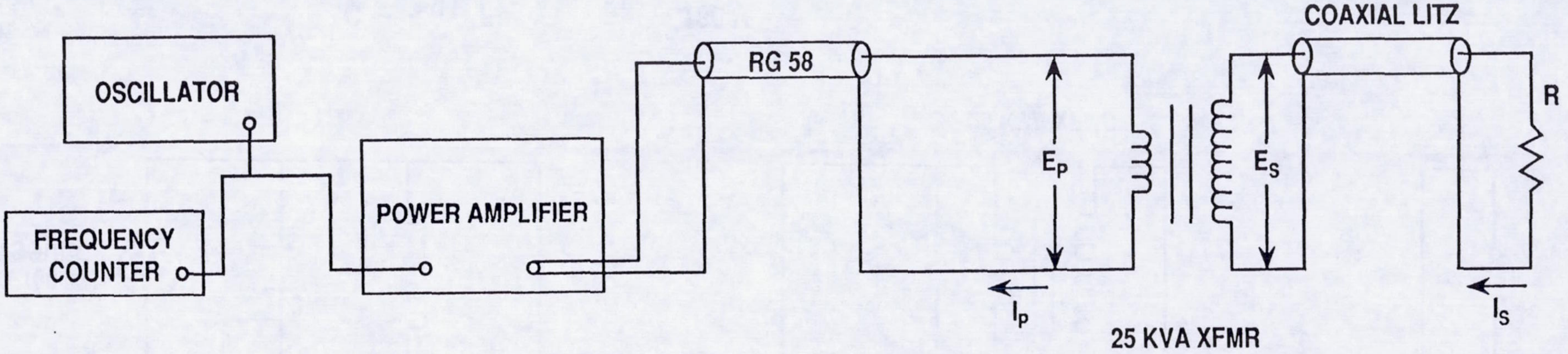
References

1. "High Power, High Frequency Component Test Facility", by Mary Ellen Roth and Walter Krawczonek, February 1990, NASA TM 102500.
2. "Design and Development of Multi-kW Power Electronc Transformers", by James P. Welsh, NASA CR 168082, February 1983.

