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PULSE TRANSFORMER DESIGN STUDY

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20. ABSTRACT (cont.)

The described pulse transformers are intended for repetitive pulse operation with output voltages of about 200 kV into matched resistive loads. Output pulse width and risetimes are about 10 μ s and 1 μ s (10 to 90 percent) respectively.

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PREFACE

High voltage testing of the described pulse transformers was performed at the United States Electronics Command, Ft. Monmouth, New Jersey by Mr. John Creedon and his staff.

The author acknowledges the effort and enthusiastic support of Mr. Gregory Frank and Mr. Donald Sink of Physics International Company.

Mr. Frank designed and fabricated the winding apparatus for both the demonstration and prototype pulse transformers. Mr. Frank also wound the transformers and performed much of the work required to bring them to completion.

Mr. Sink proposed the experimental apparatus and performed the Kapton dielectric film breakdown measurements. His comments were invaluable with regard to the interpretation of the experimental results.

SECTION 1

INTRODUCTION

This report presents the results of a pulse transformer development program conducted for the U.S. Army Electronics Command (E-COM), Ft. Monmouth, New Jersey. Principal program objectives were the development of fabrication techniques, fabrication and limited testing of two pulse transformer designs, a reduced scale "demonstration" transformer, and a full scale "prototype" transformer.

The described program began 8 December 1975. Two demonstration transformers were delivered to the E-COM about midway through the program. The program culminated in March of 1977 with the delivery of one full scale prototype unit.

The pulse transformer designs that are the subject of this final report are air core, near uniform field designs first developed and patented by J. C. Martin and I. Smith, AWRE (Atomic Weapons Research Establishment), Aldermaston, England. Transformer construction and design parameters are presented in Reference 1.

The principal distinguishing characteristic of the described pulse transformers is the nearly uniform field operation of the dielectric material that provides turn-to-turn insulation. This attribute, in conjunction with impregnation of the winding with a high dielectric constant medium to eliminate corona and to permit operation of the dielectric at high stress, minimizes the

1. H. Aslin and P. Chao, "Pulse Transformer Design Study," E-COM-75-1340-F (1976).

volume of dielectric material and reduces stray series inductance. Thus transformer high frequency response is improved in comparison with more conventional pulse transformer designs.

The purpose in designing reduced scale demonstration transformers, rather than proceeding directly to the full scale prototype unit, was threefold: first, the demonstration size transformers provided the opportunity to develop and refine transformer fabrication techniques in a size that was amenable to expeditious revision. Secondly, and more importantly, the average power capability of the prototype transformer exceeded the capability of existing driving sources. Thus, to evaluate transformer electrical design, an interim reduced power pulse transformer was required, but in a design that incorporated the principal features of the full power unit. Thirdly, the electrical design of the reduced scale transformers was guided in part by the anticipated need for a pulse transformer to satisfy the requirements of a related, but near term Army pulsed power system.

Section 2 of this final report describes pulse transformer design and fabrication. Section 3 presents test results, both the low voltage testing conducted at PI and the relevant results from the high voltage tests conducted at the E-COM. Section 4 presents a summary and conclusions.

The transformers are constructed by winding a wide, thin sheet of conducting material onto a cylindrical dielectric form with film type dielectric insulation between turns (Reference 1). The secondary is wound on first, and short rod conductors, distributed over the width of the secondary conductor at its end, penetrate the dielectric cylinder and provide the transformer output connection on the inside diameter of the cylindrical form.

After the secondary is wound onto the form, a soldered splice connection is made to thicker conducting material, the primary, and it too is wound onto the cylinder. Although several variations exist with regard to the manner in which connection is made to the start and end of the primary, the approach taken here is one in which a series of rod conductors, distributed over the width and soldered to the end of the primary (adjacent to the splice to the secondary conducting sheet), pass through holes cut into subsequent primary turns. This approach is taken to reduce stray inductance associated with the connections to the transformer in order to improve transformer high frequency performance. The hole diameter is made large in relation to the rod diameter to provide the necessary insulation against the applied electrical stress.

A similar set of rod conductors is soldered to the start of the primary conductor. Thus, the transformer input connections take the form of two rows of conducting rods separated by a distance sufficient to sustain the applied electrical stress.

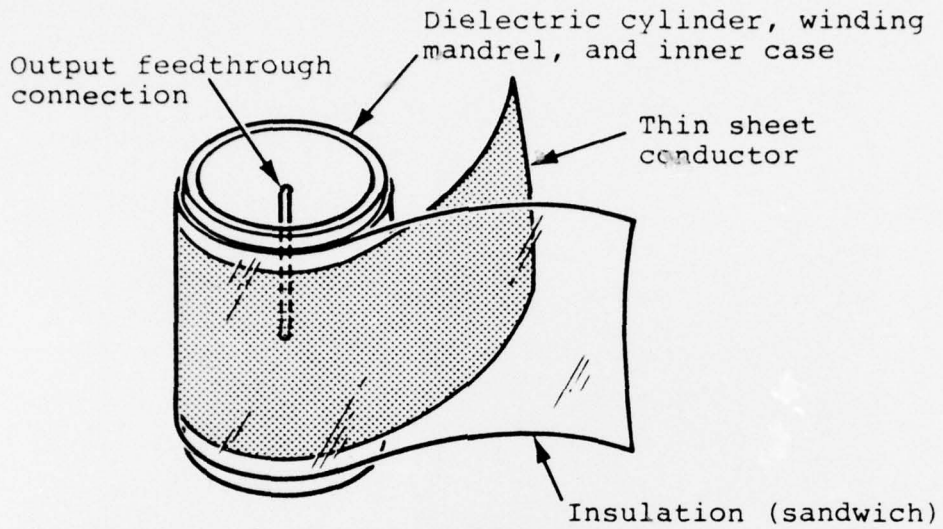
After the winding is complete, a cylindrical fiberglass outer case is installed. The outer case is divided into three segments, one of which contains clearance holes through which the transformer input connections pass. The segmented outer case is bonded together over the winding and plastic bushings that seal the input rod conductors are bonded onto the case.

Following installation of the outer case, end caps are installed creating a completely sealed annular volume that contains the transformer winding.

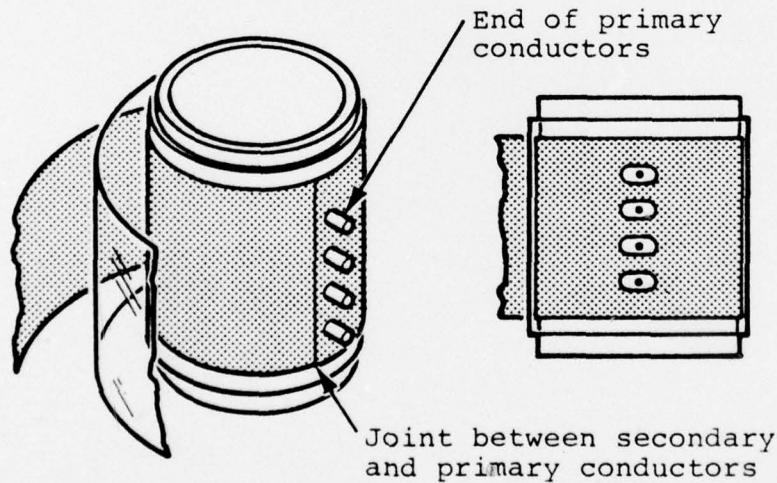
Polyester fiberglass is wrapped onto the diameter of the assembled unit for strength.

Finally, the annular volume containing the winding is vacuum impregnated with ethylene glycol, a high dielectric constant liquid ($\epsilon_r \cong 41$). The purpose of the impregnant is to displace air from the winding, and, by virtue of the large ratio of dielectric constants between the ethylene glycol and plastic film, to force the impressed electric fields into the electrically stronger film dielectric material.

The described transformer construction is illustrated in Figures 1 and 2. The construction of the demonstration and prototype pulse transformers are described in more detail in the following section.



a) Winding of secondary conductor.



b) Winding of the primary conductor and feedthrough conductor installation.

Figure 1 Uniform field pulse transformer construction.

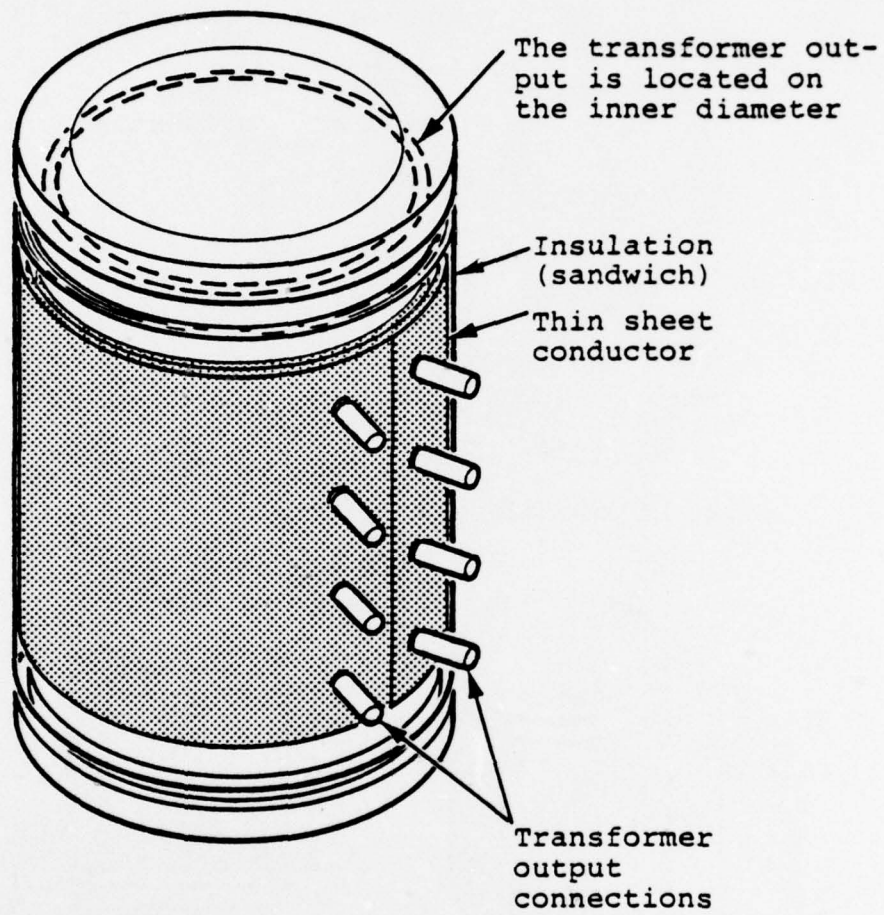


Figure 2 Completed uniform field pulse transformer.

SECTION 2

PULSE TRANSFORMER DESIGN AND FABRICATION

2.1 DEMONSTRATION TRANSFORMER

Demonstration transformer electrical requirements are summarized in Table 1. The demonstration transformers are intended for use in an electrical circuit as illustrated in Figure 3. A pulse forming network (PFN), resonance charged to 100 kV, is thyatron switched into the transformer primary. The transformer is connected in autotransformer mode, i.e., the primary and secondary windings are connected in series.

The electrical design of the demonstration pulse transformer is described in Appendix A of this report and is based upon the design development contained within References 1 and 2.

Table 2 summarizes transformer physical and electrical parameters and projected performance characteristics.

The following paragraphs describe transformer construction and components.

2.1.1 Inner Dielectric Cylinder. The inner dielectric cylinder upon which the transformer is wound and which forms, in part, the transformer case is illustrated in cross-section in Figure 3. The cylinder is polyester fiberglass with a finished wall thickness of nominally $\frac{1}{2}$ inch. The thickness of the cylinder

2. H. Aslin, "Uniform Field, Air Core Pulse Transformers," NSWC Pulsed Power Work Shop, September (1976).

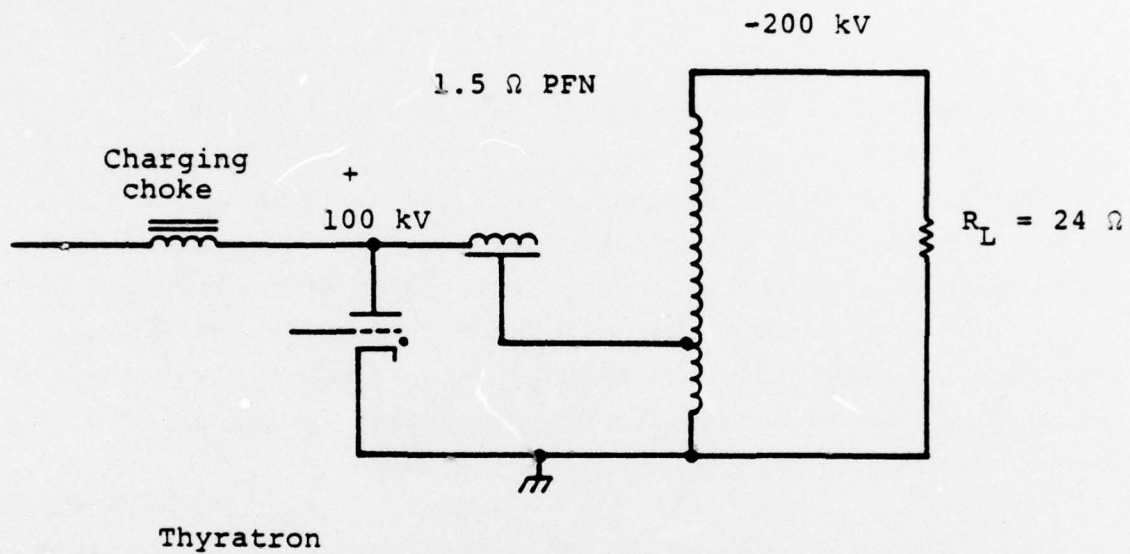


Figure 3 Pulse modulated electrical circuit (demonstration transformer).

TABLE 1. DEMONSTRATION TRANSFORMER ELECTRICAL REQUIREMENTS

Output voltage (into a matched load)	200 kV
Output peak current	8.3 kA
Load resistance	24 ohm
Input voltage (matched load)	50 kV
Output pulse width	5 μ sec (FWHM)
Output pulse risetime	\leq 1 μ sec (10-90%)
Pulse droop	\leq 5% in 5 μ sec
PRF	\cong 60 pps
Duty	burst mode

TABLE 2. DEMONSTRATION TRANSFORMER DESIGN SUMMARY (REVISED)

Mean winding diameter	= 51 cm
Width of winding	= 51 cm
Number of primary turns	= 15
Number of secondary turns	= 47
Primary inductance	= 75 μ H
Pulse droop	= 4.6% in 5 μ sec
Conductor material	Copper
Current density (peak)	60 kA/cm ²
Primary conductor thickness	0.004 inch
Secondary conductor thickness	0.001 inch
Insulation thickness* (Kapton/paper/glycol)	0.0035 inch
Insulation stress	1.67 kV/mil
Total winding thickness	0.32 inch
Leakage inductance	1.4 μ H
Risetime (10 to 90%)	1.09 μ sec
Primary conductor length	78.4 feet
Primary resistance (20°C)	7.9 m Ω
Secondary conductor length	246 feet
Secondary resistance (20°C)	100 m Ω
Case material	Polyester-fiberglass
Case dimensions	
<u>Outer</u>	
Outside diameter	~ 21.5 inches
Inside diameter	~ 21.0 inches
<u>Inner</u>	
Outside diameter	~ 20.0 inches
Inside diameter	~ 19.0 inches
Length	~ 26 inches
Weight	~ 145 pounds

* The insulation consists of a "sandwich" of two sheets of 0.001-inch-thick Kapton film separated by 0.0005-inch-thick paper (3 sheets).

is determined principally by the material strength necessary to sustain the compressive stresses produced by the magnetic forces acting upon the transformer current carrying conductors. For the required electrical operating conditions, the peak mechanical pressure exerted upon the transformer case is about 59 psia (Appendix A).

Before the inner cylinder is machined, four fiberglass "spiders" are installed in the cylinder inner diameter to provide additional mechanical strength. These "spiders" also accommodate an axial shaft for machining of the cylinder outer diameter and for installation into the transformer winding apparatus.

The finished outer diameter and length of the inner cylinder are 20 inches and 25-3/4 inches, respectively.

The thickened region of the inner dielectric cylinder illustrated in Figure 4 provides a flat surface on the inner cylinder inner diameter for installation of the output conductors. A longitudinal slot, about 1½ inches wide by ½ inch deep is milled into the outer diameter of the cylinder in the thickened area. This slot accommodates two brass bars between which the end of the secondary copper conductor is sandwiched. The upper bar contains three studs that pass through clearance holes in the lower bar and cylinder wall. One stud is located at the center of the cylinder (longitudinally) and the other two are spaced 8 inches to each side of center. The studs are sealed by means of O-rings on the outer diameter of the dielectric cylinder.

After machining and clean-up, the finished inner cylinder is installed in the winding apparatus, Figure 5. The inner

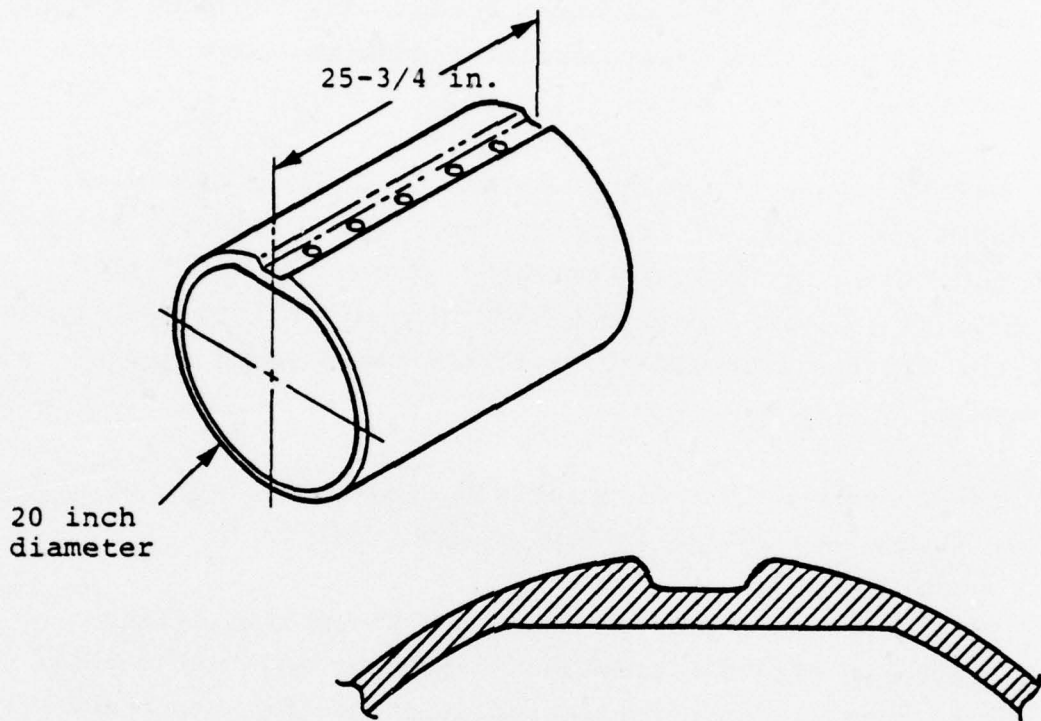


Figure 4 Inner dielectric cylinder.

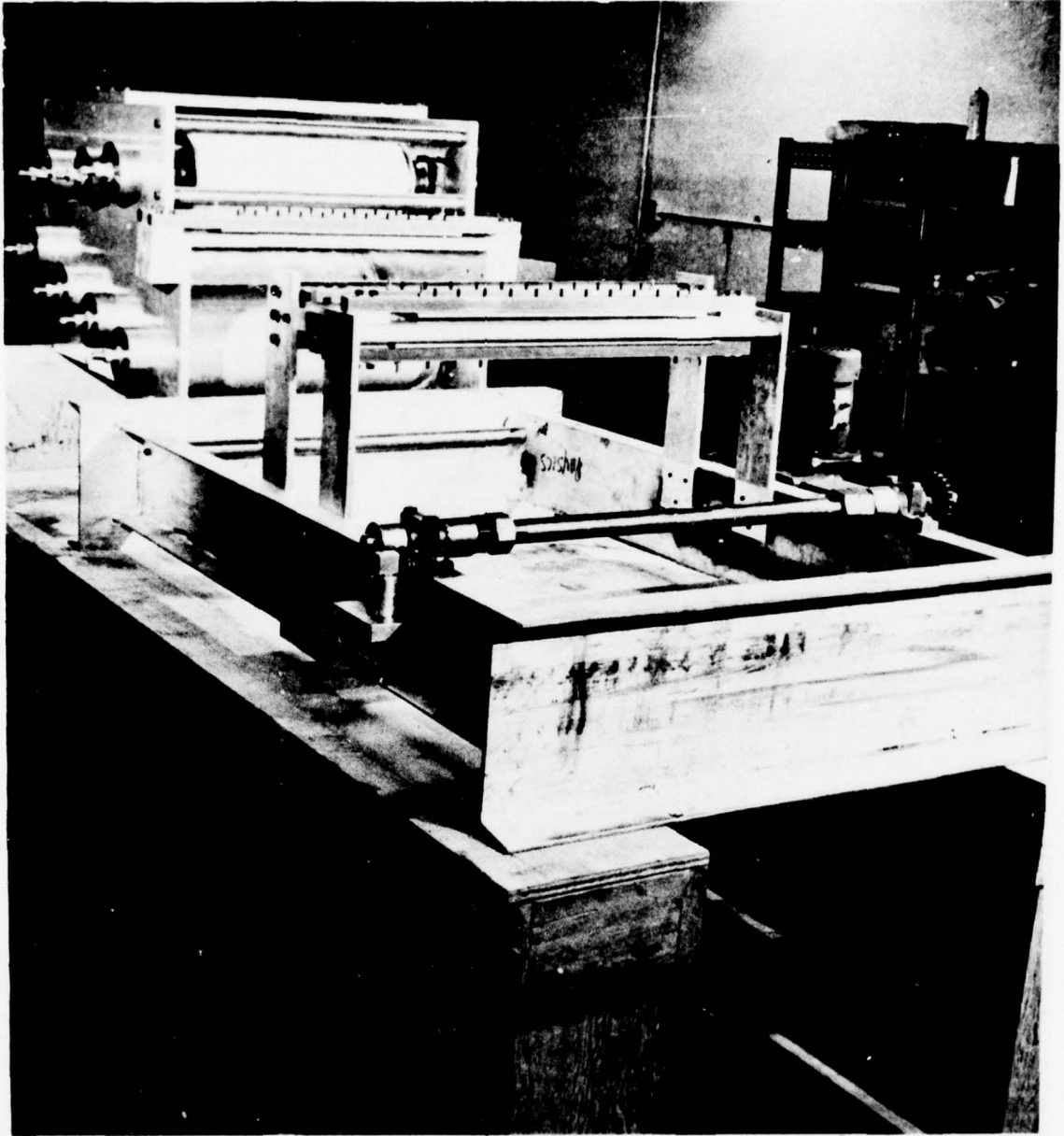


Figure 5 Demonstration transformer winding machine.

cylinder is not shown in Figure 5, but it is installed on the horizontal motor driven shaft at the front of the winding apparatus. Also shown in Figure 4 are the rolls of conducting and dielectric material which are collected and wound onto the inner cylinder.

2.1.2 Winding Conductor. From Table 2, the thicknesses of the transformer winding copper conducting material is 0.001 inch and 0.004 inch for the secondary and primary conductors, respectively.

From Reference 1, the use of aluminum conducting material is preferred if minimization of transformer weight is a prime consideration. However, in the present case, transformer high frequency response is of greater importance; and thus, copper conducting material is used. For equal heating, the thickness of copper conducting material is about two-thirds that of aluminum. Thus, using copper, the thickness of the winding is reduced, and, since the transformer high frequency response is inversely proportional to the winding thickness (Reference 1) copper conducting material is preferred.

The width of the copper conducting material is 20 inches; from Appendix A the current density in both the primary and secondary conductors is 60 kA/cm^2 .

Annealed copper alloy, ASTM type 110, was used in the demonstration transformers. This alloy is greater than 99.9 percent pure copper and is widely used in electrical and electronics applications because of its ductility and ease of soldering.

2.1.3 Dielectric Material. The dielectric "sandwich" which provides transformer turn-to-turn insulation consists of two sheets of 0.001-inch-thick Kapton* dielectric film (type H) and

* Kapton-Dupont polyimide film.

three sheets of 0.0005-inch-thick capacitor grade kraft paper. The paper separates the sheets of Kapton from themselves and from the copper conducting material.

Paper is used as a "wick" to aid impregnation of the winding to insure penetration of the impregnant into the winding.

The choice of Kapton film was based principally upon its ability to withstand relatively high temperatures without significant degradation of its electrical and mechanical properties, and by virtue of its high breakdown field strength in thin sheets.

With regard to the insulation strength of Kapton, Appendix B describes breakdown field strength measurements and results for Kapton film. In these measurements, stacks consisting of 3 sheets of 1-mil film, imbedded in ethylene glycol, were tested under pulsed conditions to breakdown. The volume of film which comprised a test sample was about 7 cm^3 . Although there is considerable scatter in the measured results, depending upon the cleanliness of the test setup and the care with which the film material was handled, the best results yielded breakdown field strengths of more than 6 MV/cm (15.2 kV/mil). In comparison, the mean peak design stress in the Kapton film for the demonstration transformer is about 0.66 MV/cm (1.7 kV/mil).

The width of the dielectric material is 24 inches and extends 2 inches beyond the conducting material at each edge.

2.1.4 Impregnant. The choice of impregnant in the present application is ethylene glycol, a high dielectric constant liquid ($\epsilon_r \cong 41$). Water is frequently used in these applications as well, but in this case, because the boiling point of ethylene

is about 197°C, the material is more compatible with the temperature capability of the Kapton dielectric film material.