APPENDIX A

SECTION 1: TESTS IN ATMOSPHERE

TEST SET-UP FOR 1000 W POWER TEST IN ATMOSPHERE



E_P = 200 V

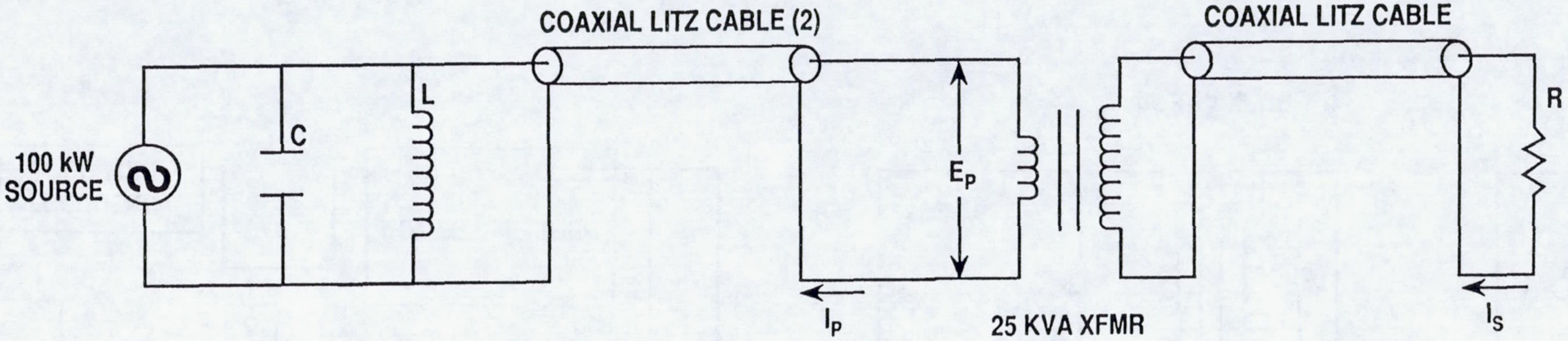
I_P = 5.37 A

I_S = 0.65 A

R = 2.25 KΩ

POWER = 1040 W

5000 W POWER TEST



$C = 5.0\,\mu F$

$L = 12.5\,\mu H$

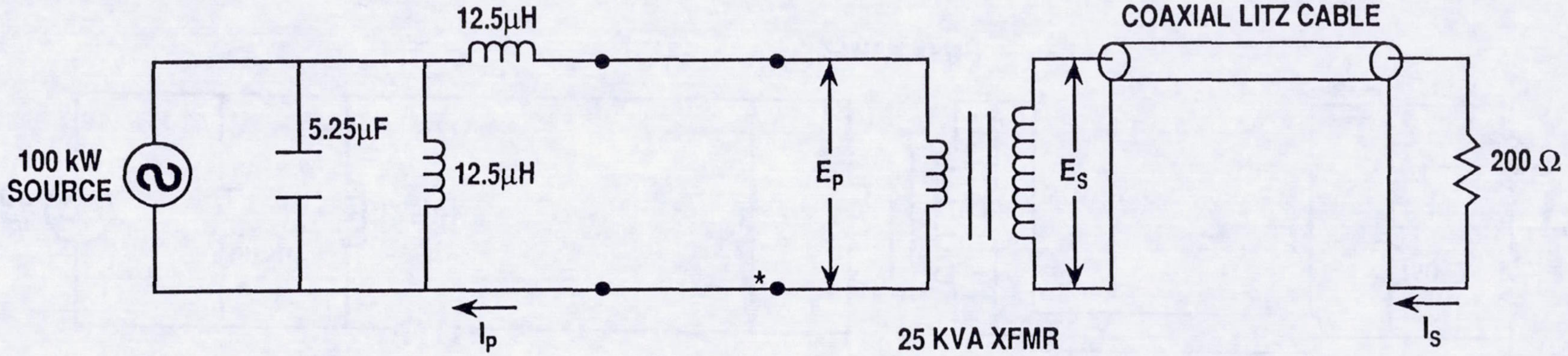
$R = 400\,\Omega$

$E_P = 180$ V

$I_P = 25.8$ A

$I_S = 3.33$ A

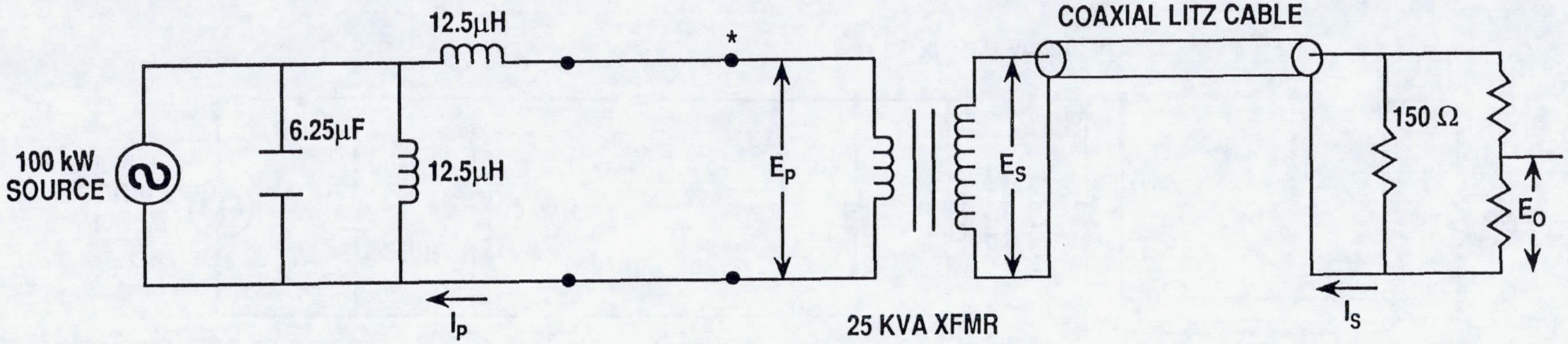
10,000 W POWER TEST



E_P = 200 V
I_P = 60.7 A
I_S = 7.68 A

* DOUBLE #2 AWG WELDING CABLES TO PRIMARY

15,000 W POWER TEST #1

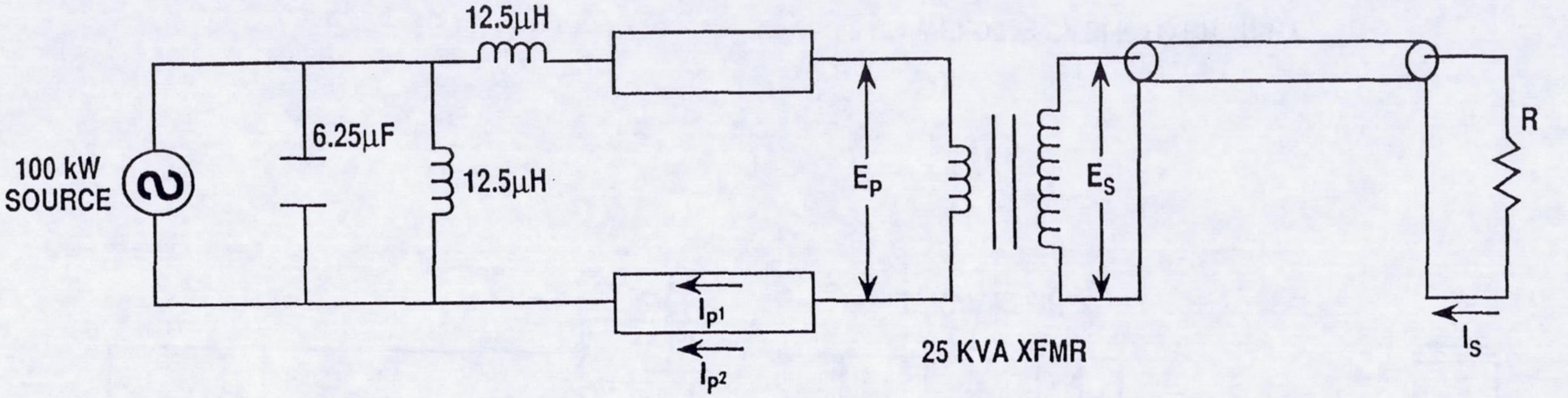


$E_P = 200$ V
$I_P = 84.7$ A
$I_S = 10.2$ A

* DOUBLE #2 AWG WELDING CABLES TO PRIMARY

FAILURE #1: SECONDARY SHORTED TO CASE - 45 MINUTES INTO TEST

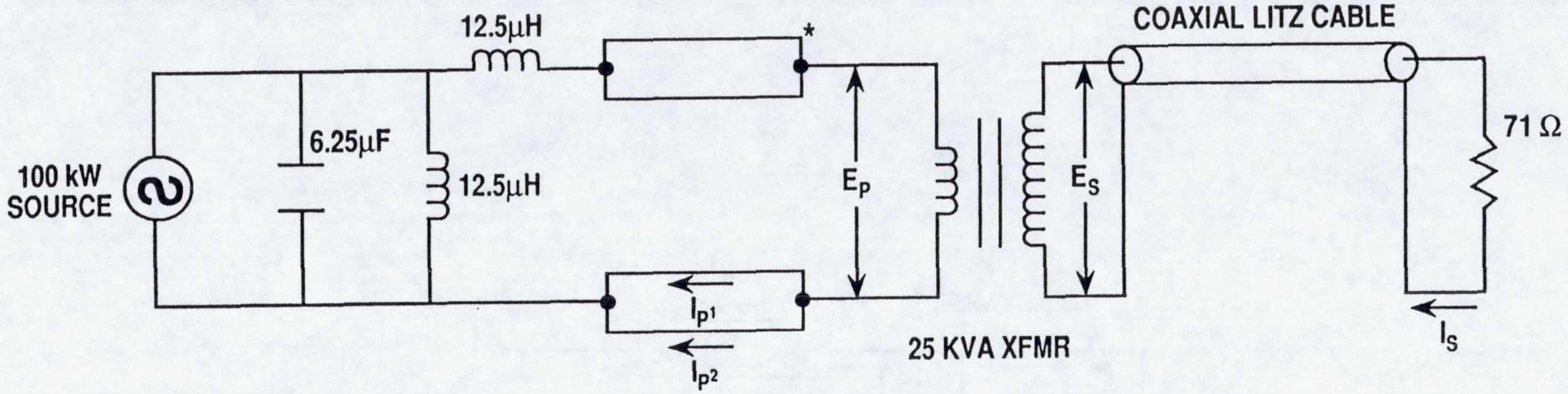
TEST SET-UP FOR 15 kW (Run #2) & 17,500 POWER TEST IN ATMOSPHERE



POWER	R	E_p	I_{p1}	I_{p2}	I_s
15000 W, run #2	92 ohms	160 v	57.4 a	44.3 a	13.13 a*
17500 W	82 ohms	160 v	60.3 a	49.3 a	14.44 a