2.1.5 Outer Case. The outer case, like the inner, is polyester fiberglass. Its inner diameter is about 20.6 inches, and its length is 25-3/4 inches, equal to the inner cylinder length. Wall thickness is about 1/4 inch. After fabrication, the outer case is slit lengthwise into three equal pieces. Clearance holes to accommodate the input connections are drilled into one of the segments.

2.1.6 Demonstration of Transformer Winding. After the inner dielectric cylinder and winding materials are installed in the winding apparatus and aligned, winding begins with installation of the secondary conductor. The dielectric materials are gathered together as they leave their rolls and form a "sandwich" (paper-Kapton-paper-Kapton-paper). Thickness of the sandwich is 0.0035 inch excluding the effect of small wrinkles that tend to increase its thickness. The dielectric "sandwich" and copper conducting material are brought together at a point past the cutting bars (Figure 5) which are used to prepare the cut-outs in the primary conducting material. The inner cylinder is motor driven on its shaft and the winding materials are pulled onto the cylinder outer diameter.

Tension of the materials is controlled by means of adjustable friction bearing surfaces associated with the shafts of each roll of material.

The secondary winding of the demonstration transformer consists of 47 turns of material, and the minimum thickness of the completed secondary winding is about 0.21 inch.

Following completion of the secondary winding, the conductor is parted and soldered, using an overlap solder joint, to the thicker (0.004 inch) primary conducting material. At the same time, discrete rod conductors, which form the end of primary feedthrough for external electrical connection, are soldered to the thicker conducting material near the primary secondary joint. The feedthrough conductors are relatively short (approximately $\frac{1}{2}$ inch), but after the winding is complete, longer rod extensions are screwed into them.

After the primary secondary solder joint and means for connection are complete, the primary conductor is wound onto the cylindrical assembly. Before each turn is wound on however, holes are cut into the conducting and dielectric material, through which the feedthrough conductors pass. Hole location in the material to be wound onto the transformer is determined by measurement of the transformer circumference. This measurement, including a correction for the small increase in diameter due to the thickness of the following turn is translated to the feeding conducting sheet and dielectric "sandwich." The shape and dimensions of the holes cut into the primary conductor are illustrated in Figure 6.*

The holes are oblong in shape to accommodate circumferential misalignment. This misalignment arises as a result of the difficulty of translating the circumferential hole location measurement, and its correction, to the feeding conducting material. This difficulty in combination with variation in the "tightness" of the

*The first transformer tested by the E-COM contained five feedthrough conductors in each row. Cut-out width and length were $1\frac{1}{2}$ inches by $2\frac{1}{2}$ inches, respectively. Feedthrough conductor diameter was $\frac{1}{8}$ inch. Cut-out dimensions were increased to those shown in Figure 6 for the second "demo" transformer to reduce the electric field in the feedthrough cut-out regions. To offset the resulting decrease in the remaining conducting material, the number of feedthroughs was reduced from five to three.

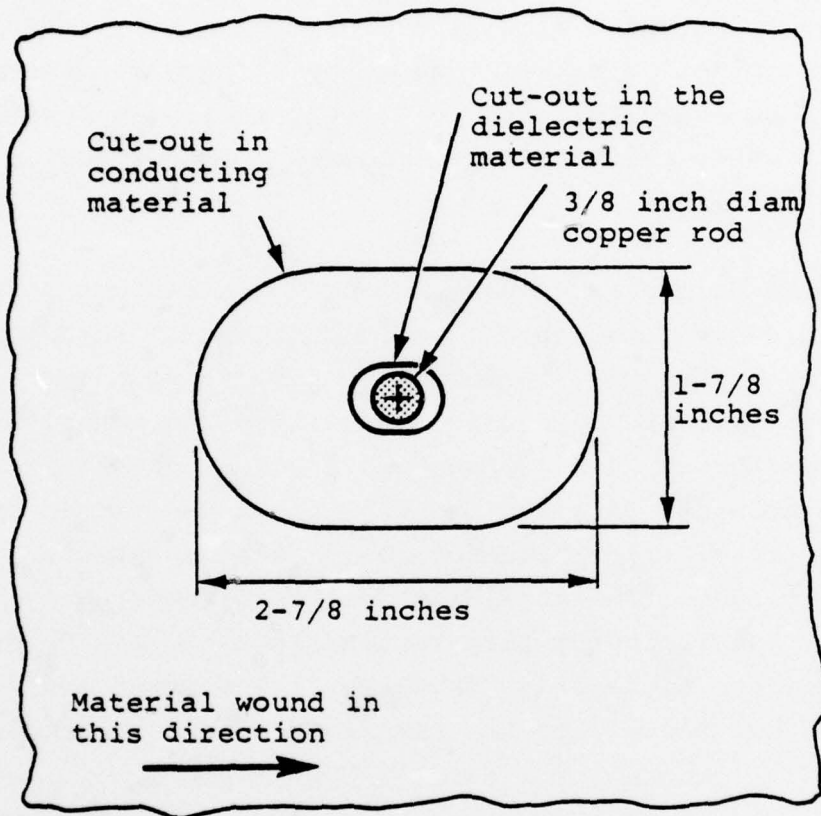


Figure 6 Demonstration transformer feedthrough cut-out dimensions.

turn leads to the described circumferential misalignment. Alignment of the feedthrough hole edges over the width of the winding is relatively easily controlled; it is only necessary that the conducting material be fed straight onto the cylinder.

The "demonstration" transformer primary winding is 15 turns. Conductor thickness is 0.004 inch and, as before, the dielectric "sandwich" is 0.0035-inch thick. Thus, the minimum thickness of the primary winding is about 0.11 inch. Total thickness of the winding is about 0.32 inch (0.82 cm).

A row of conducting rods, identical to the "end of primary" feedthrough conductors, are soldered to the last primary turn. Separation between the two resulting rows of conductors is about 4 inches. This spacing is sufficient to sustain 50 kV applied voltage without breakdown in air.

After completion of the winding and its connections, the three piece polyester fiberglass outer case is installed over the winding and bonded together.

Dielectric feedthrough bushings are bonded onto the case over the feedthrough conductors. The bushings contain O-rings that seal against the feedthrough conductors (Figure 7).

After the outer case is installed, the partially completed transformer is removed from the winding apparatus and fiberglass ends are bonded onto the case. When bonding is complete, the winding is contained within the completely sealed annular region between the inner and outer dielectric cylinders. However, tapped holes are provided in one end of the unit for impregnation of the winding.

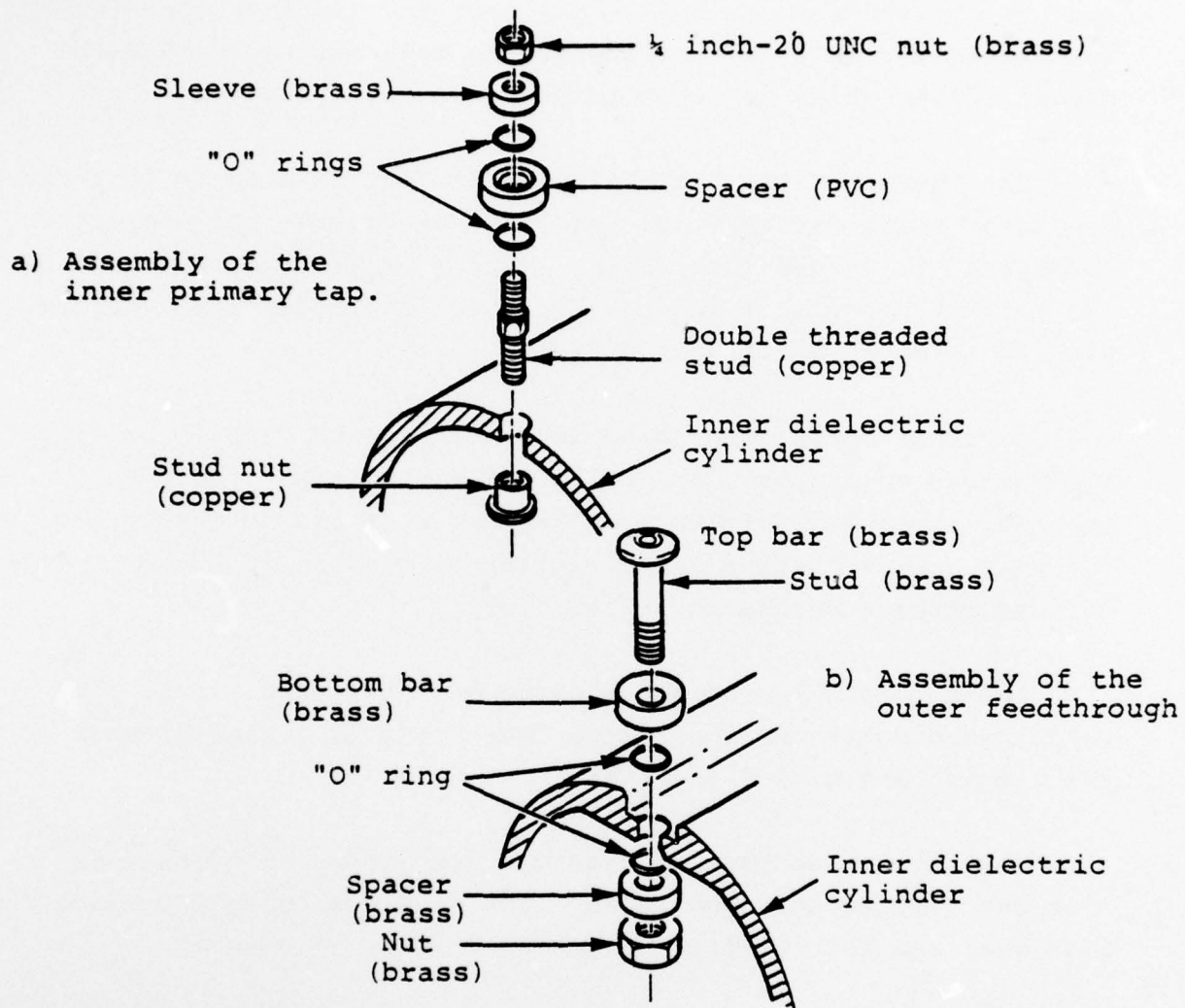


Figure 7 Transformer bushing assemblies.

Before the unit is impregnated however, additional polyester fiberglass is wound onto the transformer outer diameter for strength.

2.1.7 Impregnation. The transformer winding is vacuum impregnated with ethylene glycol to displace air from the winding, and, by virtue of its high dielectric constant ($\epsilon_r \cong 41$), to force the applied electric fields into the electrically stronger Kapton film dielectric material. Ethylene glycol is also compatible with Kapton in terms of operating temperature; the boiling point of glycol is 197°C .

Impregnation of the transformers was first performed within a large vacuum tank; a tank large enough to accommodate the glycol in its container as well as the transformer. This was done to degas the glycol before introducing it into the transformer winding.

However, because of the long pumping time required to achieve an acceptable vacuum, this approach was abandoned in favor of pumping directly upon the annular volume of the winding in its housing. As illustrated in Figure 8, two stand pipes, diametrically opposed, were installed onto one end of the unit. Vacuum was drawn from the top of one stand pipe, and a thermocouple gauge was installed at the top of the other to provide a means of measuring the vacuum.

The winding was evacuated using a 5 CFM mechanical pump. The winding was evacuated for at least 24 hours at which time the internal pressure was about 0.3 torr and was stable at this pressure.

Ethylene glycol was introduced near the bottom of the stand pipe containing the vacuum connection. The glycol was poured

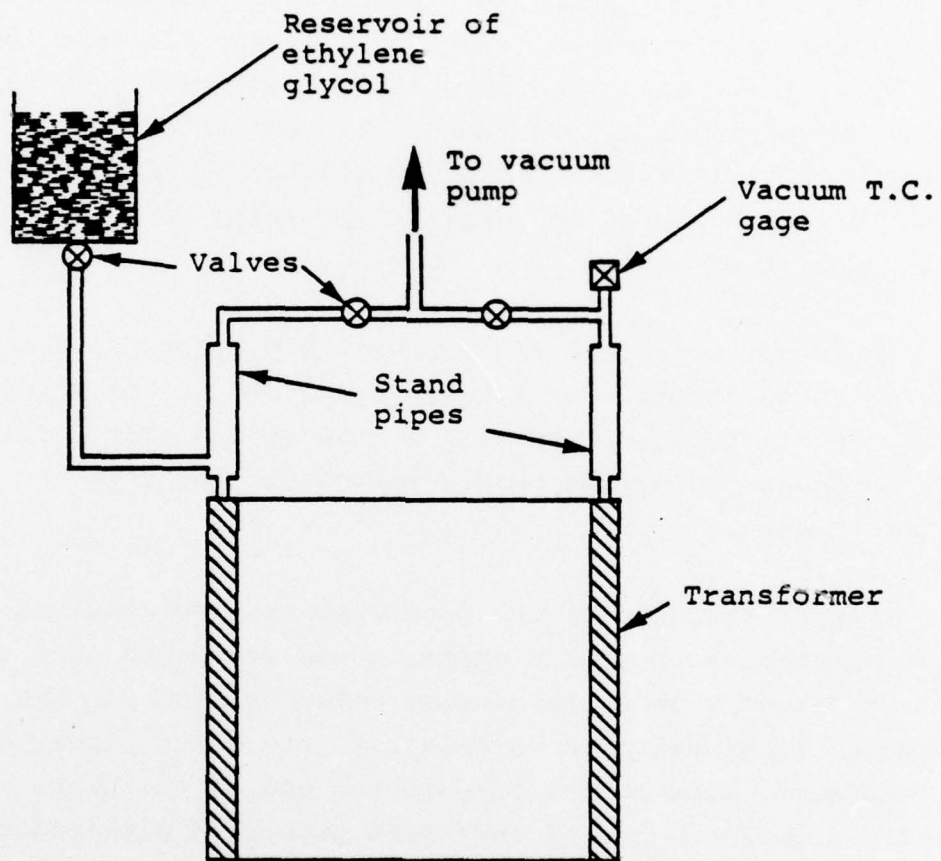


Figure 8 Vacuum impregnation setup.

slowly into the winding under vacuum conditions; slowly enough to permit de-gassing of the glycol. Vacuum was maintained until the glycol completely covered the winding. At this point, the standpipes were let back up to atmospheric pressure to force the glycol into the winding. At no time was the glycol level allowed to fall below the height of the winding. Performed in this way, a successful, bubble free, complete impregnation was achieved.