* secondary current was 12.98 amps at the end of the test

20,000 W POWER TEST



E_P = 160 V
I_{P1} = 72 A
I_{P2} = 58 A
I_S = 16.7 A

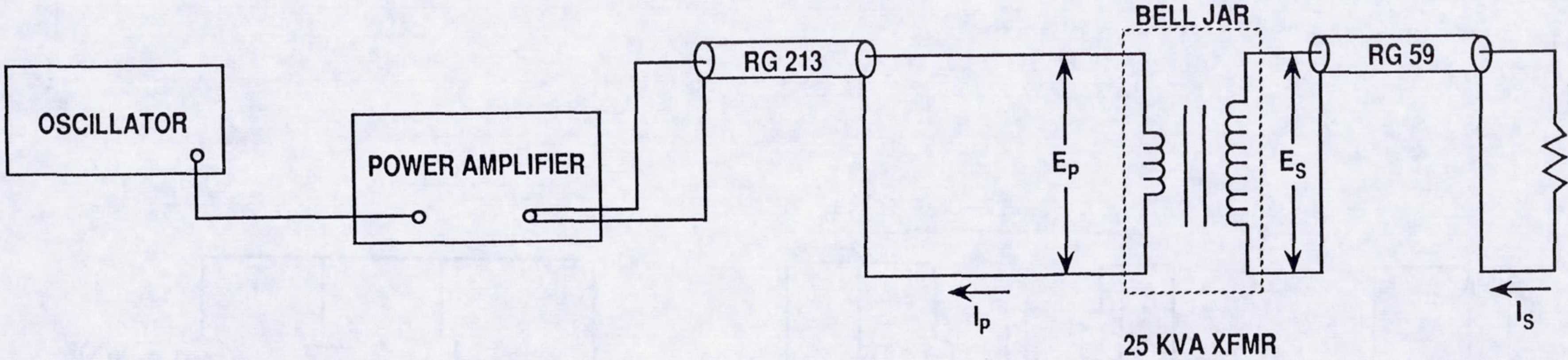
* #4 WELDING CABLE TO PRIMARY

FAILURE # 2

APPENDIX A

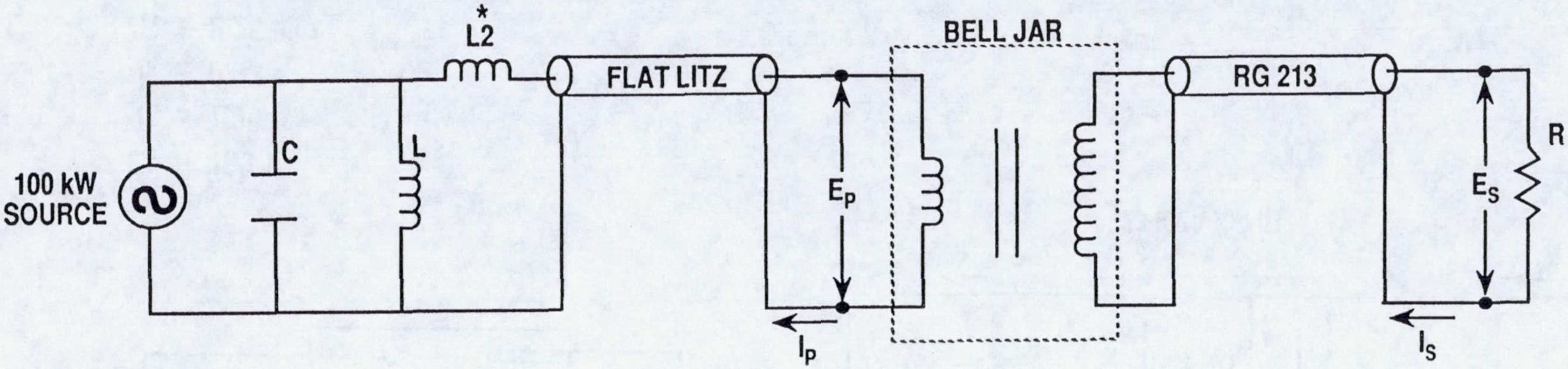
SECTION 2: TESTS IN VACUUM

TEST SET-UP FOR 1000 W POWER TEST IN VACUUM



$E_P = 159$ V
$I_P = 7.38$ A
$I_S = 0.93$ A
$R = 2.25$ KΩ

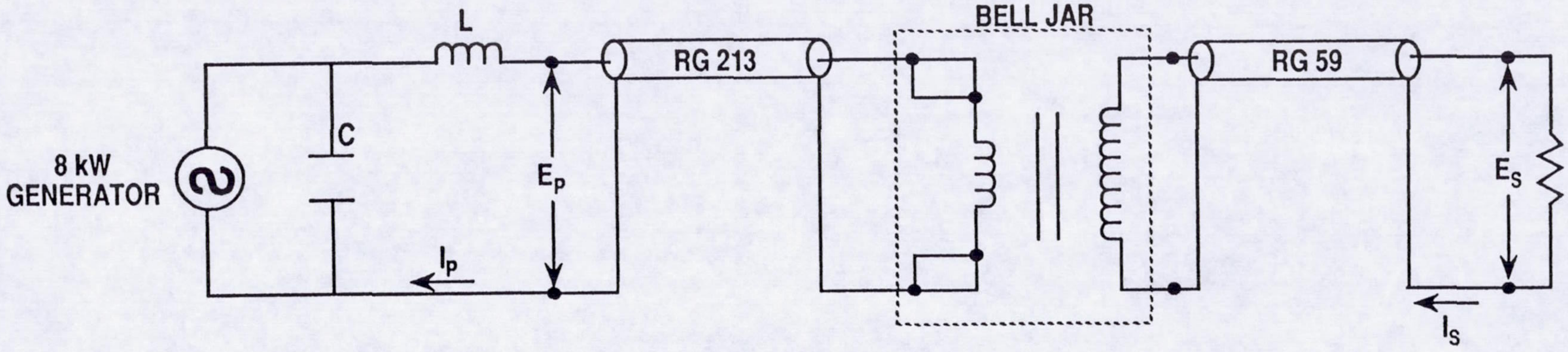
TEST SET-UP FOR 17.5 and 20 kW TESTS IN VACUUM



Power	C	L	R	E_p	I_p	I_s
17500 W	6.25uF	12.5uH	80 ohms	156.8 V	107.1 A	14.1 A
20000 W	6.75uF	12.5uH	75 ohms	159.8 V	129.2 A*	15.5 A

* small spike on primary current, see photo on page ??

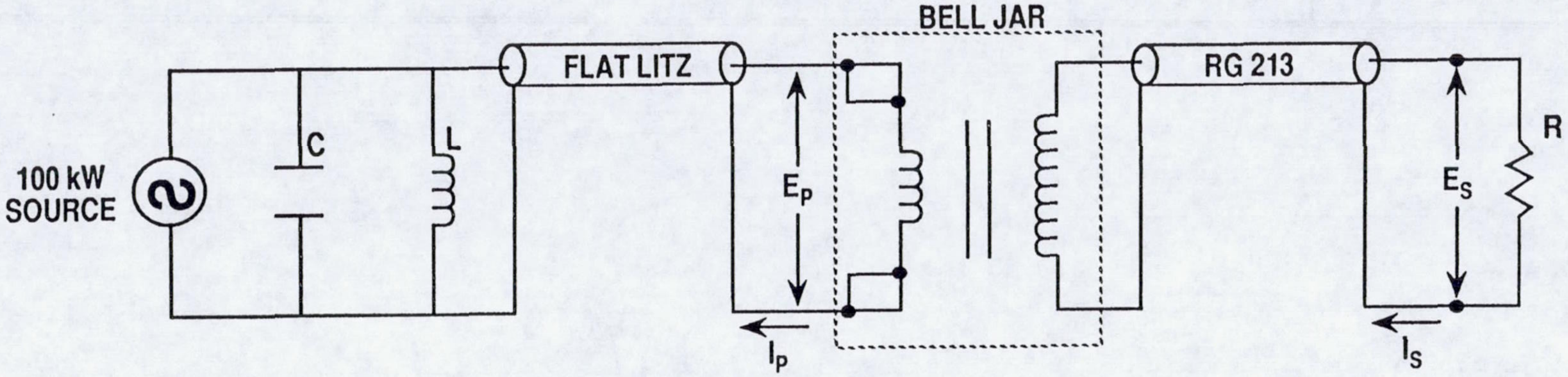
TEST SET-UP FOR 2.5, 5, and 8 kW TESTS IN VACUUM



Power	C	L	R	E_p	I_p	I_s
2500 W	0.43uF	*	630 ohms	160.1 V	14.99 A	1.9 A
5000 W	0.43uF	*	300 ohms	160 V	29.5 A	3.78 A
8000 W	uF	*	175 ohms	158.4 V	50.8 A*	6.61 A

* adjustable coil "tuned" to achieve maximum power transfer

TEST SET-UP FOR 10 and 13 kW TESTS IN VACUUM



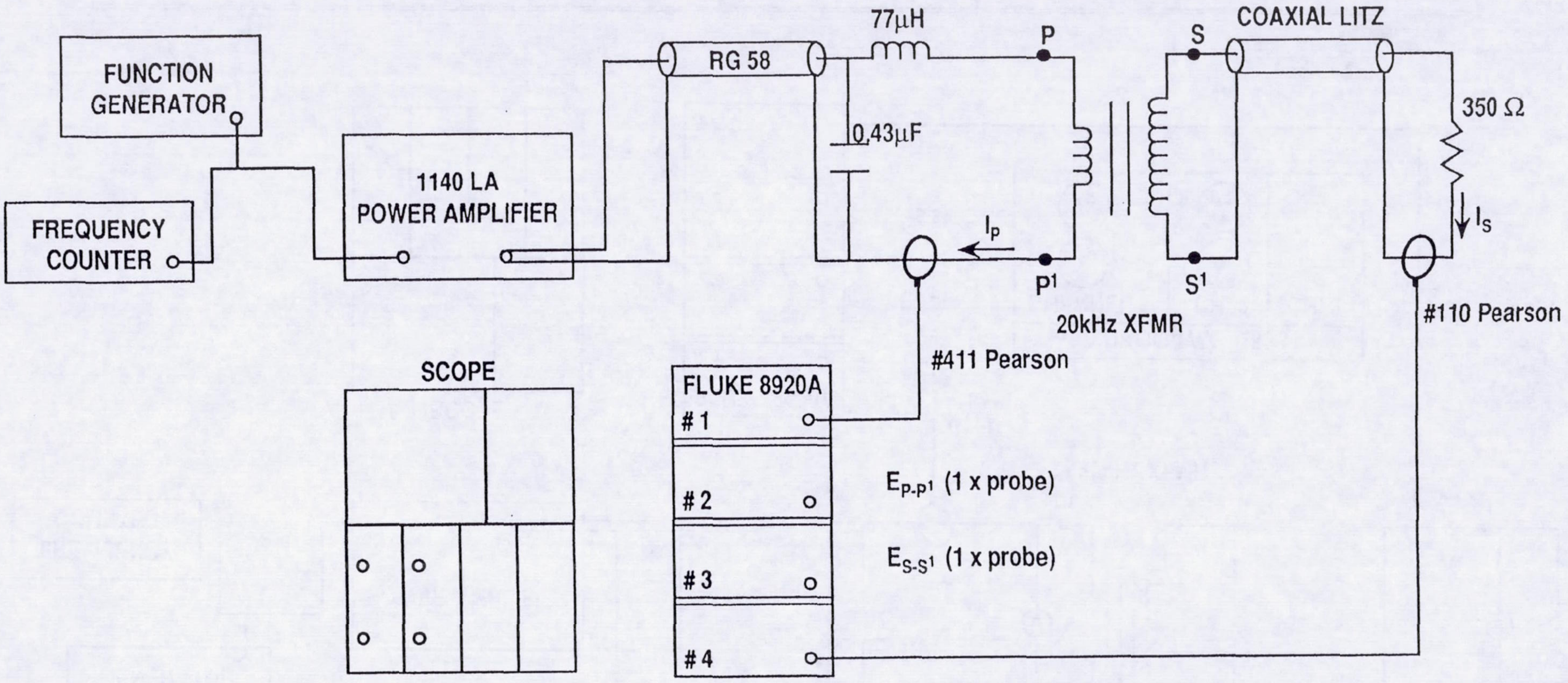
Power	C	L	R	E_p	I_p	I_s
10000 W	9.5uF	6.25uH	137 ohms	155.3 V	67.4 A	8.6 A
13000 W	9.5uF	6.25uH	105 ohms	159.4 V	102.3 A*	11.14 A