After impregnation, one of the impregnation holes was sealed off and a glycol filled volume compensator was connected to the remaining inlet. The compensator maintains a small positive pressure in the annular region containing the winding and permits the glycol to expand and to contract with temperature changes without drawing air into the volume.

The second demonstration transformer completed in the course of this program is shown in Figure 9. The transformer weight is about 190 pounds, of which more than half is the combined weight of the inner and outer cases. The thickness of the outer case is greater than actually required and transformer weight could be reduced by 30 pounds without any loss of required strength.

2.2 PROTOTYPE TRANSFORMER

Prototype transformer electrical requirements are summarized in Table 3 and the electrical circuit in which it is to be used is illustrated in Figure 10. The transformer in this case too is driven from a thyatron switched PFN. However, in contrast to the demonstration transformers, the prototype unit is operated in "conventional" rather than autotransformer mode.

The electrical design of the prototype transformer is presented in Appendix C, and Table 4 summarizes the principal electrical and electrical quantities.

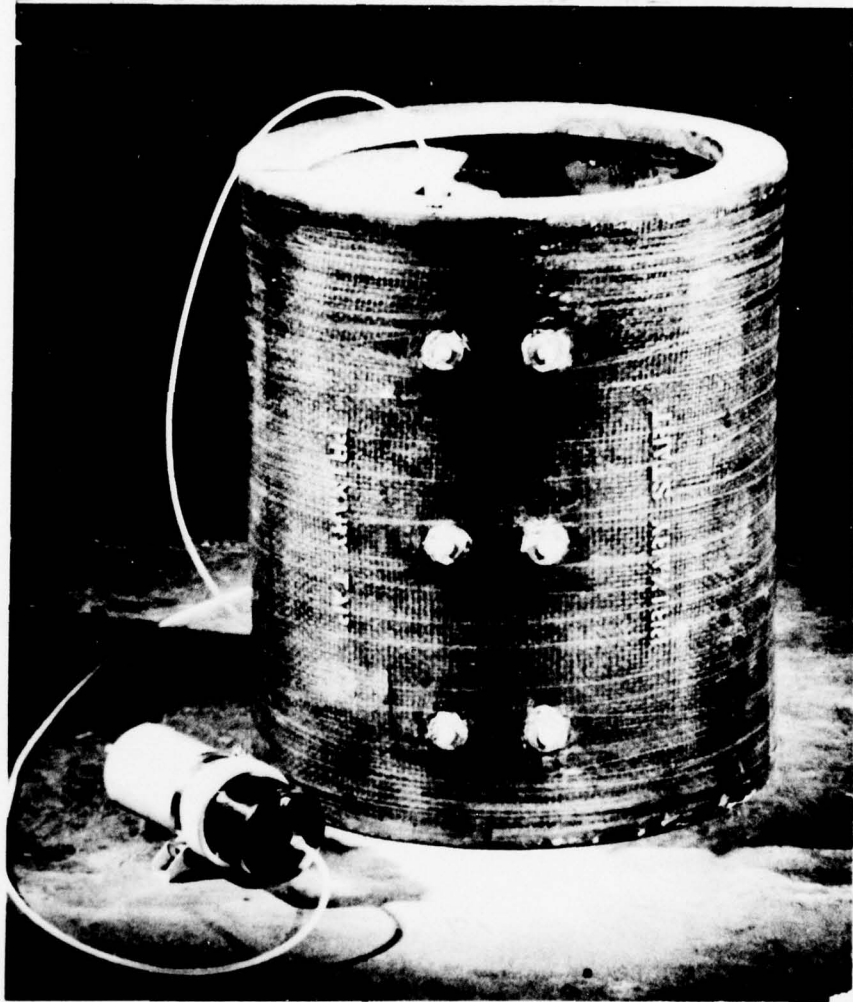


Figure 9 Completed demonstration transformer.

TABLE 3. PROTOTYPE TRANSFORMER ELECTRICAL REQUIREMENTS

Output voltage (into a matched load)	163 kV
Output peak current	32.2 kA
Load resistance	5.06
Input voltage (match condition)	19.2 kV
Output pulse width	10 μ sec (FWHM)
Output pulse risetime	$\leq 1 \mu$ sec (10-90%)
Pulse droop	$\leq 5\%$ in 10 μ sec
PRF	120 pps
Duty	Burst mode

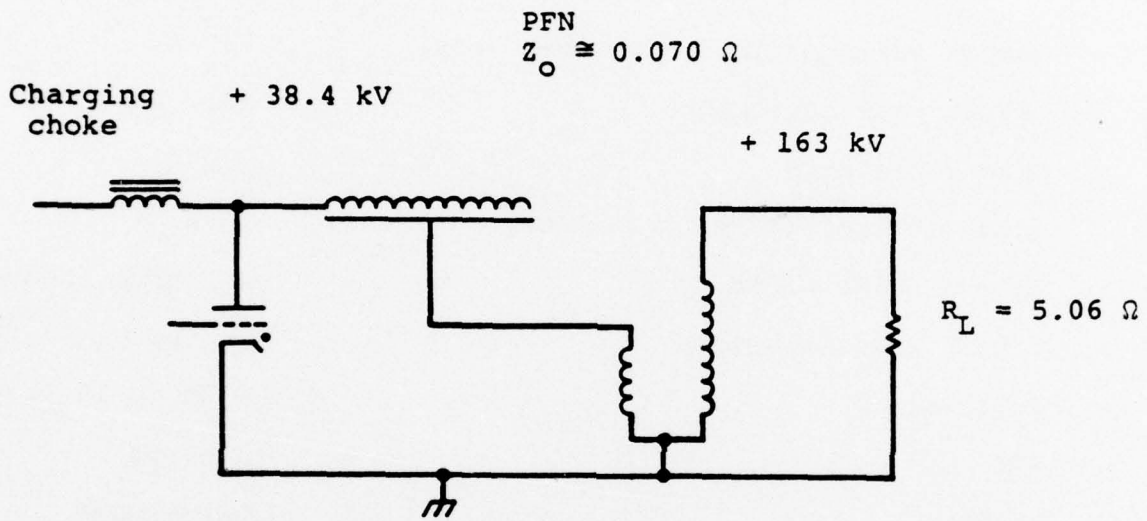


Figure 10 Pulse modulator circuit (prototype transformer).

TABLE 4. PROTOTYPE TRANSFORMER DESIGN SUMMARY

Mean winding diameter	~ 108 cm
Width of winding	~ 100 cm
Number of primary turns	3
Number of secondary turns	27
Primary inductance	6.7 μ H
Pulse droop	4.6% in 10 μ sec
Conductor material	copper
Current density (peak)	60 kA/cm ²
Primary conductor thickness	0.020 inch
Secondary conductor thickness	0.002 inch
Insulation thickness* (Kapton/paper/glycol)	0.0055 inch
Insulation stress	1.6 kV/mil
Total winding thickness	0.27 inch
Leakage inductance	88 nH
Risetime (10 to 90%)	1.5 μ sec
Primary conductor length	1.02 x 10 ³ cm
Primary resistance (20°C)	0.34 m Ω
Secondary conductor length	9.2 x 10 ³ cm
Secondary resistance (20°C)	31 m Ω
Case material	Polyester-fiberglass
Case dimensions	
<u>Outer</u>	
Outside diameter	43.5
Inside diameter	43.0
<u>Inner</u>	
Outside diameter	42.5 inches
Inside diameter	41.5 inches
Length	~ 50 inches
Weight	~ 690 pounds

*The insulation consists of a "sandwich" of two sheets of 0.002-inch-thick Kapton film separated by 0.0005-inch-thick paper (3 sheets).

Construction of the prototype transformer is very similar to the demonstration units except for size and some details.

2.2.1 Inner Dielectric Cylinder. The diameter of the prototype unit inner polyester fiberglass cylinder is 42.5 inches. Wall thickness is 0.5 inch.

To provide added strength, four fiberglass rings were installed in the cylinder inner diameter. Aluminum "spiders" were attached to the rings to accommodate an axle for machining of the cylinder and for transformer winding. The "spiders" were removed after completion of the winding.

As was the case with the demonstration unit, the prototype inner cylinder contained a thickened region and was slotted to accommodate metal parts for electrical connection to the end of the secondary conductor, which forms the output connection. The number of discrete conductors that form the output connection was increased to eight because of the higher current in the prototype unit.

The winding apparatus for the prototype unit is shown in Figure 11 with the inner cylinder in place and in the process of being wound. The winding apparatus is similar to the one used for the demonstration units, except much larger.

2.2.2 Winding Conductor. From Table 4, the thickness of the copper conducting material (alloy No. 10), which comprises the prototype transformer winding, is 0.020 inch and 0.002 inch for the primary and secondary, respectively. Conductor width is 40 inches but because of the unavailability of suitable material in single widths, two 20 inch strips of copper were used. The strips were wound onto the transformer together. Spacing between strips was about $\frac{1}{4}$ inch.

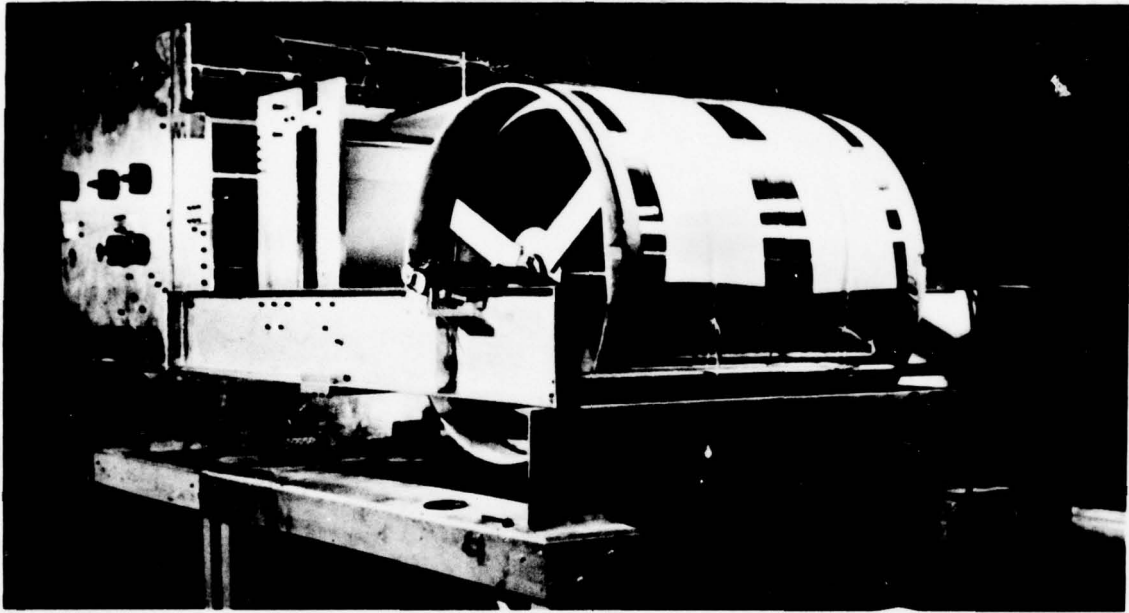


Figure 11 Prototype transformer apparatus.

The primary conductor was too large to be conveniently wound onto the transformer in a single thickness, and thus, the conductor consisted of two sheets of 0.010-inch-thick material, one on top of the other. The sheets were separated by a single thickness of 0.0005-inch-thick paper except at their ends where they were soldered together. The paper insulation permitted the magnetic field to penetrate between the sheets. As a result, current flowed on both sides of the individual thickness of the conductors and skin effect was reduced.

2.2.3 Dielectric Material. The dielectric material used in the prototype transformer consisted of two sheets of 0.002-inch-thick Kapton film, and three sheets of 0.0005-inch-thick kraft paper. Width of the material is about 44 inches in single sheets. Thus, the material extends 2 inches beyond the winding conductor at each side. The dielectric "sandwich" thus formed was very similar to that used in the demonstration transformers except for thickness.

2.2.4 Impregnant. The impregnant used for both the demonstration and prototype transformers was the same; ethylene glycol.