* 100 amp current spike on primary waveform

APPENDIX A

SECTION 3: EFFICIENCY TESTS

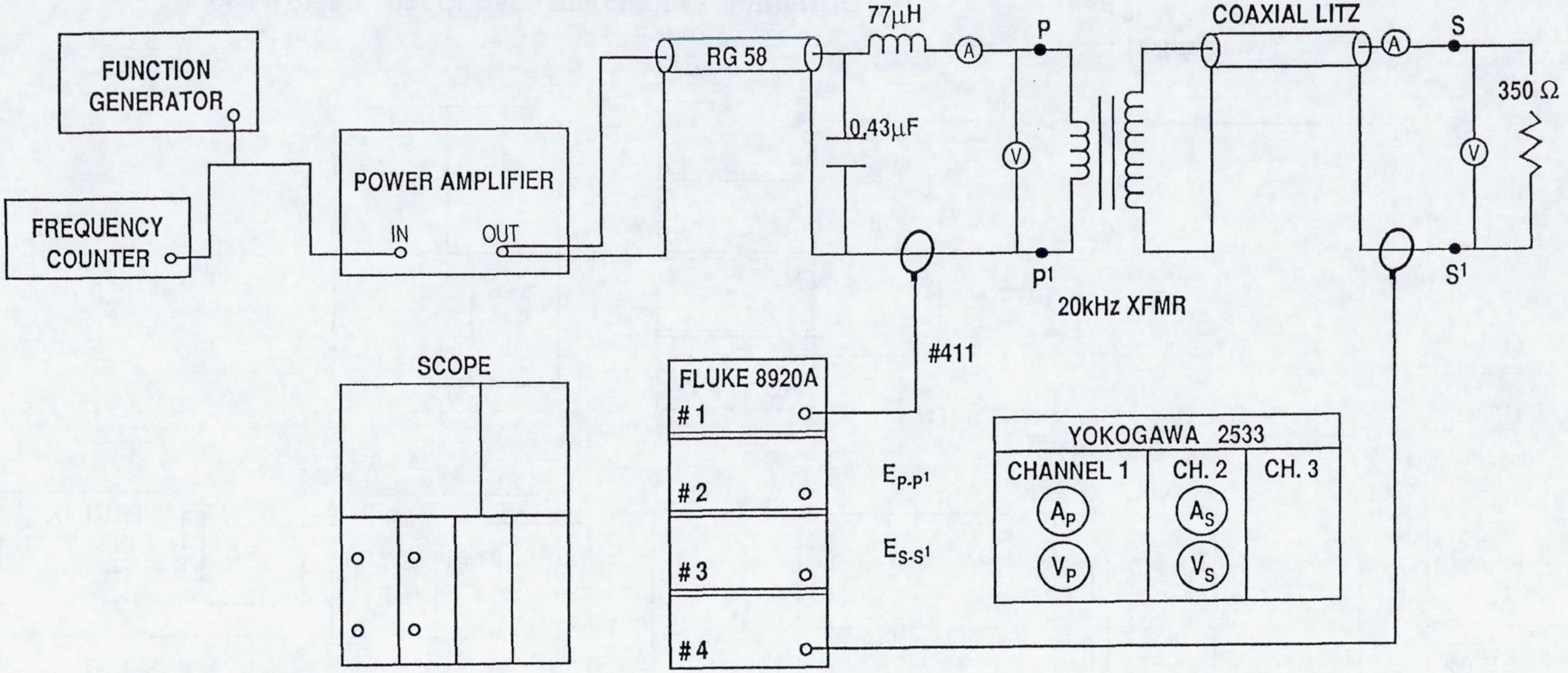
1000 W EFFICIENCY TEST: PHASE 1



I_P = 12.8 A
E_P = 80 V
E_S = 600 V
I_S = 1.65 A

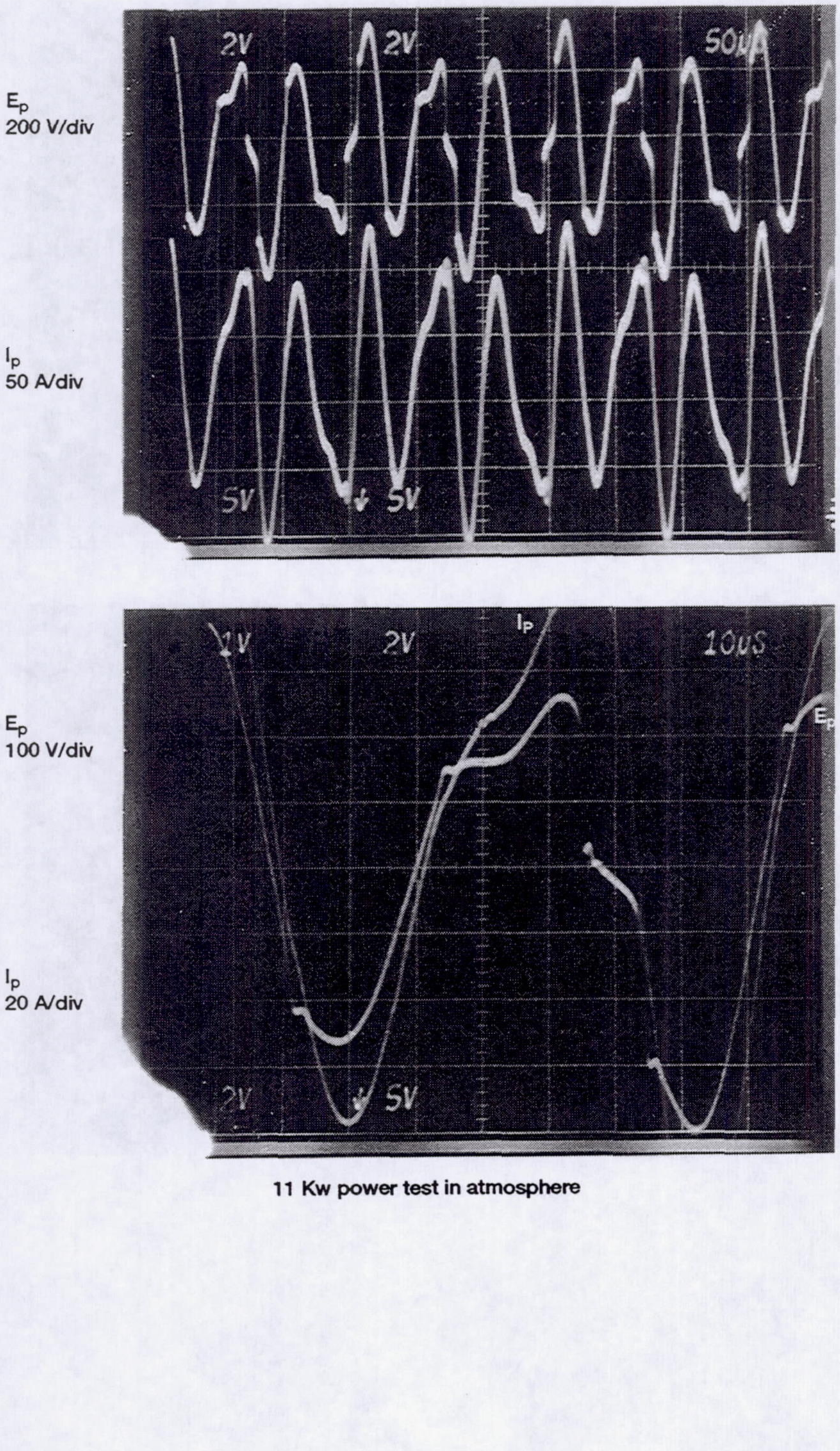
* PRIMARY AND SECONDARY PHASE MEASUREMENTS MADE ON CHANNEL 1 OF SCOPE

1000 W EFFICIENCY TEST: PHASE 2

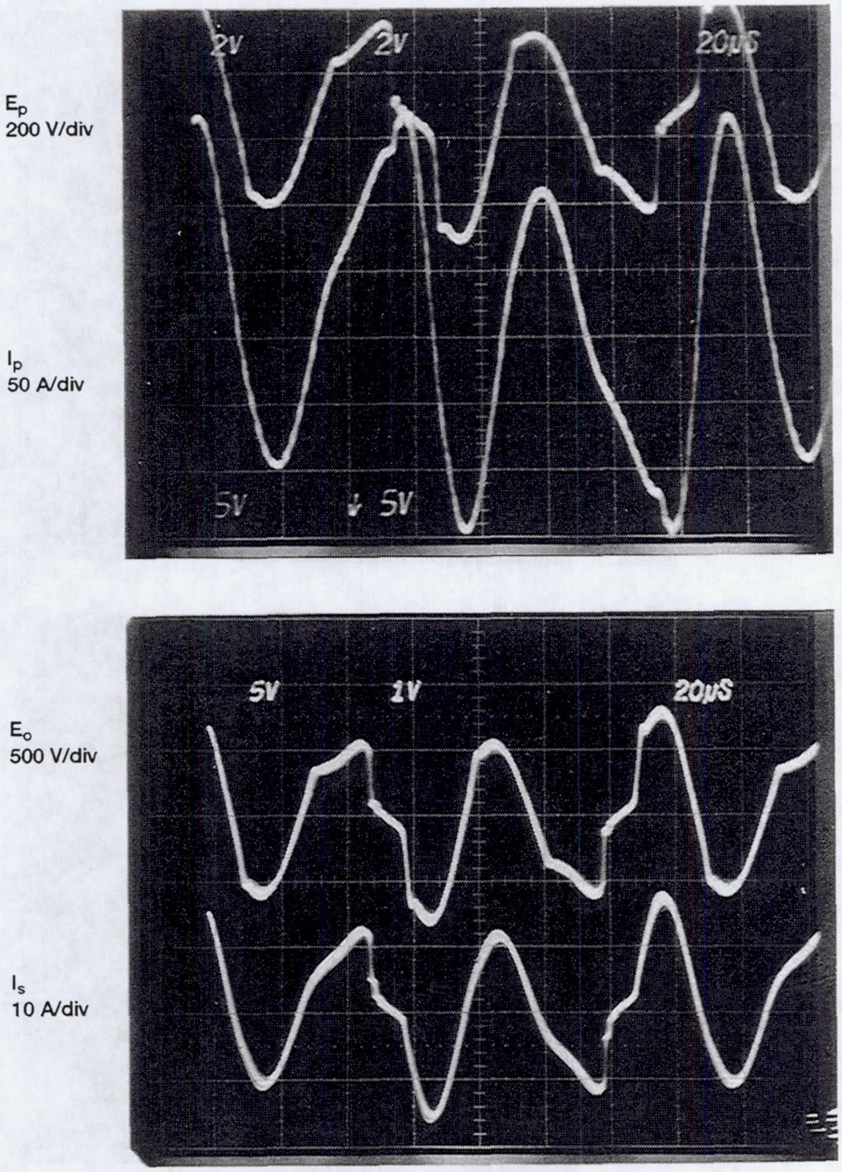


Instrumentation	E_p	I_p	E_s	I_s
Fluke 8920A	80 V	12.76 A	603 V	1.65 A
Yokogawa 2533	78.9 V	12.67 A	600.5 V	1.65 A

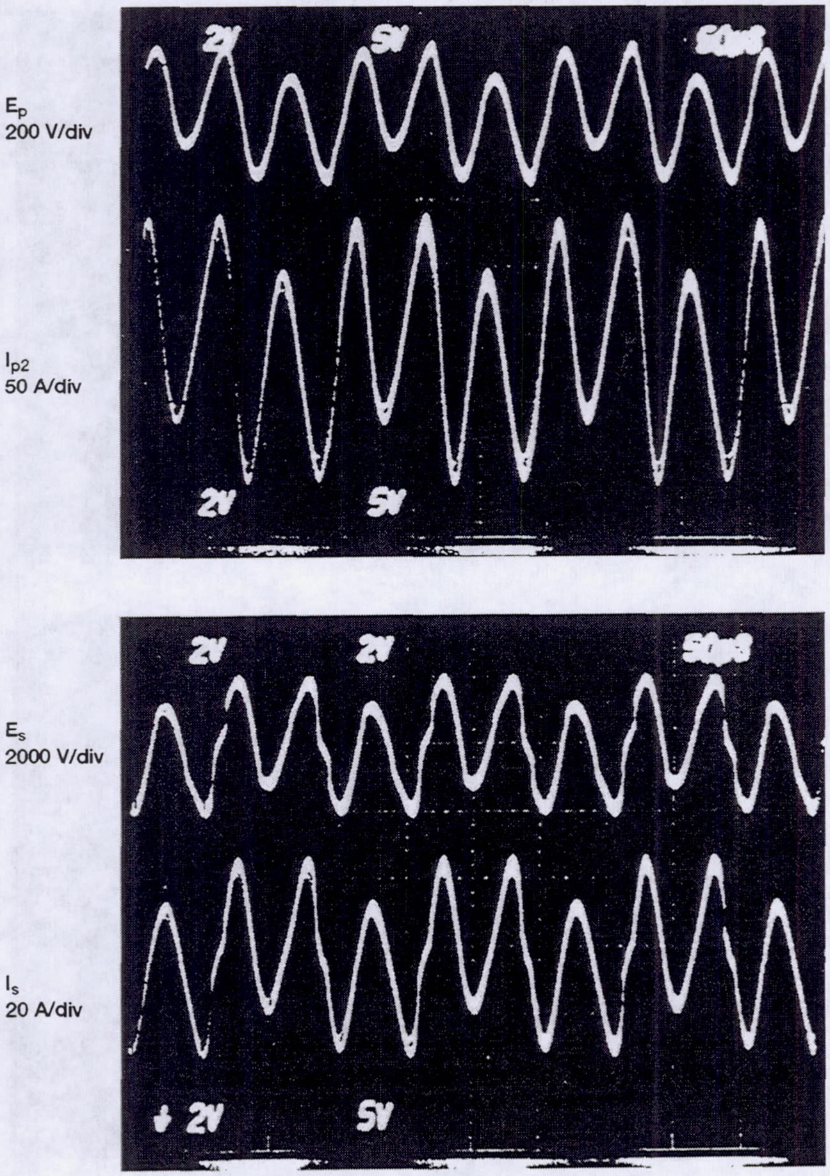
APPENDIX B



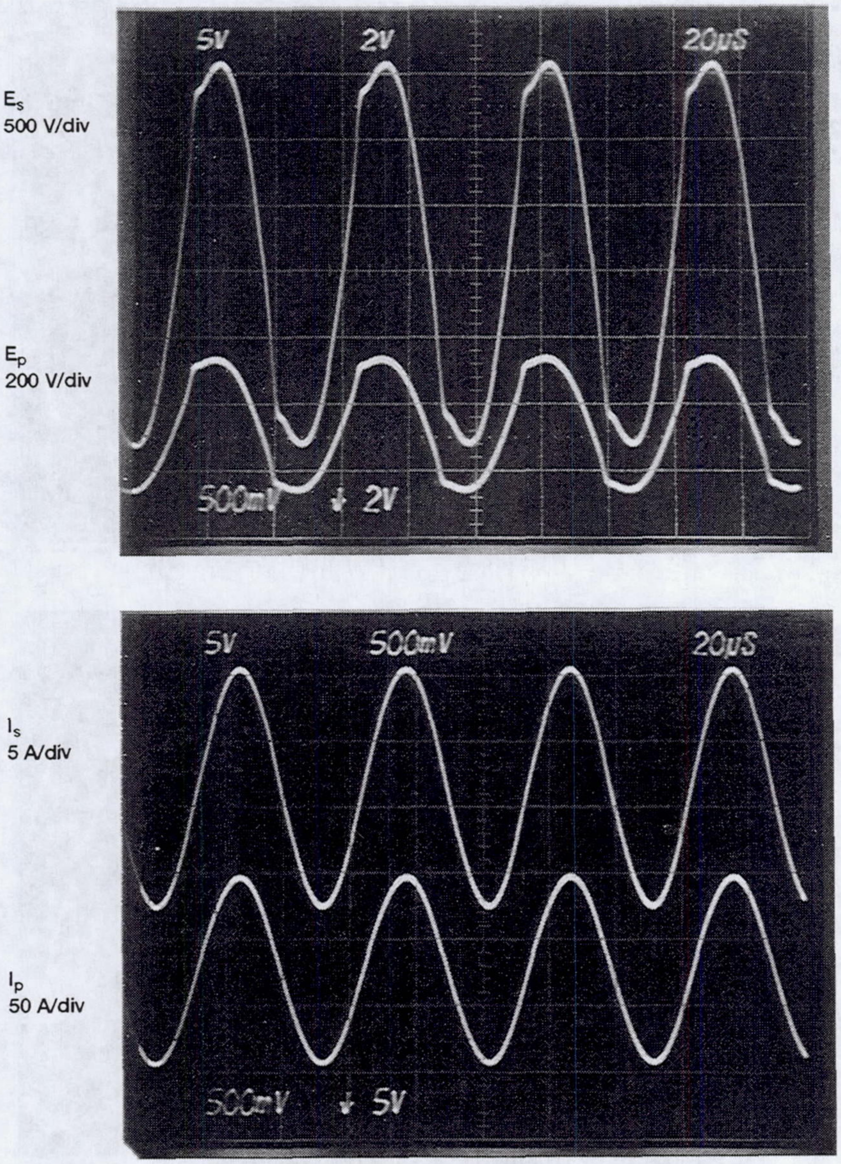
11 Kw power test in atmosphere



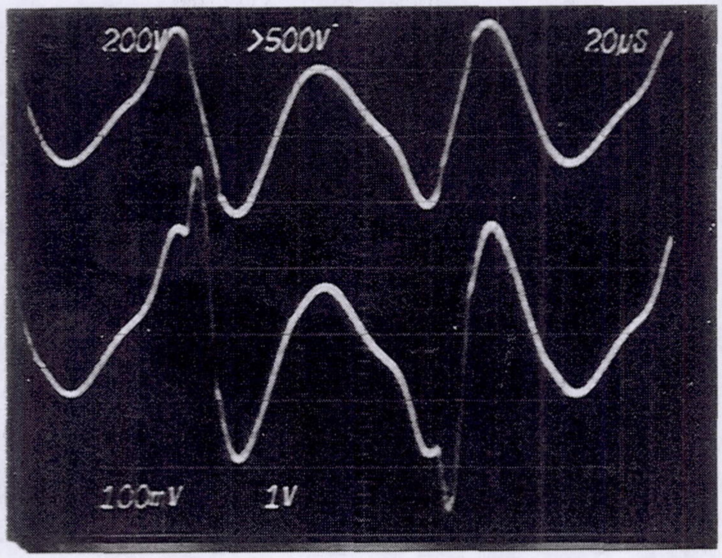
15 Kw power test in atmosphere

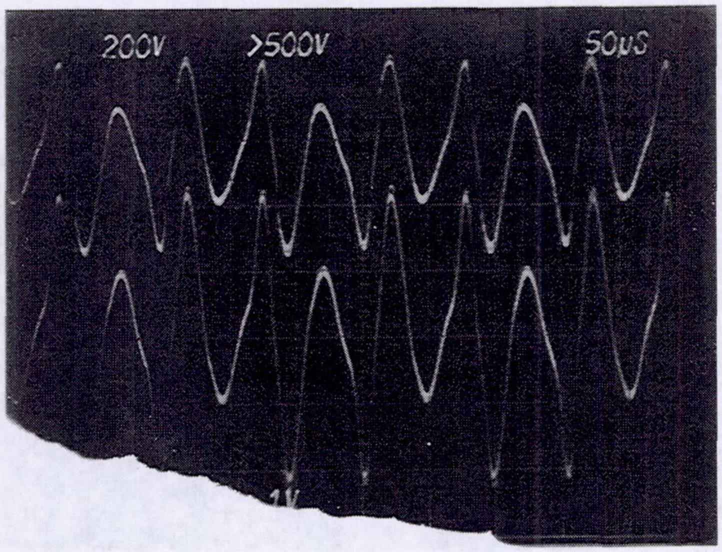


20 Kw power test in atmosphere



8 Kw power test in vacuum

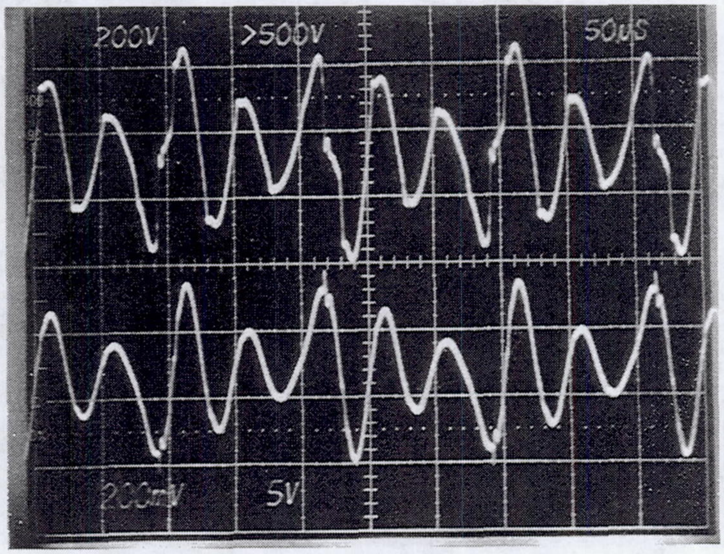




16 Kw power test in vacuum

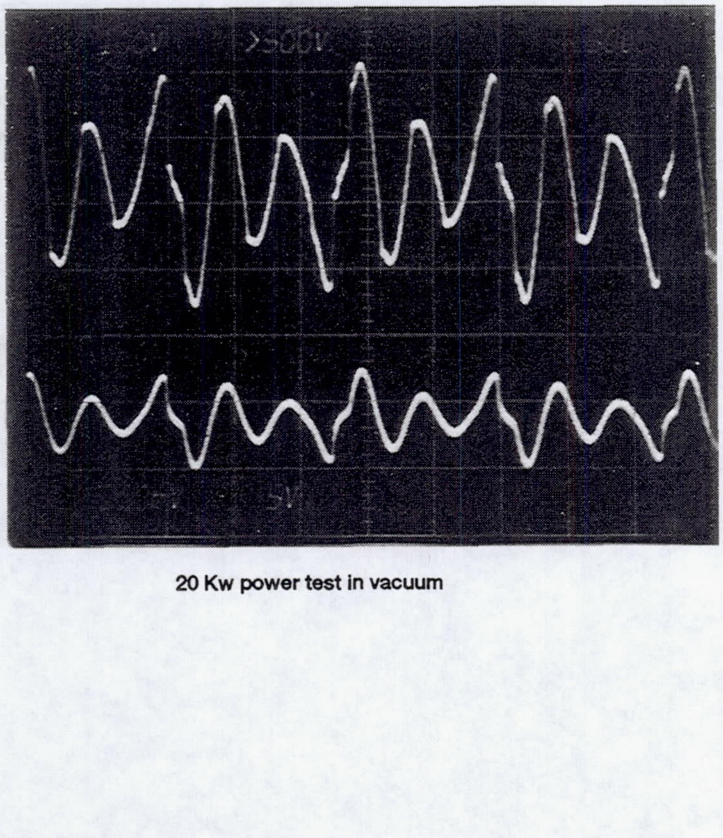
E_p
200 V/div

I_p
200 A/div



E_s
>500 V/div

I_s
50 A/div



20 Kw power test in vacuum

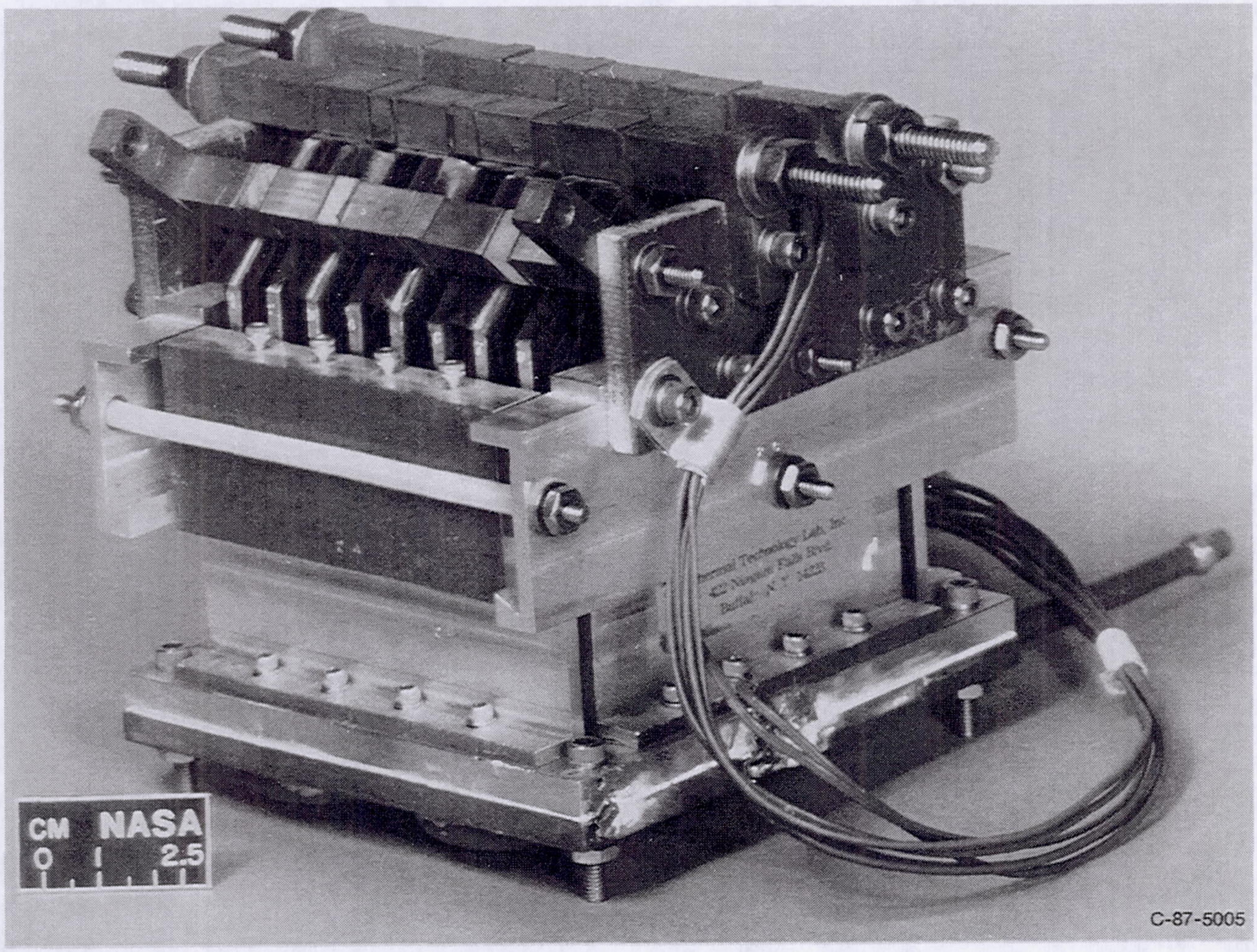


Figure 1.—Multi-kW high frequency transformer.

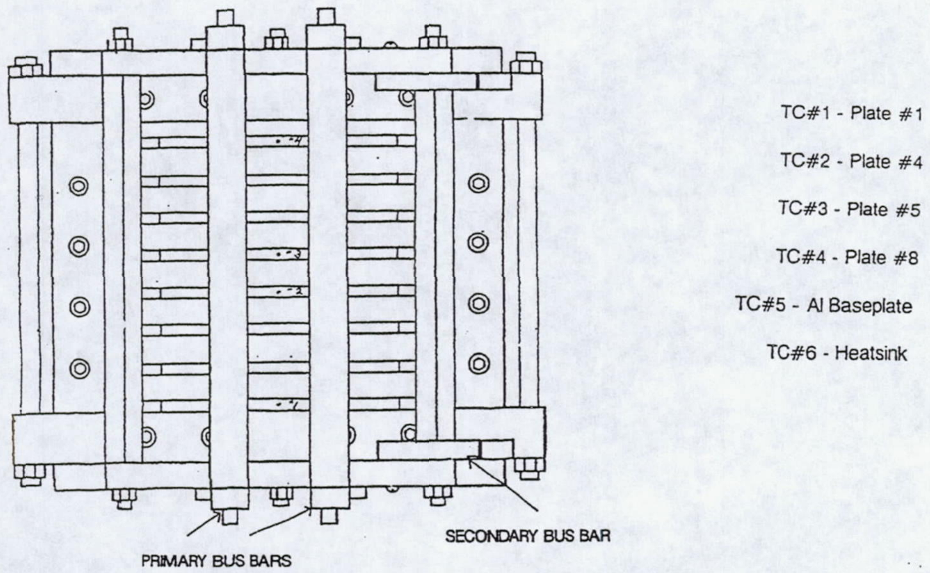


Figure 2.—Thermocouple placement.

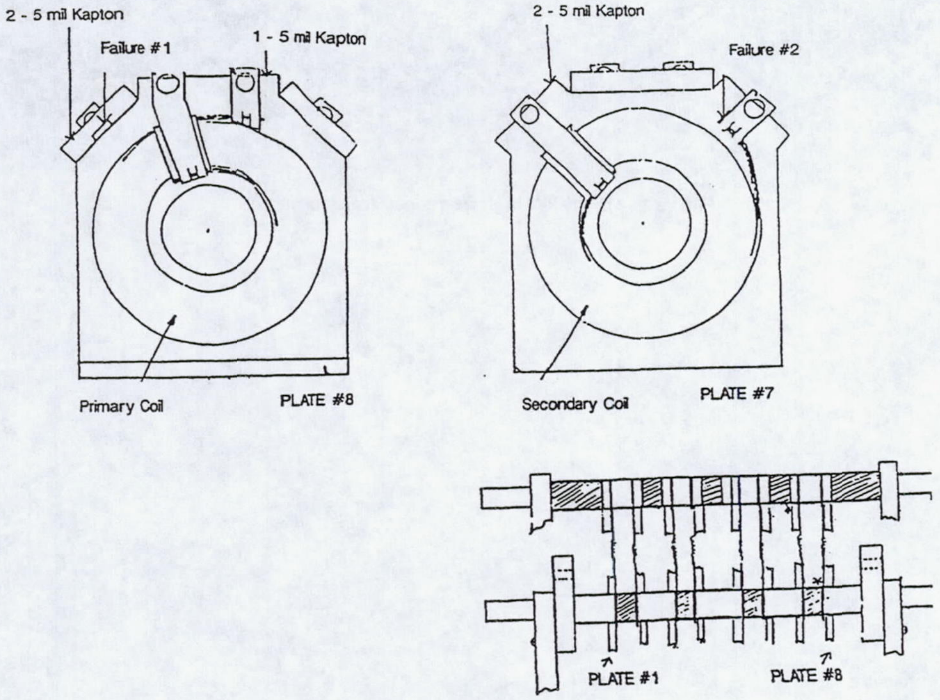


Figure 3.—Locations of failures.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
August 1994

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Evaluation of a Multi-Kw, High Frequency Transformer for Space Applications

5. FUNDING NUMBERS
WU–233–01–01