2.2.5 Outer Case. The prototype transformer outer case was similar to the demonstration units except larger. Its inner diameter is about 43 inches, and it is about 48 inches long. Wall thickness is about $\frac{1}{4}$ inch.

2.2.6 Prototype Transformer Winding. Winding of the prototype transformer was similar to the previously described demonstration units. The secondary was first wound onto the inner cylinder, but in this case the secondary consisted of 27 turns.

At the "start" of the secondary, a soldered splice connection was made to the thicker primary material. Eight rod feedthrough conductors were also installed at this point, i.e., at the "end" of the primary. Then the primary winding was wound onto the unit. Holes were cut out in subsequent primary turns to clear the feedthrough conductors. Cut-out dimensions for the prototype transformer are shown in Figure 12.

The primary winding consisted of three turns, and when completed, a second row of eight rod conductors was installed at the "start" of the primary winding. Thus, as was the case with the demonstration transformers, the input connections to the prototype unit were two rows of rod conductors separated by about 3 inches. Because of the higher current of the prototype unit, eight rod conductors were used in each row.

After the winding was finished, the transformer fabrication was completed in the same way as were the demonstration units. A three piece epoxy fiberglass outer case was installed over the winding and the sections were bonded together. Feedthrough bushings were installed over the input connection rod conductors. The transformer was then removed from the winder and epoxy fiberglass ends were installed. Finally, epoxy fiberglass was wrapped onto the outer diameter to provide additional strength.

2.2.7 Impregnation. Impregnation of the prototype transformer was performed in the same manner as were the demonstration units; the annular volume containing the winding was evacuated and back filled with ethylene glycol.

The completed prototype transformer is shown in Figure 13. Total transformer weight is 806 pounds. More than half the transformer weight is associated with the inner and outer epoxy fiberglass cases. Although, as was the situation with the demonstration units, the weight of the outer case can be reduced by about 800 pounds without loss of necessary strength.

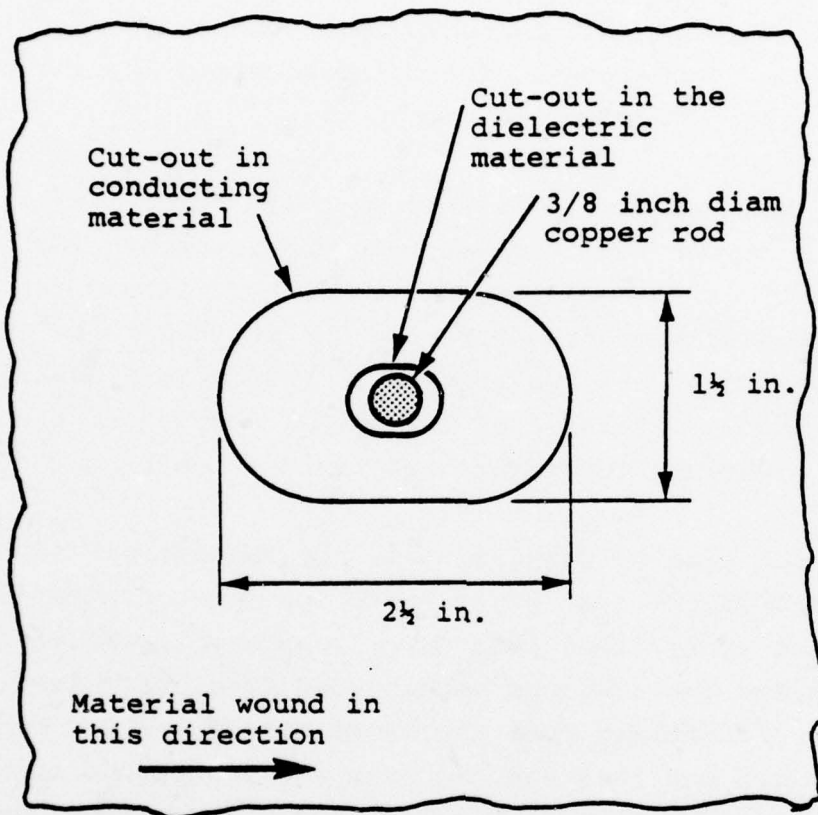


Figure 12 Prototype transformer feedthrough cut-out dimension.

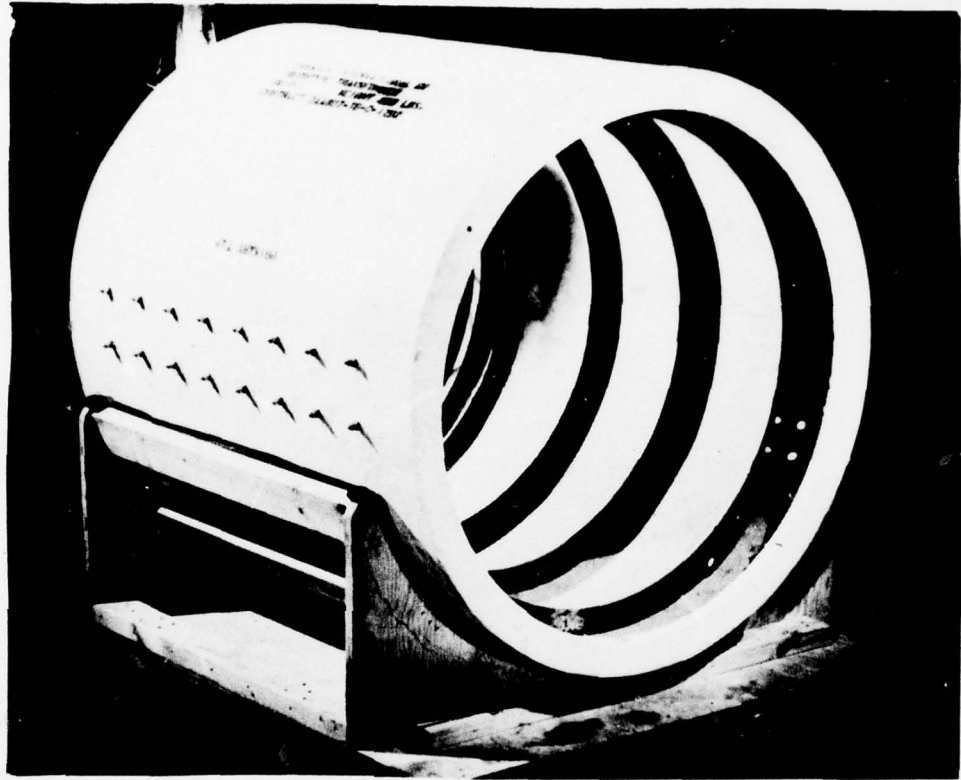


Figure 13 Completed prototype transformer.

SECTION 3

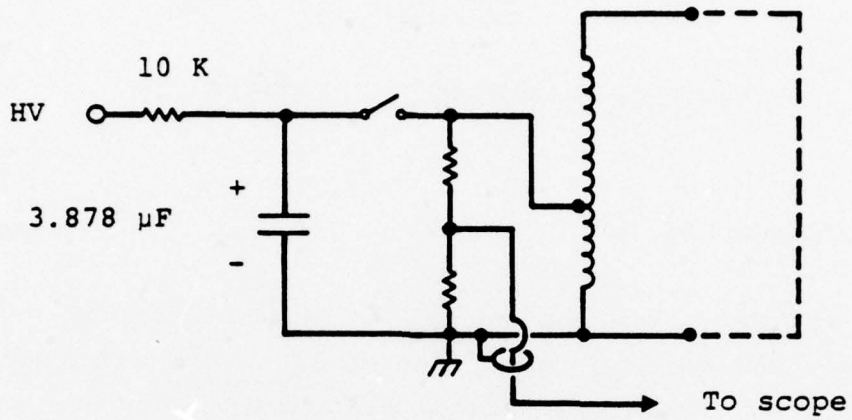
TRANSFORMER TESTING AND TEST RESULTS

3.1 TRANSFORMER TESTING

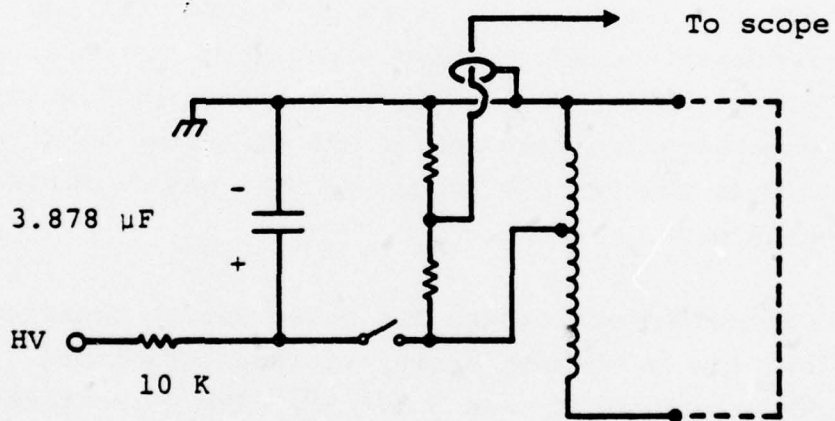
Both the demonstration and prototype transformers were tested under low voltage conditions at PI to accurately characterize their equivalent electrical circuits.

The test circuit is illustrated in Figures 14a and 14b for the demonstration and prototype transformers respectively. The transformers were tested in their intended configuration, i.e., the demonstration transformer was connected in auto-transformer mode whereas the prototype unit was connected in "conventional" mode.

For testing in both cases, the pulse source consisted of two parallel, low inductance energy storage capacitors. Their combined measured capacity was 3.878 μF . The capacitors were connected to the transformer under test by means of a low inductance strip line feed (Figure 15). The upper conductor consisted of two overlapping parts separated by a thin sheet of Mylar. For testing, the capacitors were dc charged to about 2 kV and a thumb-tack, located in a close fitting hole in the upper conductor, was driven through the Mylar sheet and into the lower conductors. The "thumb-tack" switch thereby completed the circuit, and the source capacitors were discharged into the transformer primary.



a) Demonstration transformer.



b) Prototype transformer.

Figure 14 Transformer test circuit.

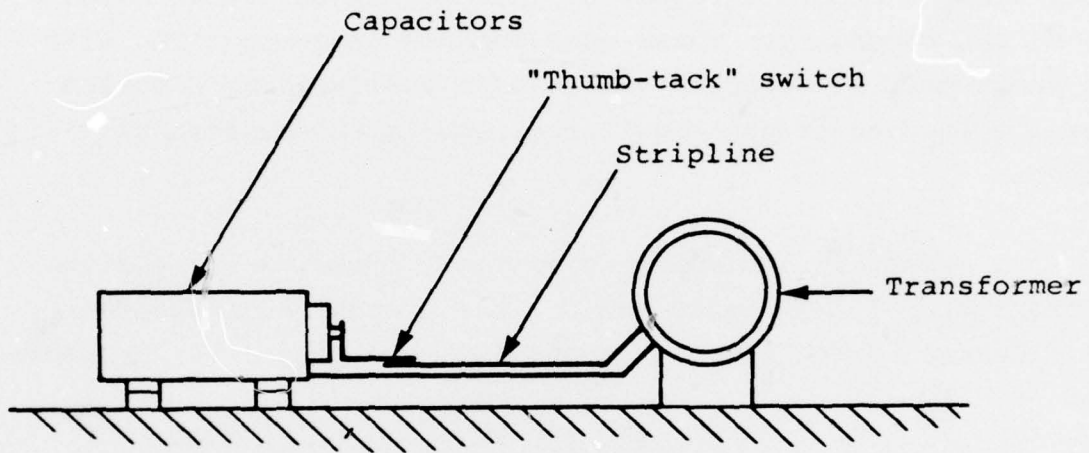


Figure 15 Transformer low voltage test.

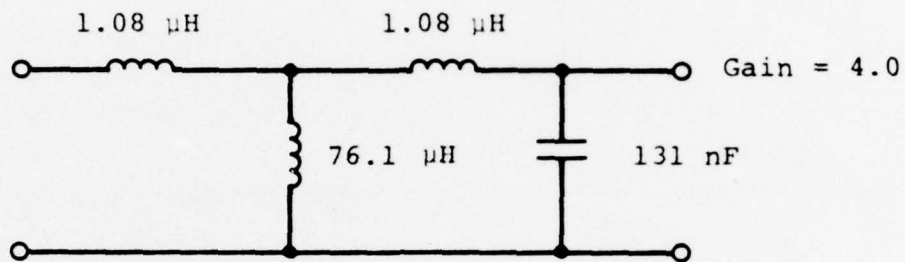
Transformer measurements were made for two conditions; the secondary (1) open circuited and (2) short circuited. Using a resistive divider monitor and oscilloscope, the resulting oscillatory waveforms produced by discharge of the source capacitors into the transformer and test were recorded. Measurements were made both directly at the primary of the transformer and at the secondary. These measurements in conjunction with the known driving capacity and voltage permitted an accurate characterization of the transformer equivalent electrical circuits.

The resulting equivalent electrical circuits for the two demonstration transformers and for the prototype transformer are illustrated in Figures 16a and 16b, and Figure 17, respectively.

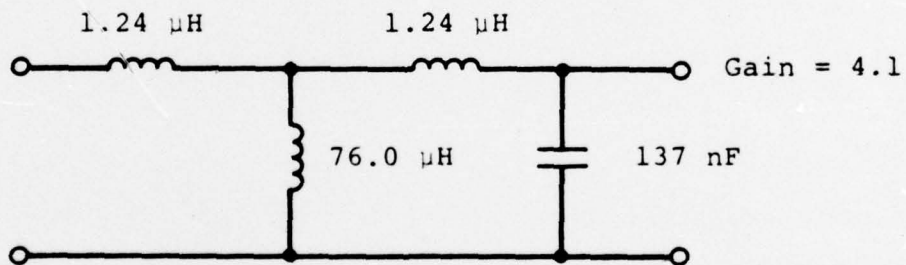
3.2 TEST RESULTS

The measured values of primary inductance agree very closely with the calculated values for both the demonstration and prototype transformers. Agreement with regard to the leakage inductance is less satisfactory, however. This apparent discrepancy arises as a result of the actual thicknesses of the transformer windings compared with the ideal values. The dielectric film material tends to wrinkle and increase the "sandwich" thickness appreciably. The measured values of leakage inductance are a direct consequence of this effect.

In Figure 16, the leakage inductance of the second demonstration transformer is greater than the first. This is due principally to the reduction of input connecting rods from five to three.



a) Unit No. 1 delivered to the E-COM.



b) Unit No. 2 delivered to the E-COM.

Figure 16 Demonstration transformer equivalent electrical circuits (all values referred to the primary).

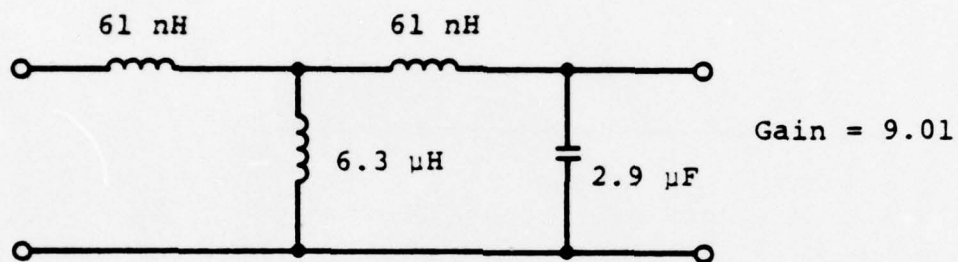


Figure 17 Prototype transformer equivalent electrical circuit
 (all values referred to the primary).

Wrinkles in the dielectric material can be substantially reduced by using "herringbone" rollers in the winding apparatus. These rollers contain grooves that apply a lateral force on the dielectric material and smooth it out.

Both demonstration transformers were tested at the E-COM under high voltage conditions. Unit No. 1 was operated to full output voltage in single shot mode at which point it failed after very few shots. The transformer was subsequently examined at PI. Examination revealed that the breakdown had occurred in one of the conductor feedthrough locations where the end of primary conductors passed through holes cut into the primary winding. There was no clear indication of the cause of breakdown, but at least two possibilities exist.

First, the feedthrough conductors in unit No. 1 were simply bonded to the outer case to effect a seal. The mechanical strength of the bond joint became questionable even during low voltage testing at PI. One conductor had parted slightly from the case and glycol was observed to "weep" from the hairline crack. This joint was re-sealed with epoxy prior to shipment of the unit to the E-COM. Thus, it is possible that air had been permitted to enter into the region and induce breakdown.

The second alternative recognizes that enhancement of the electric fields exists within the feedthrough region; although, the mean field is quite modest for glycol, about 32 kV/cm (for unit No. 1). The cut-out in the outermost turn is the region of highest field and is electrically "exposed." That is to say, the conductor edge is subject to high field enhancement since no additional conducting surface exists to grade the field at that location.

Two modifications that address the issues discussed in the foregoing paragraphs were incorporated into the second demonstration transformer. Bushings, incorporating O-ring seals, were designed (Figure 7) to mechanically support and seal the feedthrough conductors. In addition, the cut-out dimensions in the primary conductor were increased (Figure 5) to reduce the mean electric field in those locations (to 26 kV/cm). However, no provision to shield the edge of the cut-out in the outer most primary turn was provided.

Since the cut-out width was increased, reducing the effective width of conducting sheet at that location, the number of feedthroughs was reduced from five to three.

The second demonstration transformer was operated under repetitive pulse conditions, 10 pps and in some cases 20 pps. Numerous runs were taken beginning at low voltage, with burst durations of 10 to 20 seconds. During the second run at 80 percent of full voltage (\cong 160 kV), the unit failed.

Subsequent examination of the failed unit has revealed that it too failed at one feedthrough location. There is little question at this juncture that shielding of the outermost conductor cut-out edge is required to reduce the high fields at those locations and eliminate the breakdown.

SECTION 4

SUMMARY AND CONCLUSIONS

The principal distinguishing characteristic of the transformers that are the subject of this final report is the nearly uniform field operation of the dielectric material which provides turn-to-turn insulation. This attribute in conjunction with impregnation of the winding with a high dielectric constant medium to eliminate corona and to permit operation of the dielectric at high stress, minimizes the volume of dielectric material, reduces stray series inductance, and thus improves transformer high frequency response in comparison with more conventional pulse transformer designs.

The objectives of the project described in this final report were to develop transformer fabrication techniques and to fabricate and test the described demonstration and prototype pulse transformers. These objectives were accomplished.

Low voltage testing of the fabricated transformers to characterize their equivalent electrical circuits has revealed excellent agreement between calculated and actual values of transformer primary inductance.

In contrast, actual leakage inductance values were greater than calculated values by more than 50 percent; but this is a result of increased winding thickness due to wrinkling of the dielectric material. The thickness of the winding can be reduced by refining the winding technique, i.e., by using special rollers to smooth the material as it is wound onto the form.

The most serious problem associated with the described transformers was the design and fabrication of the transformer connections. The approach chosen here was a design that minimized the stray inductance associated with connections to one external driving circuit. To accomplish this, however, conductors had to pass through the primary winding to make connection to the "end of the primary." Thus, local high stress regions were created between the feedthrough conductors and the nearby primary conducting material.

High voltage tests conducted at the E-COM have revealed feedthrough design inadequacies and, based upon examination of the breakdowns, it is clear that additional shielding must be provided to reduce the electric field enhancement existing at the cut-out edge of the first primary turn.

There is little question that the necessary shielding can be successfully incorporated into the design. One approach is to interchange the windings on the form, i.e., the primary is wound first onto the inner dielectric form. Using this approach, suitably shaped shields attached to the form provide the necessary shielding for the primary conductor feedthrough cut-out edges.

APPENDIX A
DEMONSTRATION TRANSFORMER DESIGN CALCULATIONS

The design calculations described in this appendix are based upon the design and design formulae developed in References 1 and 2.

1.0 REQUIREMENTS:

$V_o = 200$ kV (matched load)
 $V_i = 50$ kV
 $R_L = 24$ Ω
 $w = 5$ μ sec
Droop = 5% in 5 μ sec
Connection Autotransformer

2.0 ASSUMPTIONS:

$\bar{r} = 10.154$ inches = 25.79 cm
 $b = 20$ inches = 50.80 cm
 $n_p = 15$
 $n_s = 47$

3.0 DESIGN

3.1 Gain

In autotransformer mode, the minimum gain G is given approximately by

$$G = \frac{n_p + n_s}{n_p} = \frac{15 + 47}{15} = 4.13$$

3.2 Reflected load resistance

$$R'_L = \frac{R_L}{G^2} = \frac{24}{(4.13)^2} = 1.41 \text{ ohm}$$

3.3 Primary inductance

Primary inductance is given by

$$L_1 = \frac{\mu_0 \pi r^2 n_p^2}{r + b} = \frac{4\pi^2 \times 10^{-9} (25.79)^2 (15)^2}{25.79 + 50.8}$$

$$L_1 = 77.1 \mu\text{H}$$

3.4 PULSE DROOP

Pulse droop, D, is given by

$$D = 1 - e^{-\alpha t_w} \quad \text{where}$$

$$\alpha = \frac{R'_L}{2L_1} = \frac{1.41}{2(77.1 \times 10^{-6})} = 9.14 \times 10^3$$

$$D = 1 - e^{-9.14 \times 10^{-3} (5 \times 10^{-6})} = 0.045 = 4.5\%$$

3.5 WINDING

3.5.1 Assumptions

J = 60 kA/cm² in copper

F = 1.67 kV/mil in Kapton dielectric film

3.5.2 Primary Conductor

Thickness of primary conductor t_p is given by

$$t_p = \frac{i_p - i_s}{bJ} = \frac{35.48 \times 10^3 - 8.33 \times 10^3}{50.8 (60 \times 10^3)} = 8.90 \times 10^{-3} \text{ cm}$$

$$t_p = 3.51 \times 10^{-3} \text{ inch}$$

Let $t_p = 0.004 \text{ inch}$

Total thickness of primary conductor, Δ_p , is $n_p t_p = 15$
 (0.004 inch) = 0.060 inch = $\Delta_p = 0.152$ cm

3.5.3 Secondary conductor

$$t_s = \frac{i_s}{bJ} = \frac{8.33 \times 10^3}{50.8(60 \times 10^3)} = 2.73 \times 10^{-3} \text{ cm}$$

$$t_s = 1.08 \times 10^{-3} \text{ inches}$$

$$\text{Let } t_s = 0.001 \text{ inch} = 2.54 \times 10^{-3} \text{ cm}$$

$$\Delta_s = n_s t_s = 47 (2.54 \times 10^{-3}) = 0.119 \text{ cm}$$

3.5.4 Dielectric

$$\text{Volts/turn} = \frac{50 \times 10^3}{15} = 3.33 \times 10^3$$

$$t_K = \frac{V_T}{F} = \frac{3.33 \times 10^3}{1.67 \times 10^3} = 2 \times 10^{-3} \text{ inch}$$

Use 2 sheets of 0.001-inch-thick Kapton separated by 3 sheets of 0.0005-inch-thick paper (sandwich)

$$t_{p\alpha} = 3 (0.0005) = 0.0015 \text{ inch}$$

$$t_{in} = t_{p\alpha} + t_K = 0.0015 + 0.002 = 0.0035 \text{ inch}$$

$$= 8.89 \times 10^{-3} \text{ cm}$$

$$\Delta_{in} = (n_s + n_p) t_{in} = (47 + 15)(8.89 \times 10^{-3}) = 0.551 \text{ cm}$$

Total thickness of the winding Δ is

$$\Delta = \Delta_p + \Delta_s + \Delta_{in} = 0.152 + 0.119 + 0.551 = 0.822 \text{ cm}$$

3.6 LEAKAGE INDUCTANCE

Leakage inductance is given by (for an unbalanced transformer design in autotransformer mode)

$$L_{\ell} = \frac{2}{3} \pi \mu_o \frac{r}{b} \Delta n_p^2 \left(1 - \frac{n_p}{n_t}\right)^2$$

$$= \frac{2}{3} 4\pi^2 \times 10^{-9} \frac{25.79}{50.8} (0.822) (15)^2 \left(1 - \frac{15}{62}\right)^2$$

$$L_{\ell} = 1.42 \mu\text{H}$$

3.7 RISE TIME (INDUCTIVE)

For an ideal PFN, transformer output pulse risetime τ_R (10-90 percent) is given approximately by

$$\tau_R \approx \frac{2.2 L_{\ell}}{2 R'_L} = \frac{1.1(1.42 \times 10^{-6})}{1.41} = 1.11 \mu\text{sec}$$

3.8 STRAY SECONDARY CAPACITY

Stray secondary capacity is given by

$$C_s = \frac{\epsilon_r \epsilon_0 2\pi r b}{n_t s}, \text{ where}$$

s is the thickness of Kapton insulation per turn

$$C_s = \frac{3.4(8.85 \times 10^{-14}) 2\pi(25.79)(50.8)}{62(5.08 \times 10^{-3})}$$

$$= 7.86 \text{ nF (referred to secondary)}$$

$$C'_s = G^2 C_s = (4.13)^2 7.86 \times 10^{-9} = 134 \text{ nF}$$

3.9 RISETIME (CAPACITIVE)

$$\tau_R = 2.2 \frac{R_L'}{2} C_s' = 1.1(1.41)(134 \times 10^{-9}) = 0.21 \mu\text{sec}$$

therefore output pulse risetime is inductive dominated.

3.10 MAGNETIC PRESSURE

The mechanical pressure exerted on the transformer case due to the magnetic forces is given by

$$P = \frac{\mu_0 (n_p^2 (i_p - i_s)^2)}{2b^2} = \frac{4\pi \times 10^{-7} (15)^2 (27.15 \times 10^3)^2}{2 (0.508)^2}$$

$$P = 4.04 \times 10^5 \text{ n/m}^2 = 58.6 \text{ psi}$$

3.11 HEATING

3.11.1 Primary Conductor

$$\text{Length} = 2\pi r n_p = 2.43 \times 10^3 \text{ cm}$$

$$\text{CSA} = b t_p = 50.8 (1.016 \times 10^{-2}) = 0.516 \text{ cm}^2$$

$$\text{Volume} = 1.25 \times 10^3 \text{ cm}^3$$

$$\text{Density} = 8.96 \text{ g/cm}^3$$

$$\text{Mass} = 11.24 \text{ kg}$$

$$R_p = \rho l/A = \frac{1.72 \times 10^{-6} (2.43 \times 10^3)}{0.516} = 8.1 \text{ m}\Omega$$

$$U_p = (i_p - i_s)^2 R_p \tau_w = (27.15 \times 10^3)^2 (8.1 \times 10^{-3}) (5 \times 10^{-6}) = 29.9 \text{ J/pulse}$$

$$\Delta T = \frac{U_p}{c_p m} = \frac{29.9}{(0.385)(11.24 \times 10^3)} = 6.90 \times 10^{-3} \text{ }^\circ\text{C/pulse}$$

3.11.2 Secondary Conductor

$$\text{Length} = 2\pi r n_s = 2\pi(25.79)(47) = 7.62 \times 10^3 \text{ cm}$$

$$\text{CSA} = b t_s = 50.8(2.54 \times 10^{-3}) = 0.129 \text{ cm}^2$$

$$\text{Volume} = 9.83 \times 10^2 \text{ cm}^3$$

$$\text{Mass} = 8.96(9.83) \times 10^2 = 8.8 \text{ kg}$$

$$R_s = \rho \frac{l}{A} = 1.72 \times 10^{-6} \frac{7.62 \times 10^3}{0.129} = 0.102 \Omega$$

$$U_s = i_s^2 R_s \tau_w = 35.4 \text{ J/pulse}$$

$$\Delta T = \frac{U_s}{m c_p} = \frac{35.4}{(8.8 \times 10^3)(0.385)} = 1.04 \times 10^{-2} \text{ }^\circ\text{C/pulse}$$

APPENDIX B

SINGLE PULSE BREAKDOWN OF KAPTON POLYIMIDE DIELECTRIC FILM

Purpose: The purpose of the described testing was to determine the pulsed breakdown field strength of Kapton* dielectric film to provide a basis for selecting an operating field strength for the material in the pulse transformers described in this report.

Approach: To accomplish the purpose of these tests, samples of Kapton film, imbedded in ethylene glycol and "sandwiched" between plane-parallel electrodes were electrically pulsed to breakdown.

The function of the ethylene glycol was to provide an ambient medium that, by virtue of its high relative dielectric constant ($\epsilon_r \approx 41$) in relation to Kapton ($\epsilon_r \approx 3.4$), forces the applied electric field into the Kapton film material.

The pulse source for these measurements was a dc charged capacitor which was switched onto the test electrodes containing the Kapton sample.

Description of the Apparatus:

Each Kapton test sample consisted of three sheets of 0.001-inch-(nominal) thick film material (Type H) stacked together to form a pad. The thickness of the Kapton film material was checked periodically as it was used from the roll of material. The measured thickness varied from about 0.00094 inch to 0.00105, i.e., by about ± 5 percent. Thus, the film thickness was acceptably

*Kapton-Dupont polyimide film ($C_{22}H_{10}N_2O_5$).

close to the nominal value, and appeared to be nearly constant in thickness with location in the roll. Thickness measurements were not performed on the tested samples however, principally because of the difficulty of making the measurement and because of damage to the material, through handling, in making the measurements.

The individual pieces of film were assembled into the described pads under glycol to ensure an air free assembly.

The film pad was sandwiched between two aluminum disks, 13-3/4 inches in diameter. The edge of the disks contained a small radius, on the order of 0.030 inch. There is little need for a generous radius since the glycol forces the field into the film, i.e., there is little field enhancement at the edges.

The diameter of the film pads was only a little larger than the electrodes and this was satisfactory too, since the fields decrease rapidly with increasing radial distance.

The area of the aluminum electrodes is about 958 cm². Pad thickness is 7.62 x 10⁻³ cm; and therefore, the sample volume is 7.3 cm³.

Taking the dielectric constant of Kapton at 3.4, the capacity of the test sample is

$$C_K = \epsilon_r \epsilon_r \frac{A}{d} = \frac{3.4(8.85 \times 10^{-14})(958)}{7.62 \times 10^{-3}} = 37.8 \text{ nF}$$

The electrodes were contained within a shallow plastic tank containing nearly 10 gallons of glycol. The lower electrode rested upon and was in close contact with a wide copper ground plane that was carried over one edge of the tank and under the energy storage capacitor located horizontally and parallel to the side of the tank in air.

The pulse generator electrical circuit is illustrated in Figure B-1. In this circuit a 0.1069 μF capacitor, precisely measured, is dc charged and switched into the test electrodes by means of a pressurized gas spark gap.

To fire the spark gap, pressure is simply bled from the switch until it self fires.

Direct current charge of the capacitor was carefully monitored on a shot-to-shot basis using a precision resistor string ($1000\text{M} \pm 2$ percent) and a calibrated 50 μA meter. The meter is accurate to ≤ 1 percent as determined by independent measurement.

The output pulse was monitored by means of a CuSO_4 resistive divider monitor and carbon resistor attenuator. The monitor was located in air above the glycol surface and was connected to the top electrode of the test fixture by means of a short wire connection. CuSO_4 monitor resistance was about 400 ohm.

Monitor calibration, determined by direct capacitor discharge (26 kV) was 1810/1 ($\sigma = 0.3$ percent). The monitor was connected, by means of terminated 50 ohm coaxial cable, to a Tektronix No. 454 oscilloscope contained within a shielded enclosure. Overall accuracy of the pulse monitoring circuit was estimated to be ± 5 percent or less.

Two output pulse waveforms were used in the course of testing. Initially the circuit illustrated in Figure B-1 was used. The value of the series resistor (9 ohm) was chosen to critically damp or slightly overdamp the circuit.* The output voltage waveform measured across C_L in this case is illustrated in Figure B-2a.

*Circuit stray inductance is not shown in Figure B-1, but its value, determined by measurement, is about 0.75 μH .

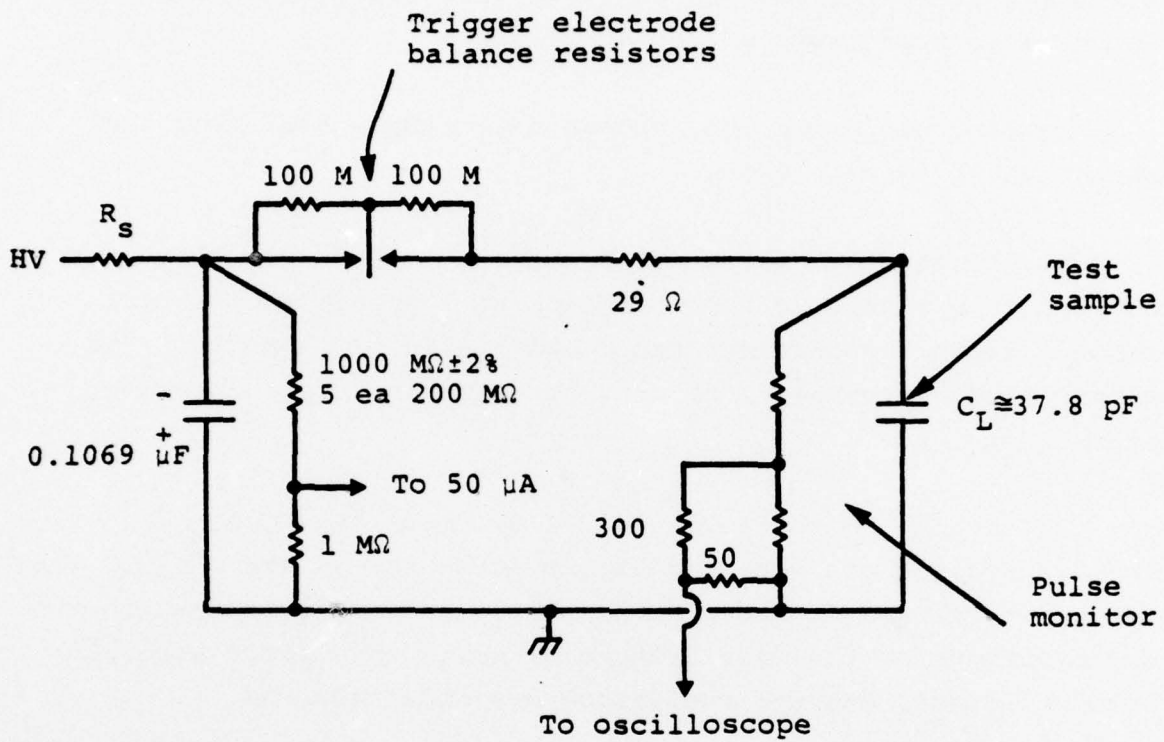


Figure B-1 Kapton test electrical circuit.



Vert: 2 V/div
Horiz: 1 μ s/div
 $V_{dc} = 30$ kV

a) Damped circuit (9 ohm installed)



Vert: 5 V/div
Horiz: 1 μ s/div
 $V_{dc} = 35$ kV

b) Oscillatory circuit (9 ohm short circuited)

Figure B-2 Load voltage waveforms.

However, for most of the testing the circuit was modified by replacing the 9 ohm resistor with a short circuit. In this case, the circuit became oscillatory and produced a $\sim (1-\cos\omega t)$ voltage waveform across the load capacity. Thus, for equal dc charge voltage, the oscillatory circuit produced a greater output peak voltage than could be obtained with a damped circuit, and the circuit modification was made for this reason.

The oscillatory pulse voltage waveform is illustrated in Figure B-2b for the condition where the film sample broke late in time, after the first few cycles.

Based upon analyses of the oscillatory waveform, in conjunction with the measured value of primary capacity and the calculated value of load capacity (the Kapton film) and monitor shunt resistance, the circuit stray series inductance and resistance is 0.75 μH and 0.40 ohm, respectively. The circuit characterization in conjunction with the measured dc charge voltage provided a convenient cross check upon pulse monitor calibration. For the waveform illustrated in Figure B-2b, the pulse monitor yielded a peak value of 49.0 kV, whereas the computed value based upon circuit performance yielded 48 kV--excellent agreement.

Test Description and Results:

Twenty-six Kapton pad samples were tested to breakdown, and the test results are summarized in Table B-1. All of the breakdowns were produced using the oscillatory pulse discharge circuit. However, in samples 1 and 3, the damped discharge circuit was also used, but prior to film breakdown.

From Table B-1, there is shown considerable scatter in the breakdown data. Breakdown fields range from 2.7 MV/cm to more than 6.2 MV/cm.

As evidenced from the summary, there was some indication that the results were influenced by the care with which the film material was handled and installed into the test fixture. And indeed, there appears to be a positive correlation in this regard. Comparatively good reproducibility of the breakdown field was achieved in the last series (Shot Nos. 21 to 26) where extreme care was used with the film. For this series of shots, the mean breakdown field was 5.6 MV/cm (14.3 kV/mil) with a standard deviation of about 12 percent.

The highest recorded breakdown field was 6.4 MV/cm (16.3 kV/mil), and the sample survived this peak, but broke down later at a lower value, later in the pulse.

It is noted that if the mean breakdown field in the Kapton is 5.6 MV/cm (Shot Nos. 21 to 26), then the field in the glycol is about one-twelfth this value (the ratio of the dielectric constants); but this field is almost 500 kV/cm. Thus, it is possible that the glycol is breaking down first; thereby inducing breakdown in the Kapton.

Another important observation is that the breakdown sites are concentrated at larger radii than would be expected based upon statistical arguments concerning the area or volume of the samples. Over 55 percent of the breakdown sites are located at a radius greater than 6 inches. However, the electrode area outside this radius comprises only 25 percent of the total area. Although speculative, this effect could possibly be attributed to transient reflections from the "open" electrode edges, which over voltage and break down the film. However, the source of such "transients" is unknown.

TABLE B-1 KAPTON BREAKDOWN TEST RESULTS

Sample No.	V _{dc} (kV)	Breakdown Voltage (kV)	Breakdown Field (MV/cm)	Radial Location of Breakdown (in.)	Remarks
1	30	> 26.3	> 3.5	≈ 5-7/8	The sample survived 5 shots at a peak pulse voltage of 22.4 kV (2.9 MV/cm) using the damped circuit waveform. The circuit was modified to the oscillatory waveform and broke on the subsequent shot. The peak voltage was off scale however.
2	26	27.2	3.6	≈ 5-7/8	The sample broke on the first shot, before peak (osc. waveform).
3	20	28.4	3.7	≈ 4-7/8	The sample was pulsed four times without breakdown using the damped waveform. Peak pulse voltages were 23.3 kV, 24.6 kV, 26.6 kV and 28.8 kV. The circuit was changed to the osc. waveform and the sample broke on the following shot.
4	30	> 37.2	> 4.9	≈ 6-3/8 and ≈ 5-3/8 diametrically opposed	The sample survived one firing (osc. waveform) where peak voltage was 28.4 kV (3.73 MV/cm). Charge voltage was raised to 30 kV and the sample broke before peak voltage. The voltage was off scale however. Two breakdown sites were produced.
5	30	31	4.1	≈ 6-1/2	The sample broke on the first shot before peak.
6	30	41.3*	5.4*	≈ 6-3/8 and at the edge, diametrically opposed	The sample broke on the first shot, but not on the first cycle. The breakdown occurred late in the pulse, off the scope scale. The peak voltage and field of the first peak were 41.3 kV and 5.4 MV/cm. Two breakdown sites were produced.

*Survived

TABLE B-1 (cont.)

Sample No.	V _{dc} (kV)	Breakdown Voltage (kV)	Breakdown Field (MV/cm)	Radial Location of Breakdown (in.)	Remarks
7	30	35.5	4.7	≈ 6-3/8	Filter installed. The sample broke on the first shot, before peak voltage.
At this point, additional care was taken with the film during its installation into the electrodes.					
8	30	40.3	5.3	≈ 6-3/8	The sample survived 5 shots at this level and then broke on the 6th. The breakdown occurred at the peak of the first cycle.
A fixture was made to hold the upper electrode to ease installation of the film. Weight was placed into the fixture to move the electrode down onto the film material.					
9	32.5	44.3	5.8	≈ 5-3/8	The sample broke before peak on the first shot.
10	32.5	45.7	6.0	≈ 5-7/8	The sample broke just before peak voltage on the first shot.
Small bubbles were observed to evolve from the glycol and cling to the Kapton. Care was taken to remove all air.					
11	32.5	46.2*	6.1*	≈ 6-1/8	The sample survived two shots (osc. waveform). Peak voltage and field were 46.2 kV and 6.1 MV/cm respectively. The sample broke on the 3rd shot before peak voltage at 36.5 kV (4.8 MV/cm).
12	35	25.2	3.3	≈ 6-1/8	The sample broke on the first shot, before peak.
13	35	28.5	3.7	≈ 5-7/8	The sample broke on the first shot, before peak.

*Survived

TABLE B-1 (cont.)

Sample No.	V _{dc} (kV)	Breakdown Voltage (kV)	Breakdown Field (MV/cm)	Radial Location of Breakdown (in.)	Remarks
14	30	45.7*	6.0*	≈ 4-7/8	The sample broke on the first shot, but on the second cycle, before peak. Breakdown voltage and field were 37.4 kV and 4.9 MV/cm.
More air noticed evolving from glycol					
15	35	47.5	6.2	≈ 6-5/8	The sample broke on the first shot, before peak.
16	35	20.6	2.7	near edge	The sample broke on the first shot, before peak.
17	~ 34	21.6	2.8	≈ 6-3/8	The sample broke on the first shot, before peak.
18	35	43.3	5.7	≈ 4-7/8 and 6-1/2 (Δθ = 80°)	The sample broke on the first shot, before peak. Two breakdown sites were observed.
Sheets were loosely stacked before Shot No. 19, no weight added, air removed.					
19	35	25.2	3.4	≈ 6-3/8	The sample broke on the first shot, before peak.
Weight re-applied before Shot No. 20.					
20	35	45.4	6.0	≈ 4-7/8	The sample broke on the first shot, before peak.

Extreme care in handling and installing the film was exercised for the following shots. Air was thoroughly removed and the upper electrode was weighted.

*Survived

TABLE B-1 (cont.)

Sample No.	V _{dc} (kV)	Breakdown Voltage (kV)	Breakdown Field (MV/cm)	Radial Location of Breakdown (in.)	Remarks
21	35	41.2	5.4	≈ 6-1/8	The sample broke on the first shot, before peak.
22	35	42.6	5.6	edge	The sample broke on the first shot, before peak.
23	35	34.1	4.5	≈ 6-1/8	The sample broke on the first shot, before peak.
24	35	43.4	5.7	≈ 6-3/8	The sample broke on the first shot, before peak.
25	35	49.0*	6.4*	≈ 5-5/8 and ≈ 5-3/8 diam-etrically opposed	The sample broke on the first shot, but survived at least two full cycles. The breakdown was off the scope scale. There were two breakdown sites.
26	47.5		6.2	≈ 5-7/8	The sample broke down on the first shot, before peak.

*Survived

Conclusions

The breakdown field strength measurements of Kapton, described here, were subject to large scatter. The observed scatter appears to correlate with the care used in handling and testing the material. In the last series of measurements conducted with the film, where extreme care was used, the mean breakdown field strength was about 5.6 MV/cm with a standard deviation of 12 percent on six samples.

The working field for the described pulse transformers is about 1700 V/mil or 0.67 MV/cm. The lowest breakdown field recorded in the above measurements was 2.7 MV/cm. The working field is smaller by a factor of four. Assuming a 12th power life dependency upon stress (Reference 1), the working field value provides a dielectric life on the order of 10^7 shots, which is satisfactory for the intended application.

APPENDIX C

PROTOTYPE TRANSFORMER DESIGN CALCULATIONS

The design calculations described in this Appendix are based upon the design and design formulae developed in References 1 and 2.

1.0 REQUIREMENTS

$V_o = 163 \text{ kV (matched load)}$
 $V_i = 19.2 \text{ kV}$
 $R_L = 5.06 \text{ ohm}$
 $w = 10 \text{ } \mu\text{sec}$
Droop $\leq 5\%$ in μsec
Connection Conventional

2.0 ASSUMPTIONS:

$\bar{r} = 21.3 \text{ inches} = 54.2 \text{ cm}$
 $b = 40.0 \text{ inches} = 101.6 \text{ cm}$
 $n_p = 3$
 $n_s = 27$

3.0 DESIGN

3.1 Gain

In conventional mode, the minimum gain G is given approximately by

$$G \cong \frac{n_s}{n_p} = \frac{27}{3} = 9$$

3.2 REFLECTED LOAD RESISTANCE

$$R'_L = \frac{R_L}{G^2} = \frac{5.06}{9^2} = \frac{5.06}{81} = 62.5 \text{ m}$$

3.3 PRIMARY INDUCTANCE

Primary inductance is given by

$$L_1 = \frac{\mu_0 \pi r^2 n_p^2}{r + b} = \frac{4\pi^2 \times 10^{-9} (54.2)^2 (3)^2}{54.2 + 101.6}$$

$$L_1 = 6.7 \text{ } \mu\text{H}$$

3.4 PULSE DROOP

Pulse droop, D, is given by

$$D = 1 - e^{-\alpha \tau_w}$$

where

$$\alpha = \frac{R'_L}{2L_1} = \frac{62.5 \times 10^{-3}}{2(6.7 \times 10^{-6})} = 4.66 \times 10^3$$

$$D = 1 - e^{-4.66 \times 10^3 (10 \times 10^{-6})} = 0.046 = 4.6 \text{ percent}$$

3.5 WINDING

Assumptions

$$J = 60 \text{ kA/cm}^2 \text{ in copper}$$

$$\bar{F} = 1.67 \text{ kV/mil in Kapton dielectric film}$$

3.5.1 Primary conductor.

Thickness of the primary conductor, t_p , is given by

$$t_p = \frac{i_p}{bJ} = \frac{307.2 \times 10^3}{101.6 (60 \times 10^3)} = 50.4 \times 10^{-3} \text{ cm}$$

$$t_p = 19.8 \times 10^{-3} \text{ inches}$$

Let $t_p = 20 \times 10^{-3}$ inches

The total thickness of the primary, Δ_p , is

$$n_p t_p = 3(20 \times 10^{-3}) = 60 \times 10^{-3} = 0.152 \text{ cm}$$

$$\Delta_p = 0.152 \text{ cm}$$

3.5.2 Secondary conductor.

$$t_s = \frac{i_s}{bJ} = \frac{32.3 \times 10^3}{101.6 (60 \times 10^3)} = 5.28 \times 10^{-3} \text{ cm}$$

$$t_s = 2.1 \times 10^{-3} \text{ inches}$$

Let $t_s = 2 \times 10^{-3}$ inches

$$\Delta_s = n_s t_s = 27(2 \times 10^{-3}) = 54 \times 10^{-3} \text{ inches} = 0.137 \text{ cm}$$

3.5.3 Dielectric.

$$\text{Volts/turn} = \frac{19.2 \times 10^3}{3} = 6.4 \text{ kV/turn}$$

$$t_k = \frac{V_T}{F} = \frac{6.4}{1.67} = 3.83 \text{ mils}$$

$$t_k = 3.83 \times 10^{-3} \text{ inches} = 9.73 \times 10^{-3} \text{ cm}$$

Use 2 sheets of 0.002-inch-thick Kapton separated by 3 sheets of 0.0005-inch-thick paper (sandwich).

$$t_{pa} = 3(0.0005) = 0.0015 \text{ inch}$$

$$t_{in} = t_{pa} + T_k = 0.0015 + 0.004 = 0.0055 \text{ inch} = 0.014 \text{ cm}$$

$$\Delta_{in} = (n_s + n_p) t_{in} = (27 + 3)(0.014) = 0.405 \text{ cm}$$

Total thickness of the winding Δ is

$$\Delta = \Delta_p + \Delta_s + \Delta_{in} = 0.152 + 0.137 + 0.405 = 0.694 \text{ cm}$$

3.6 LEAKAGE INDUCTANCE

Leakage inductance, for an unbalanced design operated in conventional mode, is given by

$$L_1 = 2/3 \pi \mu_o \frac{r}{b} \Delta n_p^2$$

$$L_1 = 2/3 \pi 4\pi \times 10^{-9} \frac{(54.2)}{101.6} (0.694)(3)^2 = 87.7 \text{ nH}$$

3.7 RISE TIME (INDUCTIVE)

For an ideal PFN, transformer output pulse risetime τ_R (10-90 percent) is given approximately by

$$\tau_R \frac{2.2 L_1}{2 R_L'} = \frac{1.1 (87.7 \times 10^{-9})}{(62.5 \times 10^{-3})} = 1.5 \text{ } \mu\text{sec}$$

3.8 STRAY SECONDARY CAPACITY

Stray secondary capacity is given by

$$C_s = \frac{\epsilon_r \epsilon_v 2\pi r b}{n_t s}$$

where s is the thickness of the Kapton film per turn

$$C_s = \frac{3.4(8.85 \times 10^{-14})(2\pi)(54.2)(101.6)}{29(0.004)(2.54)}$$

$$C_s = 35.3 \times 10^{-9} \text{ (referred to the secondary)}$$

$$C'_s = G^2 C_s = 9^2(35.3 \times 10^{-9}) = 2.86 \mu\text{F}$$

3.9 RISE TIME (CAPACITIVE)

$$\tau_R = 2.2 \frac{R'_L}{2} C'_s = 1.1(62.5 \times 10^{-3})(2.86 \times 10^{-6})$$

$$\tau_R = 0.20 \mu\text{sec}$$

Therefore output pulse risetime is inductance dominated.

3.10 MAGNETIC PRESSURE

The mechanical pressure exerted on the transformer case due to the magnetic forces is given by:

$$P = \frac{\mu_o n_p^2 i_p^2}{2b^2} = \frac{4\pi \times 10^{-7} 3^2 (307.2 \times 10^3)^2}{2(1.02)^2}$$

$$P = 513 \times 10^3 \text{ n/m}^2 = 74.4 \text{ psi}$$

3.11 HEATING

3.11.1 Primary Conductor

$$\text{Length} = \frac{2 \pi \bar{r} n_p}{V} = 1.02 \times 10^3 \text{ cm}$$

$$\text{CSA} = \frac{bt_p}{V} = 5.16 \text{ cm}^2$$

$$\text{Volume} = 5.27 \times 10^3 \text{ cm}^3$$

$$\text{Density} = 8.96 \text{ g/cm}^3$$

$$\text{Mass} = 47.2 \text{ kg}$$

$$R_p = e l/A = \frac{1.72 \times 10^{-6} (1.02 \times 10^3)}{5.16} = 0.34 \text{ m}\Omega$$

$$U_p = i_p^2 R_p \tau_w = (307.2 \times 10^3)^2 (0.34 \times 10^{-3}) (10 \times 10^{-6}) = 321 \text{ J/pulse}$$

$$\Delta T = \frac{U_p}{C_p m} = \frac{321}{0.385 (47.2 \times 10^3)} = 17.7 \times 10^{-3} \text{ C}^\circ/\text{pulse}$$

3.11.2 Secondary Conductor

$$\text{Length} = 2 \pi \bar{r} n_s = 9.19 \times 10^3 \text{ cm}$$

$$\text{CSA} = bt_s = 0.516 \text{ cm}^2$$

$$\text{Volume} = 4.7 \times 10^3 \text{ cm}^3$$

$$\text{Density} = 8.96 \text{ g/cm}^3$$

$$\text{Mass} = 42.5 \text{ kg}$$

$$R_s = e \frac{1}{A} = \frac{(1.72 \times 10^{-6})(9.19 \times 10^3)}{0.516} = 30.6 \text{ m}\Omega$$

$$U_s = i_s^2 R_s \tau_w = (32.2 \times 10^3)^2 (30.6 \times 10^{-3})(10 \times 10^{-6}) = 318 \text{ J}$$

$$\Delta T = \frac{U_s}{C_p m} = \frac{318}{0.385 (42.5 \times 10^3)} = 0.019 \text{ C}^\circ/\text{pulse}$$

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