6. AUTHOR(S)
Mary Ellen Roth

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E–8971

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, D.C. 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM–106657

11. SUPPLEMENTARY NOTES
Responsible person, Mary Ellen Roth, organization code 5430, (216) 433–8061.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Categories 15 and 20

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

Various NASA studies have shown that high power (multi-kW and higher) electrical systems for various aerospace applications favor high frequency distribution systems, due to the improved safety and weight factors associated with those systems. Other favorable characteristics include low EMI, minimal wiring and ease of system parameter sensing and control of a single phase system. In aerospace power systems, as in terrestrial AC distribution systems, transformers are needed to provide voltage changes, isolation and the resetting of ground. Under NASA contract NAS3–21948 a multi-kW high frequency transformer was designed, fabricated and tested by Thermal Technology Lab, Inc. of Buffalo, New York. "The goals of this program included the determination of the relationships between transformer weight, efficiency and operating frequency; low internal temperatures and reduced specific weight; and the validation of these new design concepts through experimentation and the fabrication and testing of transformers and their insulation systems." The transformer was delivered to NASA-Lewis, where an evaluation program was conducted in Lewis' High Power High Frequency Component Test Facility. The transformer was tested in both atmosphere and under vacuum conditions. This paper will discuss the design of the transformer, the evaluation program and test results, the failures experienced and conclusions.

14. SUBJECT TERMS
High frequency; High power; Transformer

15. NUMBER OF PAGES
38

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT