AFRL-PR-WP-TR-2005-2146

HIGH TEMPERATURE MAGNETICS FOR POWER CONVERSION

A. Brockschmidt
I. Mehdi

The Boeing Company
P.O. Box 3999, M/S/ SH-02
Seattle, WA 98124-2499

JUNE 2005

Final Report for 31 October 2001 – 01 March 2005

STINFO FINAL REPORT

PROPULSION DIRECTORATE
AIR FORCE RESEARCH LABORATORY
AIR FORCE MATERIEL COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7251

NOTICE

Using Government drawings, specifications, or other data included in this document for any purpose other than Government procurement does not in any way obligate the U.S. Government. The fact that the Government formulated or supplied the drawings, specifications, or other data does not license the holder or any other person or corporation; or convey any rights or permission to manufacture, use, or sell any patented invention that may relate to them.

This report was cleared for public release by the Air Force Research Laboratory Wright Site (AFRL/WS) Public Affairs Office (PAO) and is releasable to the National Technical Information Service (NTIS). It will be available to the general public, including foreign nationals.

PAO Case Number: AFRL/WS-05-1090, 06 April 2005

THIS TECHNICAL REPORT IS APPROVED FOR PUBLICATION.

_____//S//_____   _____//S//_____
[signature of project monitor/in-house author]   [signature of supervisor]

_____//S//_____
[signature of three letter chief]

This report is published in the interest of scientific and technical information exchange and its publication does not constitute the Government's approval or disapproval of its ideas or findings.

REPORT DOCUMENTATION PAGE			*Form Approved* OMB No. 0704-0188
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. **PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.**			

1. REPORT DATE *(DD-MM-YYYY)* **June 2005**	2. REPORT TYPE **Final**		3. DATES COVERED *(From - To)* **31 Oct 2001 – 01 Mar 2005**
4. TITLE AND SUBTITLE **High Temperature Magnetics For Power Conversion**			5a. CONTRACT NUMBER **F33615-01-C-2192**
			5b. GRANT NUMBER
			5c. PROGRAM ELEMENT NUMBER **62203F**
6. AUTHOR(S) **A. Brockschmidt** **I. Mehdi**			5d. PROJECT NUMBER **3145**
			5e. TASK NUMBER **13**
			5f. WORK UNIT NUMBER **0C**
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **The Boeing Company** **P.O. Box 3999, M/S SH-02** **Seattle, WA 98124-2499**			8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) **PROPULSION DIRECTORATE** **AIR FORCE RESEARCH LABORATORY** **AIR FORCE MATERIEL COMMAND** **WRIGHT-PATTERSON AFB, OH 45433-7251**			10. SPONSOR/MONITOR'S ACRONYM(S) **AFRL/PRPE**
			11. SPONSOR/MONITOR'S REPORT NUMBER(S) **AFRL-PR-WP-TR-2005-2146**

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES
This document contains color.

14. ABSTRACT
A high temperature ferrite material has been developed capable of operation at over 300C and at switching frequencies of up to 1MHz. A transformer was built using this ferrite and operated for over 600 hours while supplying 1,500 W of 28 V from a 250 kHz switched 270 Vdc bus.

15. SUBJECT TERMS:

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON **Russell L. Spyker**
a. REPORT **Unclassified**	b. ABSTRACT **Unclassified**	c. THIS PAGE **Unclassified**	**SAR**	**43**	19b. TELEPHONE NUMBER *(include area code)* **937-656-4780**

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

TABLE OF CONTENTS

Note: Certain slides and charts have been omitted from sections 2, and 3 due to being Magnetics, Inc. proprietary. USAF personnel and others covered by proprietary agreements many obtain the proprietary charts by request.

List of Figures

List of Tables

1.0 SUMMARY

A high temperature ferrite material has been developed capable of operation at over 300°C and at switching frequencies of up to 1 MHz. A transformer was built using this ferrite and operated for over 600 hours while supplying 1,500 W of 28 V from a 250 kHz switched 270 Vdc bus.

1.1 FERRITE DEVELOPMENT

The Magnetics Technology Center of Magnetics, Inc, a Division of Spang and Company developed the ferrite and fabricated cores for this High Temperature Magnets for Power Conversion contract. Core Curie temperature is 307°C and cores were fabricated to support actual transformer build and test.

1.2 TRANSFORMER BUILD AND TEST

Boeing built and tested numerous transformers during development. 2 final versions were built and operated at 1.5 kW, the second for over 600 hours at 290°C to 295°C ambient.

1.3 TEST RESULTS AND FUTURE EFFORTS

In the transformer operated for 600 hours, there was near total deterioration of the nominally 320°C plus rated insulation materials. Internal transformer temperatures were over 315°C. Future efforts to allow full utilization of the 300°C ferrite material should center on development of ceramic insulation for conductors suitable for high frequency, high voltage transformers. The insulation method used would be suitable for long term 250°C operation.

1.4 CONTRACT GOALS VS. PERFORMANCE

The following paragraphs, a thru j, list the contract goals and final performance achieved.

a**.** *Operating frequency greater than 200 kHz.*
Using a commercial power supply as a driver, the optimal operating frequency in the long term high temperature tests (limited by the power supply switching losses) was 250 kHz. The cores were operated at up to 450 kHz.

b**.** *Ambient operating temperature of 200 degrees Celsius with an allowable temperature rise of 100 degrees Celsius.*
Transformers were built use planar core topology and operated at up to 297 ambient with a 10°C rise. A transformer constructed totally of materials rated for 320°C or above has been constructed and has operated for 608 hours at hot spot temperatures of 315°C. This insulation system failed with a secondary short at 608 hours.

c. *Core materials should retain a saturation magnetization greater than 0.3 Tesla.*
This was an area of major trades. Core saturation at 200°C is over 0.3 T; however, as operated in the 1.5 kW, 270 Vdc to 28 Vdc forward converter, saturation begins to occur at 300°C around 800 Gauss (calculated as the integral of V*dt of the input waveform). The major trades here became core loss and winding configuration. Details are provided in later sections.

d. *Resistivity greater than 105 at 300 degrees Celsius.* Resistivity is 100-200 ohm-cm

e. *Permeability greater than 10,000 at 200 kHz.*
Permeability is in the 1500 range, less than the 10,000 goal. The inductor of the forward converter being used is 15 uH in value, and the 40 Adc current output current necessitates an air gap for the

1

inductor; hence the lower permeability is an advantage for the power section of forward converter. This was one of the parameters 'traded' early on to achieve the other operating attributes.

f. *Compromises in these parameters are acceptable, dictated by the requirements of the prototype component designs.*
The major trades have been in permeability and saturation flux density at temperature. Winding configurations were developed to account for the lower 300°C flux density capability.

g. *Core materials are envisioned to be either pressed powder, tape wound, or stacked laminations. Core geometry should follow commercially available standard geometries, either pot core or toroidal in nature.*
Toroid, planar EE cores, and ½ EE cores have been produced from commercial molds. EE 44160 core sections were used for the final transformer builds.

h. *This effort is envisioned to encompass materials development with a technology transition to sellable parts at the end of the effort.*
This material is the next step up in temperature capability from Magnetic, Inc 260°C "L" material. Magnetics, Inc has procured a 10,000 pound batch of the ferrite powder that will be available for production of high temperature cores.

i. *Success should be demonstrated by operation in a prototype switch mode converter (dependent on availability of other high temperature components) or under conditions that simulate converter operation.*
The initial foil wound planar EE transformer with 5 mil foil windings 1/2 inch wide (36 total layers, 1 layer of 9T primary, 9 layers for 3T secondary) operated over 20 hours total running time hours at 28 Vdc, 1500 W output and 270 Vdc input, ambient temperature 290°C. Highest temperature for start of saturation observed was 308.8°C, as evidenced by observing current waveforms. Copper fill is less than 50%, so could likely stretch the design to over 3 kW with more work on thermal aspects, expansion, and fill efficiency. The 2nd transformer, built with all 320°C rated materials has only 7 parallel secondary layers of 0.65 inch wide total, which is a similar cross sectional area of copper as the first operational prototypes. This transformer operated for 608 hours at which time the secondary shorted.

j. *A circuit topology of interest is an isolated forward converter running off 270 Vdc, stepping down to 28 Vdc and rated at 1 kW.*
Operation was at 1.5 kW at 28 Vdc for 270 Vdc input. A dual-switch forward converter topology was used.

2.0 MAGNETICS, INC. FERRITE DEVELOPMENT

2.1 SUMMARY

Magnetics, Inc requirements were to design and fabricate magnetic materials and cores capable of operating at 200°C ambient with 300°C peak temperature. These magnetic materials were to be used and were used in a 270 Vdc to 28 Vdc, 1 kW power supply, with switching frequencies in the range of 200 kHz to 1 MHz. 1.5 kW at 250 kHz was achieved. Boeing was responsible for the design and fabrication of the power supply; and provided Magnetics, Inc with the performance requirements for the magnetic cores.

The original proposal envisioned a power supply based on use of a low power (<10 W) existing Boeing 200°C ambient power controller which used a push pull topology*. Small gate drive transformers using the same high temperature technology as the power magnetics would be required for a full up high temperature power supply. At the start of the program, it was thought that an interleaved topology may have been needed for the 1 kW power level, in which case multiple transformers and output inductors would have been needed. As will be shown, this was not required. The program goals were that the magnetics should use an existing commercial core form factor (toroid, pot core, e-core, etc.). Overall goals were 200°C ambient, 300°C magnetics peak temperature, 200kHz operation, and 3000 Gauss saturation. Compromises in these parameters were acceptable. The final transformer for this program achieved an operational temperature of over 300°C at an ambient temperature of 295°C+ at 250 kHz. Over 3 kGauss saturation was achieved for temperatures over 200°C ambient, with the highest operational transformer built operating at 307°C and over 800 Gauss.

*The PRDA mentioned a forward converter – in conversations with AFRL, this topology is not a requirement but is meant to indicate that the end product is not to be just a piece of high temperature magnetic material. Boeing originally envisioned using a push pull topology as that was a piece of hardware in the inventory. Early in the program, it was hoped that SiC FETs would be available to fabricate a full 300°C power stage toward the end of the contract. The earliest normally off FETs are envisioned is the 3rd quarter of 2004. Thus, Boeing elected to utilize a dual switch forward converter topology to take advantage of that topologies 'forgiving' nature for leakage inductance, as the transformer operating inside a 200 to 300°C oven would necessarily have long highly inductive leads to interface with the lower temperature drivers and rectifiers.

2.2 PERIOD OF PERFORMANCE

The duration of the program was expected to be 36 months for the technical effort and an additional 4 months for the final report. (In February 2003 the schedule was accelerated and the target date for final prototype core submission was moved from February 2005 to September 2003, later to March 2004.) Magnetics, Inc. provided planar prototypes to Boeing in November and December of 2003 and a planar prototype less susceptible to thermal expansion stresses in January 2004. These prototypes were incorporated into the operational transformers.

2.3   SPECIFIC TASKS PERFORMED BY MAGNETICS, INC

Design and fabrication of magnetic materials and cores was accomplished by Magnetics, Inc.

a. Magnetic materials and cores. Magnetics, Inc successfully determined the best magnetic material and core fabrication technology to support the program goals. Magnetics, Inc had sole responsibility for the magnetic material itself. The effort included, in addition to the material itself, determining the most suitable core form factor for fabrication of the final magnetic component. In its' final form, this evolved to a pair of planar C cores to emulate an E-core set, thus relieving thermal stresses.

b. Magnetics, Inc specified the final core properties: thermal, mechanical, and electrical/magnetic.

- Mechanical properties (typical): bulk density, tensile strength, compressive strength, Young's modulus, and hardness (knoop).
- Thermal properties (typical): coefficient of linear expansion, specific heat, thermal conductivity, and Curie temperature.
- Electrical/Magnetic properties (typical): Remanence (at -55°C, 25°C, 100°C, 200°C, and 300°C; resistivity; saturation flux density (flux density @ 1194 A/m (15 Oe)) versus temperature (-55°C to 300°C) curve; initial permeability versus temperature (-55°C to 300°C) curve; permeability versus flux density (at 25°C; core loss (mW/cc) versus flux density (at 200kHz, 500kHz, and 1 MHz) curves at 200°C, and core loss (at 200kHz and 700 Gauss) versus temperature (-55°C to 300°C) curve.

c. Supply power transformer cores and inductor cores. Hardware delivered:

- Power transformer core: 4610 planar cores were provided per
- Boeing request and provided excellent thermal properties.
- Gate drive transformer cores: Not required in final versions
- Current transformer core: Not required in final versions
- Power inductor cores: 4610 planar core were envisioned, but only power transformers were fabricated.

d. Final report. Magnetics, Inc provided all data for magnetic material and core fabrication for this final report.

2.4   Boeing tasks with Magnetics, Inc support on "time available" basis

a. Drive transformer design. No drive transformers were used in the accelerated schedule.

b. Transformer and inductor design. Boeing received Magnetics, Inc' assistance to determine the turns, winding form, and wires. Magnetics, Inc provided valuable advice on thermal expansion mitigation techniques (foremost of which was pairs of C cores to use as E-cores). Magnetics, Inc provided Boeing with sources for high temperature wire. A very high temperature ceramic wire by Ceramawire was used by Magnetics, Inc in testing but was not used by Boeing due to its low (150V) breakdown voltage.

c. Build and deliver the operating power supply. Magnetics, Inc supported the thermal management design task with design data. Originally, Magnetics, Inc was to be requested to perform thermal shock test on the parts (-55°C to 300°C), but time constraints precluded this. The worst case thermal shock range encountered by completed transformers was –10C to +310°C in 1 hour.

d. Overall support of design tasks and trade studies. Boeing and Magnetics, Inc held numerous informal e-mail and telephone conferences in the latter stage of the program. 2 formal interchanges were held early in the program.

e. Final report. This document is the final report.

2.5   MAGNETICS, INC APPROACH TO MATERIAL DEVELOPMENT

Background
Manganese-zinc ferrites exist over a broad compositional range and manufacturers guard their chemistries and processing methods aggressively. Ferrites have been used over the years in a multitude of applications, each of which required the optimization of different characteristics of the material. Those who used ferrites in high-Q filters were concerned with loss factor at low drive levels and tuning the inductance to exact values. When applied to EMI and RFI filter applications, ferrite materials were designed to optimize loss factor and impedance values over wide frequency ranges and to have very high permeabilities. In the case of high frequency power supplies, ferrites became popular in power inductor and power transformer applications where saturation flux density, high Curie temperatures and low core loss under specified conditions were the most desired properties. While manganese-zinc ferrites possess the capability of performing well in all of these applications, it falls to the material scientist to understand how composition and processing influences the material to achieve the desired properties.

Composition of the material is engineered on two levels. Main components consisting of oxides of Fe, Mn and Zn, and minor additions of the oxides of Ca and Si form the basis of all Mn-Zn ferrite compositions. Trace additions can include the oxides of Nb, Ti, Co, Sn, Zr, Ta, Na, Mo, Bi and P to name a few. These trace additions are used to control, among other things, grain size and uniformity, permeability, flux density, and the influence of temperature on properties. The combination and permutations of additions leads to the rich character of this group of materials and their flexibility in satisfying many design requirements.

Processing the raw materials into ready-to-press ferrite powder requires attention to cleanliness and process control. It is during this phase of manufacture that the reactivity and shrinkage of the powder is set. Should a powder be less reactive than desired even ideal firing conditions might not bring out the full electrical and magnetic properties of the pressed core.

Other than proper control of the chemistry, firing is the most critical operation if ideal properties are to be achieved. Manufacturers are faced with a series of process control challenges if the sintered cores are to be the right size, with minimal distortion and with the proper crystalline structure. Most critical is the intimate relationship between time, temperature and oxygen levels in the sintering atmosphere. To maximize the material properties, manufacturers concentrate on controlling the oxygen content of the kiln atmosphere as cores are cooling down from sintering temperatures. Deviations of as little as 10% of the target value of oxygen can degrade the magnetic properties of the cores. Ideal control of oxygen and temperature were described in the patent by J. M. Blank where the relationship between oxygen and temperature was described in terms of atmospheric parameter (AP) as represented by the equation:
AP=log PO2-(14540/T(K))
Where PO2 is the partial pressure of oxygen and temperature is in degrees Kelvin.

Development of Higher Curie Temperature Materials
In the 18 months prior to this contract, Magnetics, Inc developed a new MnZn ferrite material called L-perm (Lμ) and applied for patent protection of the process and composition. This material has a permeability of 750 and a Curie temperature (T_c) of ~280°C. L-perm was designed to have low power losses at operating frequencies from 500 kHz to 3 MHz. Development of this material involved creating an empirical model for material chemistry and performance. This model was

used as a starting point for developing a material for Boeing with a T_c above 300°C. Toroidal cores of Magnetics, Inc's Lµ material with T_c of 280°C were delivered to Boeing on 4/5/02 as an example of the current state of the art in ferrite materials. In early 2003 testing, Boeing operated these cores at over 256°C ambient. Magnetic test data for this material was supplied to Boeing for use in their initial PSPICE modeling work.

Magnetics, Inc planned to develop the new material in four phases:
- Identify the preferred Fe-Mn-Zn ratios
- Optimize Ca and Si additions
- Study benefits of trace element additions
- Optimize the firing conditions
- This material chemistry is significantly different from any commercially available MnZn ferrite. The concentration of iron oxide for typical MnZn ferrites is on the order of 51 to 54-mole %. The move toward a higher concentration of iron oxide predicted by our chemistry model is in agreement with Figure 32.7 from Smit and Wijn's 1959 book "Ferrites", showing the Curie temperature and saturation magnetization of various ferrite materials. Increasing the amount of iron oxide in the composition effectively increases the amount of $FeFe_2O_4$ in the composition, which by itself has a Curie temperature above 500°C. Use of significant amounts of MnO and smaller amounts of ZnO allow the material to retain soft magnetic properties as opposed to pure $FeFe_2O_4$, which is a hard magnet. As an item of practical interest here, it is noted that Boeing designers experienced a physically perceptible retentivity of the new material when testing cores and dis-assembling them at room temperature, which is not usually perceptible on ferrites.

Identify Preferred Fe-Mn-Zn Ratios
The empirical model predicted that Tc could be maximized at 306°C by creating a material with the following composition:
- 59.00 mole %
- 39.00 mole % MnO
- 2.00 mole % ZnO

The predicted composition was synthesized in our laboratory from a blend of iron, manganese, and zinc oxides. Standard ferrite powder processing techniques were used. The starting ingredients were mixed in a high-shear blender, calcined at 900°C in air, and ground in a stirred ball mill for 2 hours to an average particle size of approximately 1 micron. Various organic binders and dispersants were added at the milling step to enhance particle size reduction and improve pressing characteristics. The material was spray dried into a fine powder with an average particle size of about 60 microns. This process was followed for all subsequent powder lots.

The composition was labeled X7611 and represented the first attempt to create a material with a Tc above 280°C and possessing the desired magnetics properties. Sample toroids (22mm x 13.7 mm x 6.35 mm) were pressed and fired in a laboratory batch kiln using a temperature and atmosphere profile previously developed for L-perm material. Fire number F6503 resulted in a material with a permeability of 300 that was relatively flat with respect to temperature from -60°C to 250°C (the limit of the existing temperature cabinet). Permeability began to roll off with frequency at 6 MHz. Saturation magnetization (Bmax) was 4600 G at 25°C. Power loss for this material was 4600 mW/cc at 250 kHz, 1000 G, 200°C. Power losses of this magnitude will

not be acceptable considering the material is expected to operate at flux densities well in excess of this value.

Samples of composition X7611 from fire F6503 were subjected to metallographic analysis to determine grain size and size distribution. (See images below.) Examination by optical microscope showed a significant population of grains with abnormal size and reflectivity. Based on the material composition and sintering conditions it was hypothesized that these abnormal grains were pure iron oxide that precipitated from the ferrite solid solution. Analysis of the fired material by x-ray diffraction confirmed the presence of Fe_2O_3. This phase separation explains the high watt loss values measured in the sample, and highlights the importance of properly processing this unusual composition. The photos below are 50X magnification.
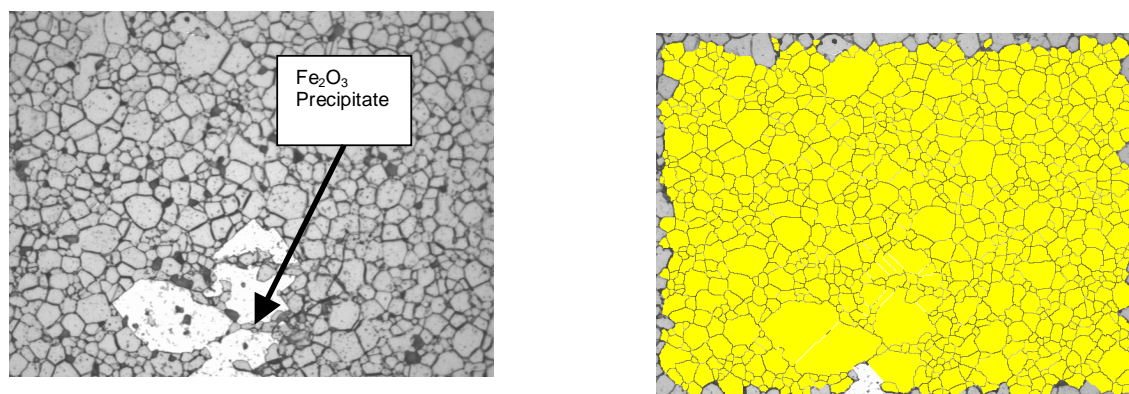
Figure 1. Samples of Composition X7611 from Fire F6503
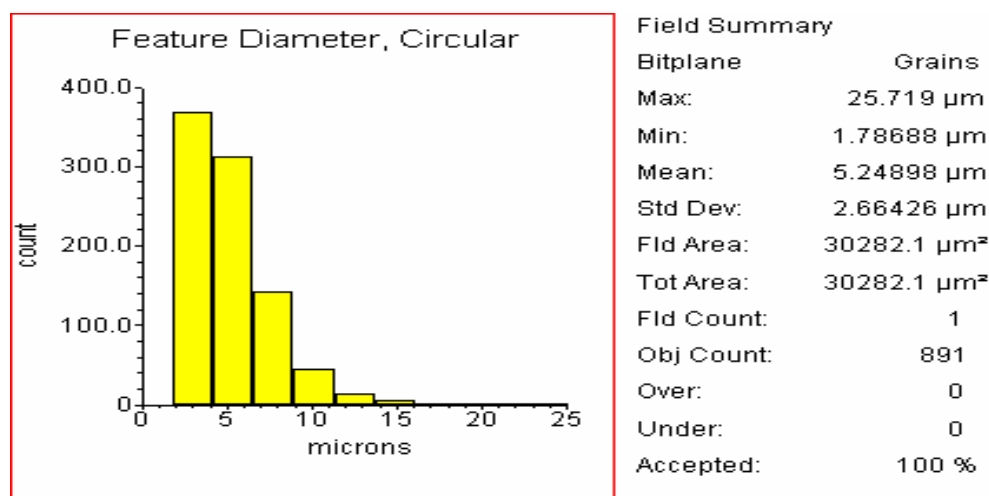
Figure 2. Grain Size of X7611

A second attempt was made to sinter X7611 using a more reducing atmosphere in order to keep the iron oxide in solid solution. Samples from fire F6522 were examined by optical microscopy and did not show the two-phase microstructure. Room temperature permeability of this material was still ~300 and varied with temperature, an indication that a proper ferrite crystalline structure was now being formed. The secondary permeability maximum (SPM) occurred at a temperature of -40°C, indicating that watt loss in the target temperature region of 200°C would not be minimized, since the lowest watt loss occurs near the peak of the SPM. Frequency roll off remained at 6 MHz. Bmax at room temperature increased to 5400 G. Power losses at 250 kHz, 1000 G, 200°C, decreased to 3500 mW/cc. Power losses at 200kHz, 800G,

200°C were 2000 mW/cc. Samples of X7611 from fire F6522 were evaluated for Curie temperature using a crude test set up in a muffle furnace. The results indicated that the Curie temperature was in excess of 300°C. This agrees with the prediction of 306°C from the empirical model.

Compositions X7617 and X7618 were variations of the same major chemistry as X7611 but with additions of Co_3O_4 in amounts of 0.050 wt% and 0.200 wt% respectively. Additions of cobalt oxide can shift the location of the secondary maximum in the perm vs. temperature curve and the minimum in the watt loss vs. temperature curve. Samples were fired in a computer-controlled laboratory batch kiln. Watt loss, permeability, and saturation flux density were adversely affected by the addition of Co. Watt loss at 200kHz, 800G, 200°C increased to 3000 mw/cc. Room temperature permeability dropped to 300 for X7617 and to 150 for X7618. Bmax decreased to 4950 G and 4600 G respectively. Cobalt additions were eliminated as a means of controlling the shape of the perm versus temperature curve, and no data is presented on these compositions.

Additional firing trials for X7611 were made to evaluate the effect of varying atmospheric oxygen levels on magnetic properties of the test cores.

The chemistry model was reviewed to determine if a change in the Fe_2O_3 concentration could be used to shift the perm vs. temperature curve in a direction favorable to low watt losses at elevated temperatures. Composition X7626 succeeded in shifting the watt loss minimum point from −30°C to +20°C and watt loss values at 200kHz, 800G, 200°C were reduced from 2000 mW/cc to 1000 mW/cc. The goal is to reach 400 mW/cc or lower at these conditions.

Based on these first exploratory compositions, Magnetics, Inc estimated the material response curves for permeability versus temperature (µ vs. T) and watt loss vs. temperature as shown below.

Figure 3.   **Target Perm vs. Temperature for X material**

9
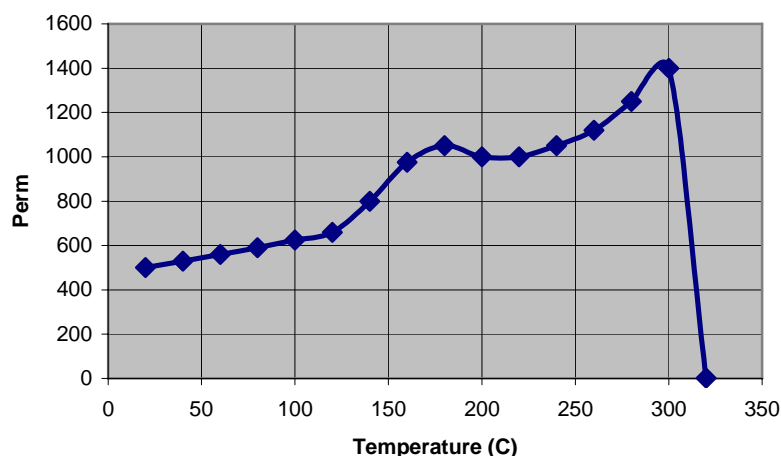
Figure 4. **Target Watt Loss vs. Temperature for X material (200 kHz, 800 G)**
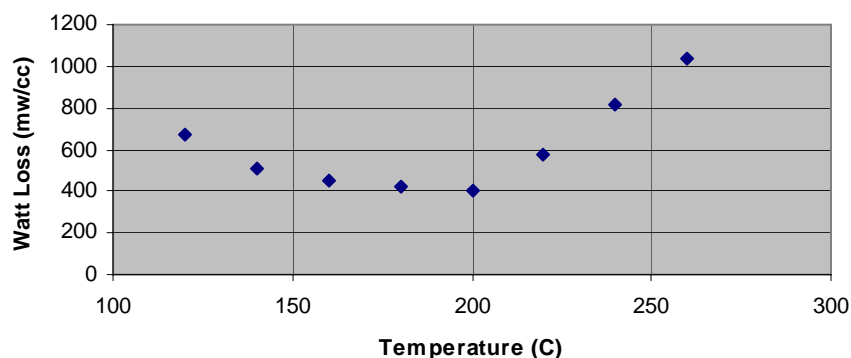
The Curie temperature response surface originally generated in Magnetics, Inc's Lµ development work will be used as a guide to selecting new compositions (see graph below).

Figure 5. Curie Temp Response Surface
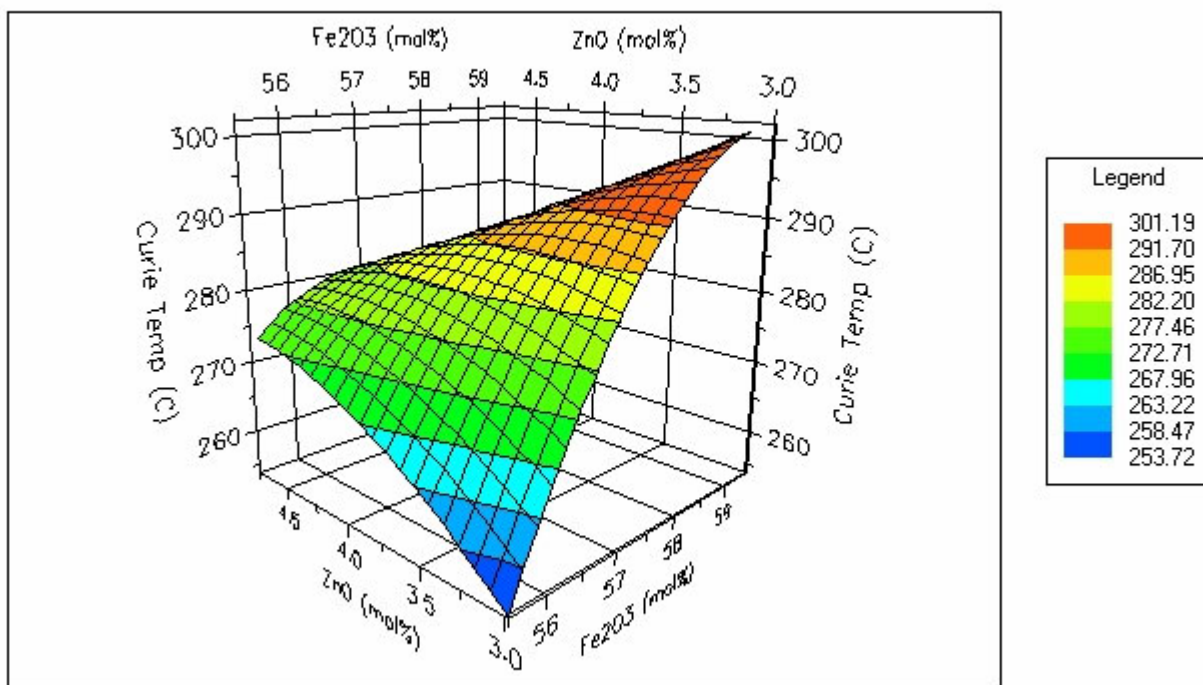
A literature search for information on the effect of composition on T_C was initiated. The most relevant paper is one written in 1960 by E. Ross and E. Moser in *Z. Angew. Physik*. The paper is in German but defines an empirical relationship between Fe_2O_3, ZnO, and Tc:

$$T_C = 12.8(mol\%Fe_2O_3 - 0.66*mol\% ZnO)-354°C$$

This relationship holds for typical MnZn ferrites such as Magnetics, Inc P, R, & J materials. However it does not predict the behavior of materials with low ZnO concentrations such as L material.

Smit & Wijn's book on ferrites shows in Figure 48.2 the effect of Zn concentration on the T_C of MnZn ferrites. This figure shows a maximum possible T_C of 275°C.

However, the curve assumes a nominal value for excess Fe_2O_3 of 5%. X7611 used an excess of 12% Fe_2O_3. The screening experiments will verify whether or not the use of excess Fe_2O_3 was the reason for the increased T_C.

A screening experiment involving a total of eleven runs was developed to assess the effect of Fe_2O_3, ZnO, and firing atmosphere on T_C and the watt loss minimum. Two compositions appear to have secondary permeability maximums around ~180°C suggesting that their minimum watt loss should occur at a similar temperature. The results were entered into design of experiments (DOE) software to create a rough map of T_C and watt loss minimum vs. composition. This defined the area in which more detailed mapping of the composition and firing parameters took place.

In parallel with the effort to raise Curie temperatures, composition X7626 was fired using a series of modified atmosphere profiles. The minimum in the watt loss vs. temperature curve could be moved from 20°C to ~200°C depending on the atmospheric parameter used in firing. Watt loss decreased to 300 mw/cc at 200kHz, 800G, 200°C. (The Curie temperature of this material was 330°C, but was unknown until later in the project when a higher temperature oven became available.).

Composition X7626 was used to fabricate cores in 4916 and 2206 toroid sizes and submitted as Round #1 prototypes to Boeing. The initial assessment of the data indicates that the composition range selected for the screening experiments was too broad. As a consequence the model did not accurately predict the effect of chemistry on the location of the SMP. Additional runs were processed to refine the model, and to get a first look at the effect of trace element additions on the performance of an X7626 type composition. The data indicates that further adjustments of the Ca, Si, and Nb levels will be necessary.

Additional powder lots and fires were processed to refine the screening experiment for basic chemistry and firing conditions. Curie temperature data has been collected and entered into the model. Based on the trends displayed in the model the optimum chemistry will be in the range of 55 to 57 mole % Fe_2O_3, 1.5-2.5 mole % ZnO, and the balance MnO. An atmosphere parameter in the range of 8.9 to 9.2 will be needed to keep all of the iron oxide in solid solution.

Permeability vs. temperature testing indicates that the first round of prototypes shipped to Boeing based on composition X7626 had a Curie temperature of 320°C. The combination of high Curie temperature and acceptable watt loss suggests that we will be able to optimize this new material for both low power losses and high temperature capability.

A more detailed mapping of the Fe-Mn-Zn chemistry region was conducted and composition X7655 has shown an improvement in key magnetic properties. This material has a minimum

watt loss at 200°C and a Curie temperature of 320°C. The second round of prototypes was processed from this material.

In early 2003 Magnetics, Inc accepted Boeing's request to accelerate the completion of this subcontract item from February 2005 to September 2003, with delivery of the final report to Boeing by December 30, 2003.

The third round of prototype cores were made from lot X7693. Small additions of the trace elements tantalum and zirconium reduced the watt loss slightly over the second round prototypes made from X7655.

Optimization of the firing conditions involved investigations of sintering time, sintering temperature and atmospheric parameter (AP). Sintering time and AP variations did not result in any improvements. Increasing the sintering temperature from 1160°C to 1200°C showed an additional, albeit slight, improvement in core loss.

The culmination of chemistry, trace elements and firing condition studies led to composition X7707 that embodied the best features of each round of investigation. Boeing selected Magnetics, Inc' part number X-46410-EC (64mm planar E-core geometry) for their final core configuration, and samples were shipped in late October and early November as the 4th round of prototypes.

An additional 20 pounds of the final composition has been made and approximately 20 additional pairs of X-46410-EC can be prepared, upon request from Boeing.

The table below summarizes the composition development effort. The compositions representing each round of prototype shipments to Boeing are:

Table 1. Summary of the Composition Development Effort

Round 1	X7626
Round 2	X7655
Round 3	X7693
Round 4	X7707

Composition X7713 was a duplicate to X7693 and X7707.

The following table summarizes the firing profile development work, culminating in fire B1049 used for the fourth round of prototypes cores.

Note: The table is Magnetics, Inc Proprietary, AFRL personnel contact Boeing or Magnetics, Inc, for copy of this table.

Electrical Data Summary

2.6 TYPICAL MAGNETIC PROPERTIES OF FINAL MATERIAL

Based on the results from the first three compositions and from Magnetics, Inc's experience with Lµ material, the magnetic properties of the final high temperature material are expected to be as follows:
- Permeability @ 25°C = 500-1000
- Bmax @ 25°C = approx 4800 G
- Bmax @ 200°C approx 3000 G
- Brem @ 25°C approx 2000 G
- Brem @ 200°C approx 1600 G
- Hc @ 25°C approx 0.50 Oe.
- Hc @ 200°C approx 0.35 Oe.
- Frequency Roll Off > 6 MHz
- Watt loss minimum occurs between 180°C and 220°C
- Watt loss @ 200kHz, 800G, 200°C <1000 mw/cc (300-400 mw/cc best case)
- Resistivity = 100-200 ohm-cm
- Curie temperature > 300°C

  Since devices made from this material will experience large temperature changes, characterization of the material's thermal and mechanical properties will be important. It is anticipated that Xµ will have properties very similar to existing MnZn ferrite materials:
- Coefficient of Thermal Expansion = 10.5×10^{-6} °C-1
- Specific Heat = 1100 J/kg·C
- Thermal Conductivity = 40 mw/cm·C
- Density = 4.9 g/cc
- Tensile Strength = 48 MPa
- Compressive Strength = 430 MPa
- Young's Modulus = 120 Gpa
-

2.7 Production batch of powder

Magnetics, Inc continued planning for production of a 10,000# batch of X-material ferrite powder. The tentative date to start the manufacture of the 10,000# X-perm powder lot is 6/14/04. An estimate of "late 2004" for powder availability is appropriate for inclusion in the PESC 04 paper

3.0   1.5 KW TRANSFORMER AND TEST

At the program start, it was decided that the converter would be a 1 kW, 270 Vdc to 28 Vdc design. A 48 Vdc output design was also being considered to limit the current, but the initial voltages of the original request for proposal were retained. The switching frequencies were to be in the 200 kHz to 1 MHz range. The converter development utilized existing designs and hardware. The actual transformer test converter was a 1.5 kW, 270 Vdc to 28 Vdc, dual switch forward converter. 250 kHz operating frequency was selected as it was the best compromise between the converter drive circuitry losses and transformer losses, and was above the 200 kHz program goals.

3.1   TOPOLOGY AND CORE SELECTION

An initially proposed 200KHz 1KW High Temperature Converter is shown here. This would have used a push-pull power transformer, output inductors, and pulse transformers of the X-perm material.

The program re-scheduling and acceleration in 2003 resulted in most of these plans being discarded in favor of a simpler and faster approach with only the power transformer made of X-perm material; thus, details of the original topology studies have been omitted from this report, and can be found in the previously submitted monthly activity reports.
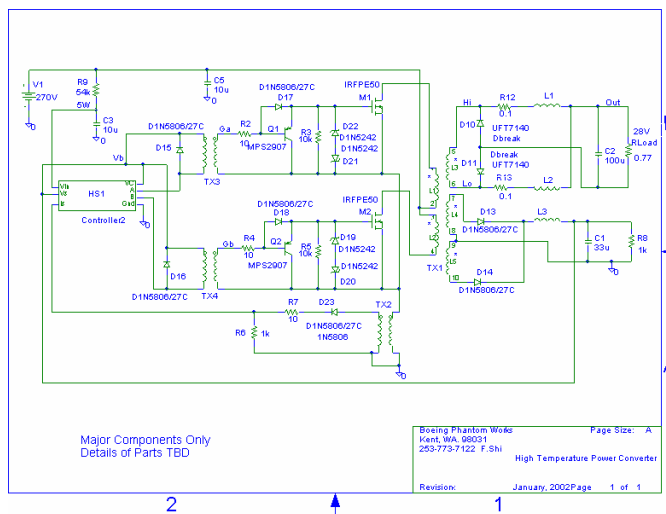

Figure 6. Temperature Converter

3.2 TRANSFORMER PRACTICAL BUILD

3.2.1   Trials and errors

Preliminary magnetic requirements and core sizing were completed in February, 2002. The core sizing studies for the converter of Figure 1 were carried over into the accelerated program designs. Boeing and Magnetics, Inc agreed at the start of the program that development of the magnetic requirements and the materials would be an iterative process. For example, having a high Bmax plus having the core loss decrease with temperature until the Curie temperature would be ideal from the transformer winding design, but is not consistent with ferrite chemistry; hence, winding design was varied to operate at low flux densities to accommodate core loss and saturation parameters at the expense of winding losses. These trades and iterations were the major technical hurdles to be solved. The magnitude of core loss at 250+ kHz and the operating flux density led a converter design aimed to operate at 800 Gauss. Core loss is typically a cube function of flux level at a given frequency. The design of switch mode power transformers often uses the lower operating flux technique to reduce core losses. For a preliminary assessment of the magnetics requirements and core sizes, a PSpice model of a simple converter was constructed. The desired form factor for the final power transformer cores is the EIA standard 46410 planar E core configuration. Magnetics, Inc used the 800 G figure as the design point to assess core losses. Studies were performed to assess the use of a smaller volume core (e.g.

14

45810) vs. the 46410 core to reduce total core losses. The 46410 core remained the selected form, and is shown in the figure and table. A pair of these cores was used for transformer assembly.

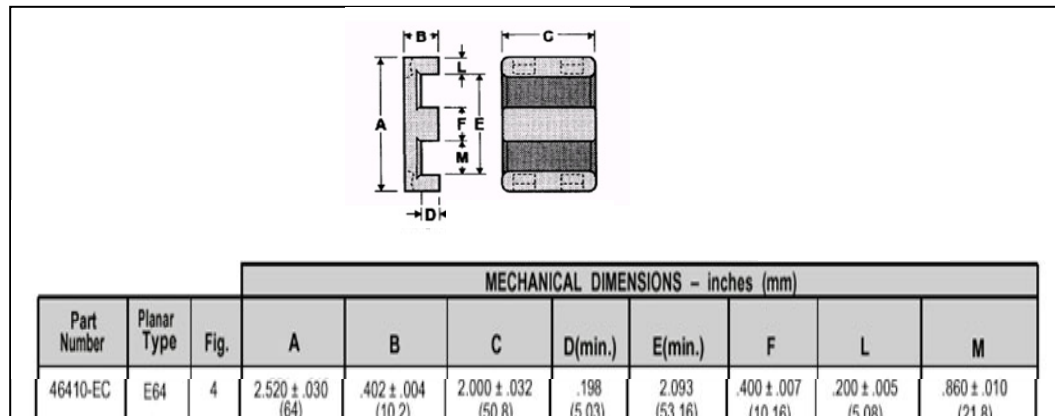| Part Number	Planar Type	Fig.	MECHANICAL DIMENSIONS – inches (mm)							
			A	B	C	D(min.)	E(min.)	F	L	M
46410-EC	E64	4	2.520 ± .030 (64)	.402 ± .004 (10.2)	2.000 ± .032 (50.8)	.198 (5.03)	2.093 (53.16)	.400 ± .007 (10.16)	.200 ± .005 (5.08)	.860 ± .010 (21.8)

Figure 7. The 46410 Core

There was concern at Magnetics, Inc that the planar E-cores would be susceptible to thermal shock if not potted and mounted correctly. On the other hand the large surface area of the part enhances thermal transfer away from the power transformer. The thermal shock issues were solved and discussed in later sections.

A decision was also made to avoid any commonly used nickel or nickel plated wire for high temperature. Nickel is used on most commercial high temperature wire due to nickel's anti oxidation capabilities. An initial net and IEEE search provided no papers on the subject of planar transformer operation with magnetic sheet windings. The possible secondary hysteresis winding loss and leakage effects of the magnetic nickel windings were determining factors.

A ceramic insulated magnet wire was found that is capable of continuous operation at 500°C. The supplier is Ceramawire, and Magnetics, Inc used this wire for their testing. This was not used for transformer construction not only because it's nickel plating or composition, but ceramic coated wires only have a 150 V dielectric rating (due to porosity). Due to the leakage inductance in a transformer and its low 150 V voltage rating, it was decided not to use the Ceramawire in the 270 V transformer.

An aromatic polyamide coated wire, Imideze, from PD Wire & Cable was also considered for high temperature windings. This wire is rated for 300 hours at 300°C and was used for preliminary transformer windings in the form of 7 strand Litz wire. As discussed later, the 21 AWG minimum size was unsuitable for 250 kHz operation due to sin effects.

BH curves were a method of defining the PSpice models that were used to determine final converter core configuration.

Magnetics, Inc provided 3 sets of prototype cores on which
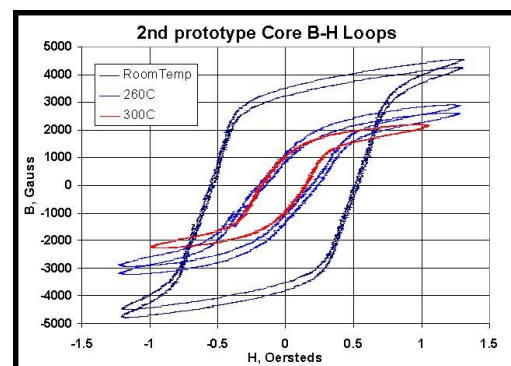BH curve testing was performed and preliminary PSpice model determined.

Figure 8. Second Prototype Core BH Loops

15

Typical PSpice model BH curve @ 300°C
.MODEL 2nd round prototypes
+ MS=261.81E3
+ A=50.384
+ C=.23804
+ K=22.926 + AREA=to be optimized in conjunction with watt loss minimum temperature
+ PATH=to be optimized in conjunction with watt loss minimum temperature

The table below is from the second prototype data, and the chart to the right of the table shows the BH curves. The room temperature and 200°C curves are consistent between the data sets, validating both Magnetics, Inc' and Boeing's different test methods.

Table 2. Bm, Br, Hc vs. Temp

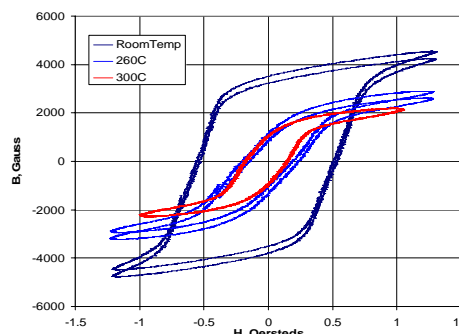| Temp (°C)	Bm (G) 2206-TC	4916-TC	Br (G) 2206-TC	4916-TC	Hc (Oe) 2206-TC	4916-TC
25	4980	4879	4089	4005	0.728	0.803
100	4406	4335	2881	3020	0.378	0.681
200	3236	3177	1370	2070	0.261	0.776
300	1456	1460	938	1171	0.215	0.827

Figure 9. X- Core BH Loops

The analysis indicated that the final core watt loss minimums should be at or above the 180 to 200°C range. Boeing and Magnetics, Inc. agreed to set 200°C as the goal for minor modifications to the watt loss minimum for the 3rd and 4th round of prototypes.

The accelerated schedule approach for the power supply was to use a commercial converter mounted at the 300°C oven wall. In this configuration, the magnetics were on the oven side of the wall and the rest of the converter on the room temperature side.

Further trades on high temperature wire indicate that the best approach was to use planar cores and sheet copper and sheet insulating materials for the windings.

A dual switch forward topology converter was selected for the final drive for the high temperature transformer. The dual switch forward topology is 'very forgiving' of leakage inductance in the transformer leads – there is added leakage inductance in transitioning the transformer input leads into and out of the oven. This provides both AC and DC core operation (the power transformer and the output inductor). . A Kepco dual switch forward topology converter was selected as the drive electronics. Testing by replacing the commercial transformer with the hi-temperature transformer, and revised the Kepco circuitry to operate at 270 Vdc and at 250 kHz. These revisions involved mainly resetting over and under voltage reset circuits and timing circuits. The frequency was made selectable thru the use of a 10-turn potentiometer in the timing circuit. A capability to change the input voltage from 250 to 385 Vdc was accomplished by replacing feedback divider resistors in the under voltage shutdown circuit. We modified commercial 350W and 1500W power supplies as the test vehicle for the high temperature transformers. The large schematic is the 1500 W Kepco supply, the circle shows the transformer replaced by the high temperature transformer.
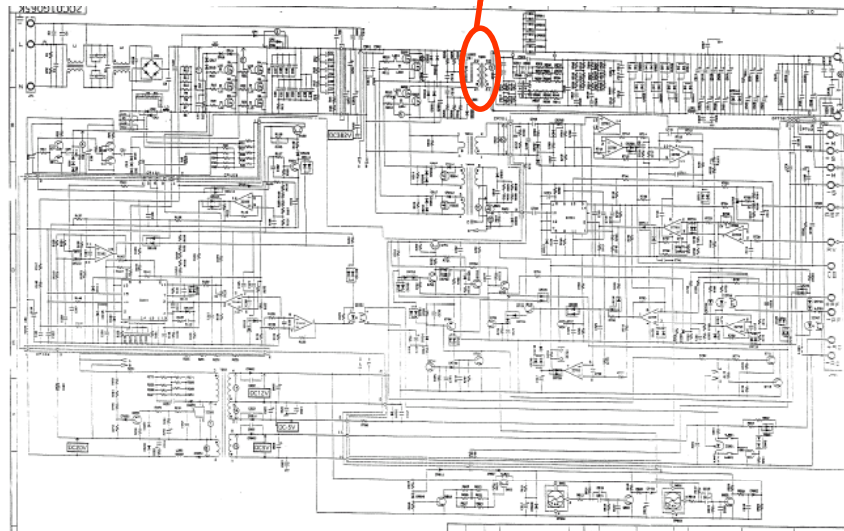
4 terminals into oven, replace transformer

Figure 10. 1500 W Kepco Supply with High Temperature Transformer

The modifications include being able to change frequency between 120kHz and 450 kHz, and to operate at 250Vdc to 385 Vdc. The inset photo is of the commercial transformer removed and 6-inch lead extensions added. The waveform is of the commercial stock transformer input voltage when the circuit has been revised to operate at 210 kHz and 270 Vdc (the commercial part as built operated at 382 Vdc and 124 kHz). We will thus be able to characterize the cores in operation over these ranges.

Lead extensions, 5 mil X ½" Cu
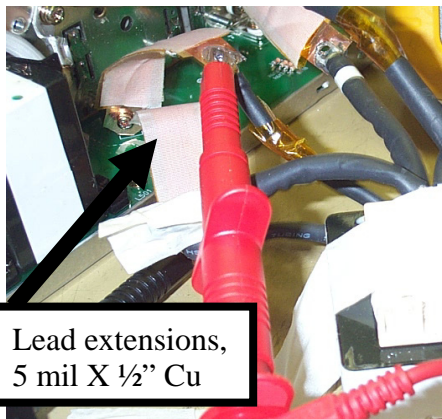
Figure 11. Commercial Transformer Removed and Lead Extensions Added

Fwd converter primary WF 270 Vdc, 211 kHz
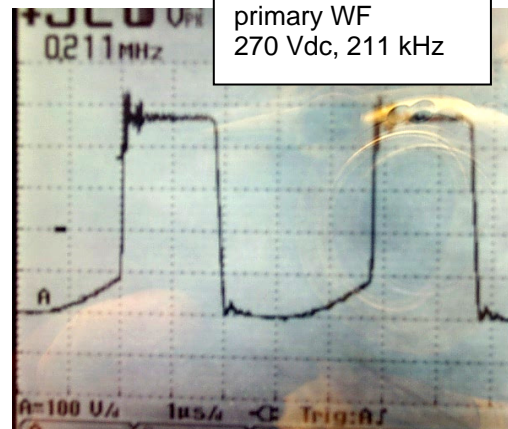
Figure 12. Waveform

The 350W unit was run with a replacement transformer constructed using Magnetics, Inc 260°C L-material and 5 mil ribbon/Kapton windings shown at right. Only room temp tests were run on this sample, the transformer had a temperature rise of 20°C, and only about 50% of window area was used for winding on this lower power prototype – only the primary is shown in the photo.
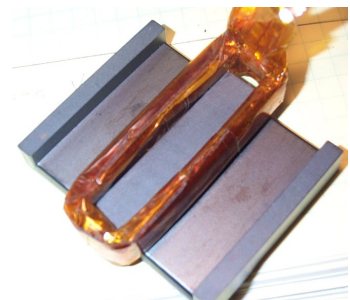
Figure 13. 350 Unit Construcion

17

340°C epoxy and 3000°C ceramic materials were ordered for fabrication using the prototype cores. 5 mil copper foil was also ordered

The transformer to converter interfaced via a relay socket – used as it was found to have good high frequency properties.

Preliminary winding investigations were carried out to verify the suitability of winding configurations; 12:4, 14:4, 9:3, and 8:3 ratios were tried.

1. Plain Litz wire type solenoid windings, 4 21 AWG primary, 4T, 12 T 21ea 21 AWG secondary. The classic Litz windings have too much leakage inductance, also, the 21 AWG wire is too large (smallest standard 260°C wire) to be effective at 200 kHz.


Figure 14. Plain Litz Wire Type Solenoid Windings

2. 5-mil foil primary with Litz secondaries. All 5 mil
3. solenoid primaries were the configuration seen at right. All solenoid type winding configuration
4. 5 mil foil solenoid primary, Litz secondaries
5. 5 mil foil solenoid primary, 5 mil X 4 parallel solenoid wound secondary
6. 5-mil foil solenoid primary, 20-mil pancake secondary.

7. 21 AWG primary spiral wound in pancake style, 5 mil foil secondaries – note: this is the usual configuration in past papers often claimed to be the best performing, but leakage inductance unacceptably high.

Figure 15. Five-ml Foil Primary

8. 8 T 5 mil pancake spiral of 1/8" wide strips primary, 3 turn secondary between 4T primary halves. The configuration as shown has a 5 mil by 1/8" wide primary ribbon, and a ¾" by 5 mil secondary ribbon. At room temperature and 1350-Watts output, temperature rise was 54°C. The winding window was only ¼ to 1/3 full, so a packed window should give temperature rises of less than 20°C in air, and only a few degrees when potted and attached to a 200°C to 290°C ambient heat sink.

Figure 16. Pancake Spiral with Five ml by 1/8" Wide Primary Ribbon and ¾" by 5 ml Seondary Ribbon

9. Full pancake primary halves sandwiching multiple parallel secondaries. Variations of this configuration were found to be best and covered in detail in later sections.

Trial windings 1 thru 6 are, per test data observations, very inferior to the pancake windings (higher leakage inductance and more ringing on transformer secondary.) Maxwell 2D thermal and eddy current models confirmed the better performance of the #7 & #8 arrangements.

A laptop computer and voltage monitoring and temperature monitoring adapters were configured to record transformer performance. Monitored items are oven temperature and 7 transformer temperatures, 28 Vdc voltage and current, output power, 270 Vdc input voltage and current. High frequency waveforms were captured via oscilloscope and transferred to data logs via floppy. BH curves, core losses and copper losses during operation were calculated from the collected voltage and current data. Unfortunately, accurate continuous temperature performance was not possible due to magnetic and HF thermocouple interference. High temperature readings were always taken with the power converter temporarily shut off.

A full pancake winding transformer configuration (#8 as discussed above) was built and tested at 200°C and 250°C successfully for initial evaluation.

The configuration was 4T primary, 3 T secondary, 4 T primary sandwich. Each layer is 5 mil by 0.75 wide copper foil interleaved with Kapton. The copper was hand cut, sanded, and etched in a 10% solution of hot Ferric Chloride for 10 minutes to deburr the edges. The primary was only one layer of 5 mil Cu, The 3 turn secondary was 6 layers of the 5 mil Cu. The foils were fan cutouts

and folded, with high temperature interconnections made by hand operated oxy/acetylene torch brazing. The unit was first run at room temp as wound, and had about a 30°C rise hot spot to heat sink with the core attached to a finned tube heat sink. The 2 straightest/widest window core halves of the first core shipment from Magnetics, Inc were used. After the room temp checkout, the assembly was vacuum impregnated with DC 997 high thermal conductivity silicone varnish, baked for 8 hours at 250°C, then rerun. There was only a 10°C rise at room temp after impregnation.
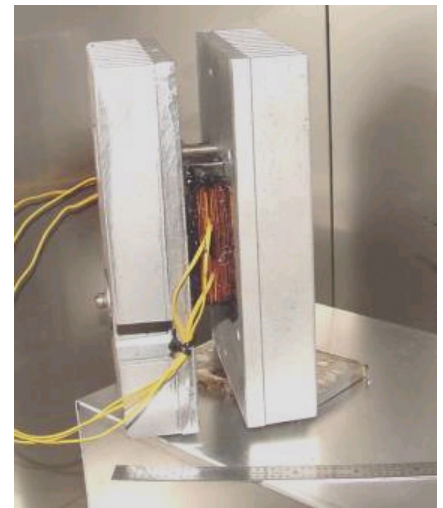
Figure 17. Pancake Winding Transformer Sandwiched Between Heat Sinks

The transformer is shown at right sandwiched between the finned heat sinks. The yellow wires are the thermocouples, the power leads go thru the temperature chamber wall on the far side (unseen) of the picture. It was found that the transformer leads that exit the chamber conducted some heat from the transfomer. The s(V*t) waveforms indicate about 980 G peak in operation at 260 Vdc input.

The data for 250°C oven setting is shown here, and includes a "power on" reference column to support the previous discussion on thermocouple error due to interference. From the power off measurements showing LOWER than oven temperature, lead thermal conduction tests were run and subsequent tests used > 6 inch lead length in the oven vs. the ½ to 1" lengths used in this first test.

Table 3. 250°C Oven Setting Data

	power off	power on (obvious noise coupling errors)
Center of left winding	242°C	252°C
Center of right winding.	242°C	240°C
Between center leg of core & winding	242°C	252°C
TC in oven	237°C	276°C
Oven indicator	242°C	242°C

19

These tests were run at 200.4 kHz, 261Vdc input, and 1.00 kW load. DC to DC efficiency of the forward converter was 90.5% at 200°C set on the oven, and 90.6% with the oven set at 250°C. The temperature rise was 242°C-237°C = only 5°C, which includes the heat sink to air drop, but not accounting for the heat loss out on the power leads of the transformer. This confirms or even shows a better watts loss minimum than shown in the 4th round prototype Magnetics, Inc data. Based on this preliminary test, we estimated that we could run at near 300°C ambient and 1500 Watts (297°C was achieved).

To establish core loss data for non-sinusoidal waveforms, the 300 W dual switch forward converter was used to drive different turn primaries at various voltages and frequencies. This was used to get data for core loss curves specifically at the operating parameters over 150 to 450 kHz and 250 to 350 Volts input and at temperatures up to 310°C. Since the forward converter core BH swings are different from sinusoidal waveforms used for classical core loss measurements, results were slightly different (higher apparent core loss) than the initial data reported by Magnetics, Inc using standard sinusoidal core loss procedures. A literature search found only a few papers that address non-sinusoidal core losses, and none that include any effects from the 4 MHz to 11 MHz diode switching ringing present in real circuits.

This data aided optimization of the transformer windings. Preliminary data indicated that at a 30% duty cycle of the forward converter, less than 8 turns for the primary allows core saturation at low frequencies and high voltages, as expected.

With proper fixturing, 8 parallel 3 turn secondary windings can be fit into a 44610 EE core. Maxwell 2D eddy current modeling at 200 kHz of a single layer 8 turn primary and an 8 layer 3 turn secondary indicated that current density will be below 3000 Amps per sq. inch even at the edges of the windings as shown at right.
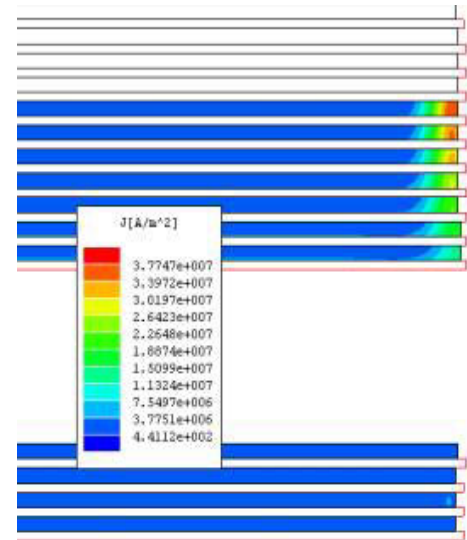
Figure 18. Core Loss Data

Some difficulty was encountered with various ground loops in the test setup and were resolved thru the use of differential probes, dedicated current transformers added to the power supply, and isolation transformers.

An initial attempt was made to build a transformer winding with 315°C epoxy and Kapton using Teflon .

Full transformer configurations were built and operated with the first core sets. BH curve instrumentation was successfully established with the forward converter waveforms. The photo shows the power supply adjacent to the oven access hole, and the transformer leads going into the oven. Isolated differential probes (TEK 5200) monitor the primary and secondary voltage, and custom current transformers monitor primary and secondary currents.

Figure 19. Test Equipment with Surrounding Equipment

20

Figure 20. Schematic/Block Representation of the Power Supply Drives, the Oven and the Transformer

Also, a 300 W supply was used to drive cores with only the primary winding, and the primary is hooked in parallel with the commercial room temperature transformer that is part of the Kepco commercial supply used to establish the operational waveform.
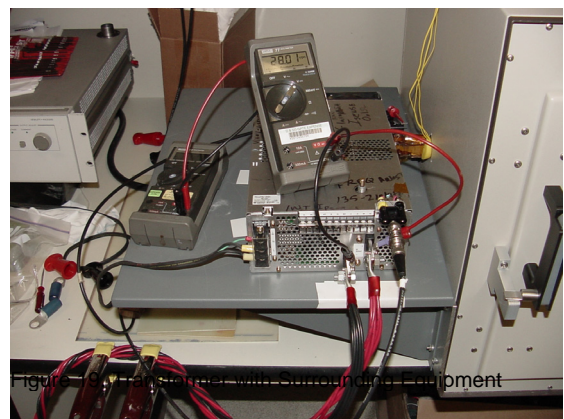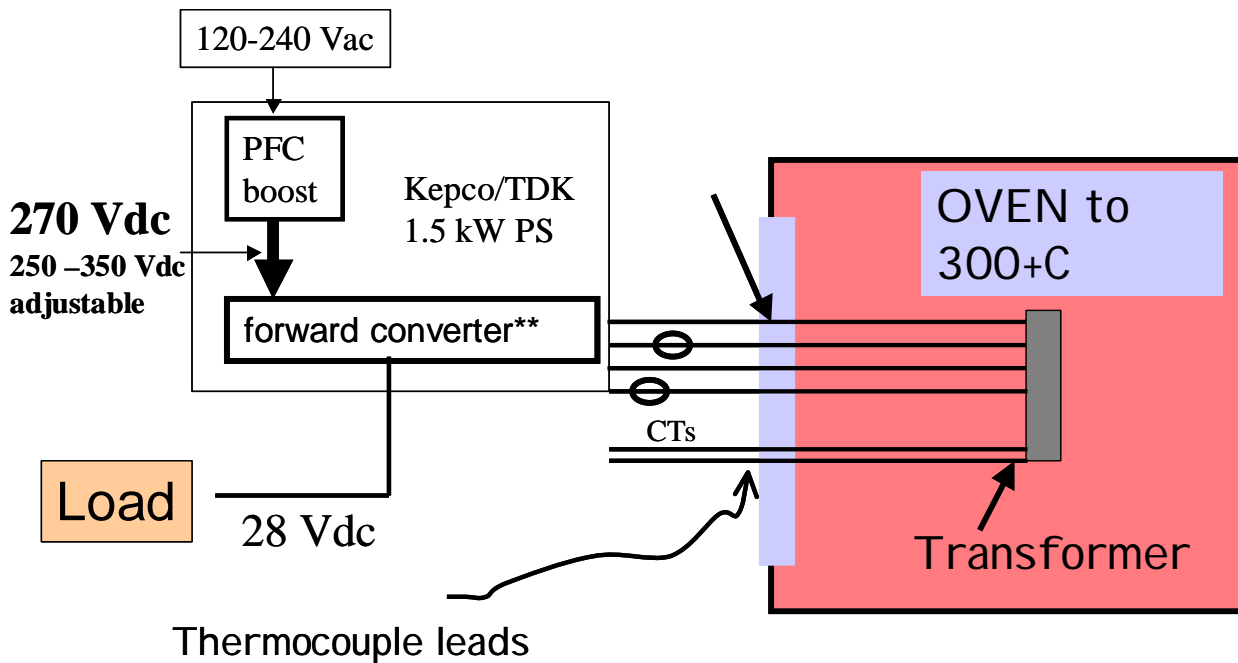
The first set of data taken was to look at core losses for the operational waveforms. The data for the graph at right was read off the Vrms and Irms math functions of the scope, and compiled on spreadsheet to generate the core loss values.

The Y axis is overall core loss for an EE 44610 core configuration, a planar core with 41.3 cc total volume. The X axis is temperature, and the Z axis frequency from 150 to

Figure 21. Core Losses for the Operational Waveforms

300 kHz. The waveform from the commercial supply was unreliable above 300 kHz, with much jitter, so no measurements of this type were taken above that frequency. This specific graph is for 270 Vdc input on a transformer with 8 primary turns and pulse width consistent with a 3 turn secondary. The core starts into saturation with high losses above 260°C for frequencies below 200 kHz with only 8 primary turns.

A more precise characterization of the core was determined by getting a digital readout of the primary voltage and current waveforms. The waveforms to the right are typical. Temperature is recorded manually, and is relatively stable (+/- 1°C over 5 minutes after 15 minute soak).
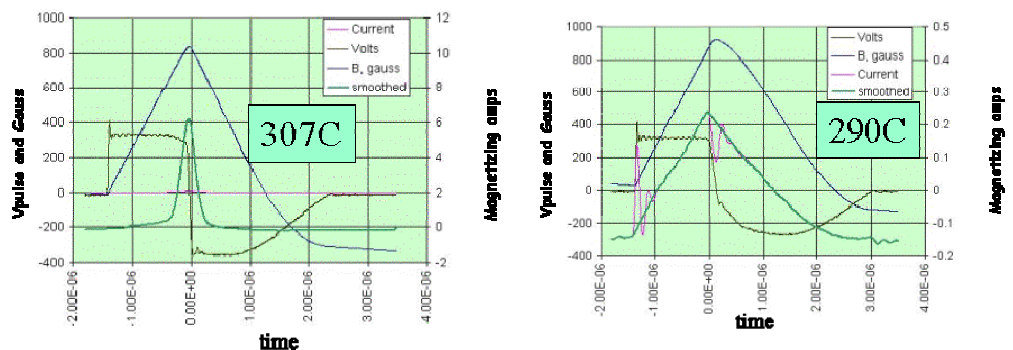
Figure 22. Waveforms of a More Precise Characterization of the Core

21

On these waveforms, no data manipulation was needed to determine flux density as integrating the voltage waveform "erases" the 4-11MHz switching noise. No manipulation was required on the 307°C saturation case as the current waveform was orders of magnitude higher than switching ringing. At 290°C, the switch snubbers insert a ringing as seen on the light blue trace, which is the raw scope data. The test core and primary is hooked in parallel with a loaded transformer that establishes the duty ratio voltage waveform. The data on spreadsheet was put thru an averaging function to filter out the ringing, resulting in the triangular current waveform without ringing.

All mechanical core parameters were added to the spreadsheet so the BH curves under forward converter operational waveforms could be developed.

An excel file with the entire spreadsheet used is included in the appendices.
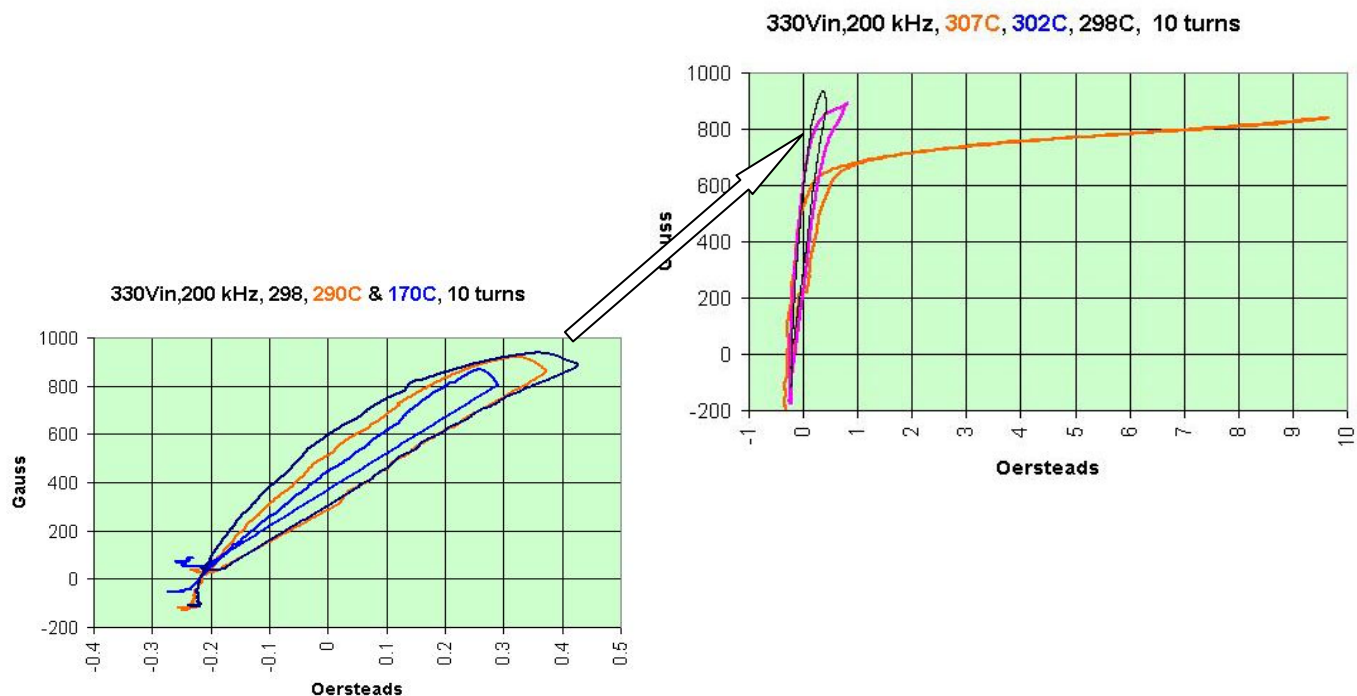
Figure 23. The BH curves results. The Lower Left Hand Graph Shows the Small BH curve at the 170°C Minimum Core Loss Temperature.

As the temperature is increased, losses increase as the area of the BH curve gets larger. The 298°C curve is shown on both graphs, which have over an order of magnitude change to the H values. At 302°C, the BH curve is starting to 'bend over', and saturation at just under 700 Gauss is seen at 307°C.
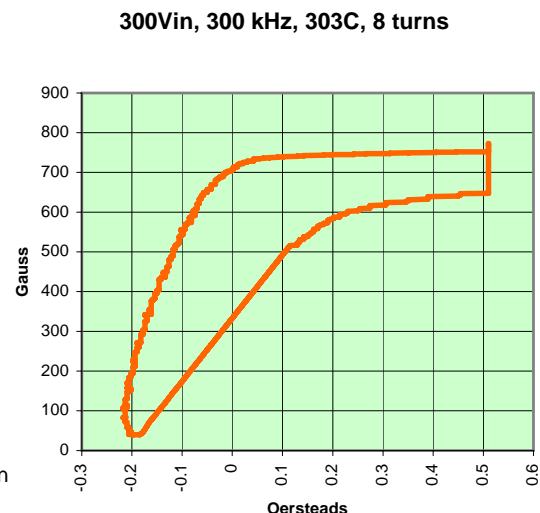
Figure 24. (to the right) BH Curve for a Transformer With an Eight Turn Primary at 303°C and the Saturation Flux Density at about 700 Gauss

Based on BH curve data, core loss graphs, and winding loss calculations, and leakage inductance discussed previously, the winding approach chosen to build transformers was initially set as using 0.7 inch wide 5 mil foil windings. Besides the simple skin depth calculation showing 5 mil foil to be a good choice for 200-250 kHz, the Maxwell 2D simulation below graphically illustrates current density as a result of skin effect. The 20 mil sheet obviously wastes copper at 250 kHz.

For DC, current density would be only 3.1 E+6 A/meter sq.

Outer 1/8 inch sections of 0.7 inch wide 5 mil strip and 0.5 wide strip carry similar currents, about 67% of the current. ¼" center strip of 0.5 inch foil carries 1.6A, while the center 0.45 inch of the 0.7" wide foil carries roughly the same current.

The initial winding used 1 mil Kapton tape and Dow Corning 260°C silicone varnish.   This transformer was successfully wound, but the insulation failed at 295°C (reverted to a liquid).
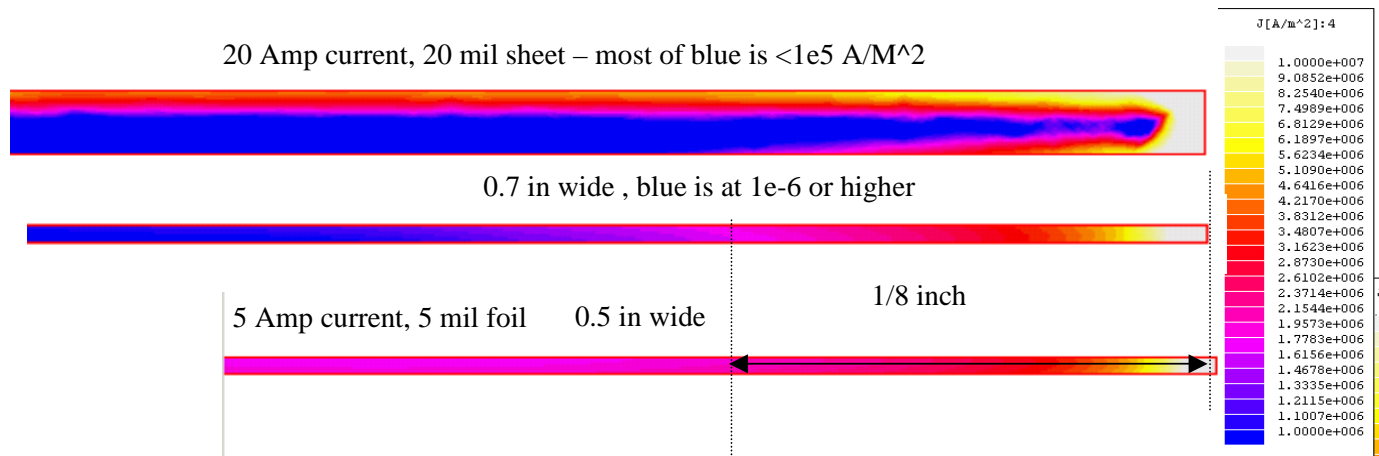
Figure 25. Maxwell 2D Simulation which Illustrates Current Density as a Result of Skin Effect

One of the informal goals of this program is to form a basis of a high temperature winding system that would have a > 200,000 hours lifetime to support long term space missions. This implies a nominal temperature rating of all materials of 340°C or more. One material with 340°C capabilities was Cotronics **Durapot™ 863** (343°C capability epoxy). (The most commonly used material properties are detailed in attach. F.)

Attempts to build a transformer winding with the 863 epoxy and Kapton MT met with mixed results, even with Teflon fixtures. Windings were hand cut in the shape seen at right, and folded into coils after sanding and etching in ferric chloride to remove burrs. In a production environment, it would be anticipated that the foil would be cut on a laser table or other production method. Using loose sheets of Kapton MT (high thermal conductivity) and the Durapot 863, 3 attempts were made to build a set of transformer windings. All failed due to turn-turn shorts. Winding movement during compaction of the foil/Kapton sandwich is the culprit, even in special fixtures. The 863 appears to be an exceptional lubricant until cure takes place. The transformer with ½ inch wide copper foil windings operated for a few days at 290+ °C is made with Kapton tape (#P-221) that is rated 250°C.

Figure 26. Hand Cut Windings

Figure 27. The Desired 0.7"
Wide Foil Winding
Configuration

23

The issue of successful layup of this type winding will have to wait for another day, as the effort for this type winding layup were discontinued.

Durapot has a room temperature pot life at 65 F of literally days, but hardens within a few hours at 250°C. The fixtures fabricated to aid in the foil winding compression and cure of the Durapot 863 were tried with Phelps Dodge Imideze 240°C wire. This wire would not be suitable for a 20 year mission, but does have a few hundred hour lifetime at 300°C.

Trials with the Imideze wire wound into a Litz configuration of 7 parallel #21 AWG strands (21AWG is the smallest that can be successfully coated with the aromatic polyimide insulation) showed that the leakage inductance of the windings were too high. It was found that with the Durapot 863 added the coils could be successfully compressed to reduce leakage inductance.   The Litz configuration was abandoned and single strand windings fabricated, which have leakage inductances as low as the foil winding. The windings made were wound one strand at a time using the fixture sets seen here. The windings are made on the lower left Teflon bobbin, transferred to the lower right Teflon fixture, compressed (in a vise, about 500 PSI), and potted. The upper fixture is of the common type used for over 100 years. After the winding is transferred to the lower fixture, a quantity of the epoxy is place on the windings and then compressed between the faces of the fixture.

Figure 28. Teflon Fixture that is Then Compressed and Potted

Figure 29. Fabricated Single Strand Windings
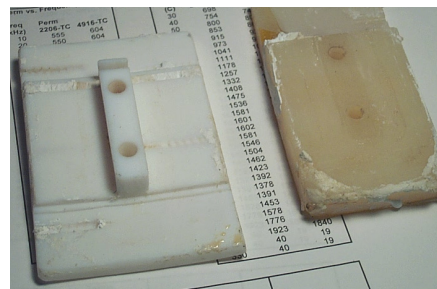
Figure 30. The Bobbin Windings are Made Upon

The fixture is then placed vertical, and set into molds and filled with the Durapot 863.

After cure, the mold is removed, the potting pops off the Teflon, and the winding removed from the fixture, ready to be set into a core after excess epoxy has been sanded away. The coil is seen in the photo above. .

A foil winding was directly potted into a core and no core cracking was seen. During and after cure, this set was held in compression between the heat sink halves (see last months report photos) and no cracking was observed, even though some was expected due to high differences in ferrite and epoxy temperature coefficient of thermal expansion (TCE).

A second try without continuous compression resulted in cracking and spalling. The photo here shows the aftermath of that attempt. In this procedure, the performed coils as in the above photo were placed in a core set (from the second set of cores), the assembly placed in a small Teflon box, and all was potted at once. There was approximately 1/8 inch of epoxy external to the core. When removed from the oven (250°C cure for 6 hours) everything looked fine, the

Figure 31. Cracked Core

24

next day the epoxy had contracted and the spalling seen above was the result. The core has 2 thru cracks along the center leg.

The transformer in the photo to the right was 'fixed' by buttering on a layer of ceramic paste, placing that on a heat sink, and curing the ceramic. The resulting assembly functioned, but deemed inferior for future usage

Figure 32. Ceramic Paste Applied to Transformer

Figure 33. Ceramic Covered Winding Ends

Another method used is simply to wet wind with ceramic slurry one 21 AWG strand at a time, a messy but effective technique. Due to the abrasive qualities of the slurry, high compression of the coils was not used so there are fewer parallel #21 AWG wire strands (20 vs. 30 for the secondary). A thin layer of ceramic will be used to bond the core to the heat sink.
The winding ends were also covered with ceramic by 'buttering' with a spatula. The photo at left shows this part.

This was limited by the poor conductivity of the 21 AWG wire at 250 kHz, but provided core data for further tests.

3.2.2 First transfomerbuild and run

After the above trials, an EE core transformer was built with materials intended for long term operation. The primary insulation system was 1 mil P221 Kapton tape applied to 5 mil by 0.5" wide copper foil. Red High temperature Loctite silicone was used for overall core fill (see attach. F for material details.) The copper foil was simply 0.7" wide foil strips folded at the corners at 45 degrees rather than the more complex zig zag cutout shown earlier. On the secondary, 3 layers at a time were folded. Folds alternated in direction to even out overall foil lengths. This transformer was mounted in a finned heat sink to hold the core at near oven temperatures. That assembly is shown to the right.

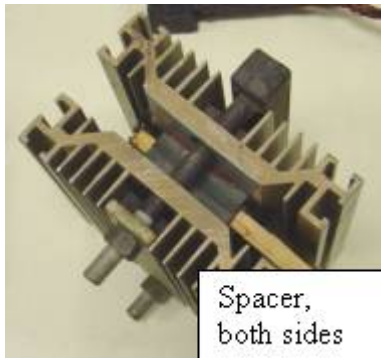Figure 34. Transformer Mounted in a Finned Heat Sink

25

Figure 35. Core Filled with Silicone

It was found that to avoid core cracking, a 30 mil space had to be left between the side core legs and the winding. That was assured during cure of the core fill silicone by use of a TFE spacer as shown to the left. The spacer was pulled from the assembly when cured.

This transformer was operated successfully for over 20 hours and used for the March 11th TI meeting demonstration.

At the March 11th TI meeting, it was determined that the best use of remaining contract funds would be to build the 10,000# lot of ferrite powder (discussed in section 2) and to built a transformer with all materials rated above 300°C to 320°C. (The P221 tape is rated at only 260°C.)

The final winding configuration was of Kapton MT and red high temp silicone insulation. The silicone was thinned 40 parts Naphtha to 15 parts RTV. Each winding consists of 2 parallel 0.32 inch wide 5 mil copper foils. 1 primary layer, 7 secondary layers.

Although the insulation methods described here failed at 608 hours operation (all over 290°C ambient), a detailed description of transformer assembly is contained here as the technique would be useful for temperatures up to 280°C hot spots.

3.2.2   Second transfomre build and run

Detailed buildup description:

The layup of the individually build winding segments is shown in the diagram at right. One 10 foot long strip of primary winding was built and 2ea 5 foot sections of the secondary segment built. An additional 5 foot section of primary type buildup was also built.
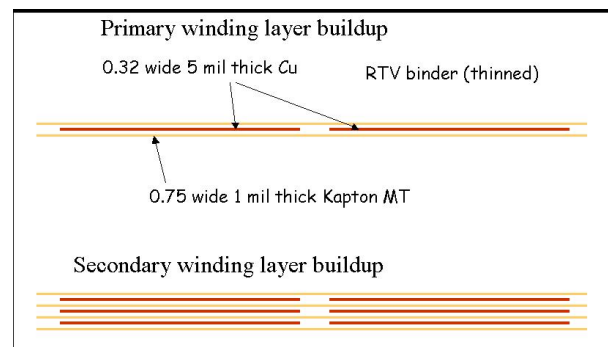
Figure 36. Layup of the Individually Built Winding Segments

In this diagram to the left, the overall stackup is shown.

The 7 secondary layers were sandwiched between the primary windings. Since the high side turn of the secondary to the adjacent low side has a 200 volt potential difference, a layer of Kapton was also added between the segments of the secondary. Each layer to layer and added Kapton layers were painted with the thinned RTV prior to assembly.

Figure 37. Overall Stackup of Windings

26

To assure good primary to secondary isolation 4 additional layers of Kapton MT were added in those areas. 4 layers of additional Kapton were also inserted between primary and core.

A 10 foot section of aluminum work surface was setup, as the 9 turn winding is less than 10 feet long. A 0.75 inch wide strip of 1 mil thick Kapton MT in laid on the aluminum and adhered to the aluminum with a water film. The water film accomplishes 2 purposes, the first to hold the Kapton in place, the second to provide a moisture source thru the permeable Kapton to allow the Loctite RTV to cure. The first layer is simply squeegeed flat with finger pressure.
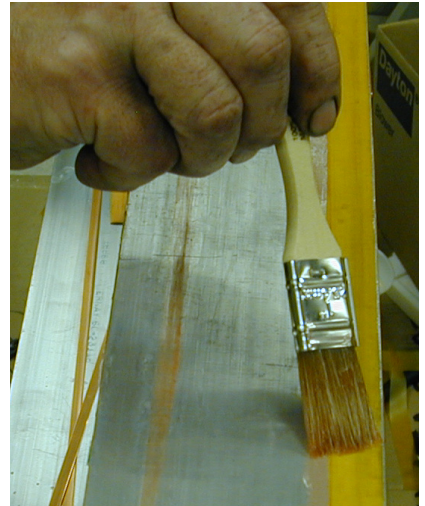
Figure 39. Brushed on RTV

Figure 38. Aluminum Work Surface with Kapton Inlay

The second step is to mix a thin mixture of Loctite Red High Temperature RTV using a mixture of 40 parts Naphtha to 15 parts RTV. This is simply brushed onto the Kapton MT.

The copper winding strips are stretched by hand to assure no crinkles and straightness. This currently is a "by feel" operation, as the yield point of the copper strip is felt by hand and approximately 1/8 inch stretch accomplished for a ten foot long strip.

Figure 40. Stretching Copper Winding Strips

These straight strips of copper are then carried flat and laid onto the thinned RTV and maneuvered into place, again with simple finger pressure.

Following a brush coat of the thinned RTV over the copper, another 1 mil layer of Kapton MT is applied.

The layup is allowed to cure overnight. As the Kapton MT to aluminum "bond" was only a water film, the conductor assembly is easily peeled from the Aluminum. The finished primary conductor is shown below.
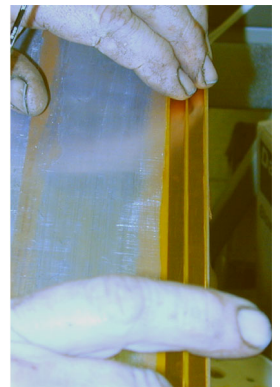
Figure 41. Copper Strips Laid Onto the RTV

Figure 42. Finished Primary Conductor

The secondary windings were made with 3 layers of copper and 4 layers of Kapton MT. 3 layers of copper was the maximum it was feasible to fold without delaminating the copper from the Kapton.

The original transformer of section 3.3.2 was built with ½ inch wide windings and had 9 total layers for the secondary. For this transformer, we limited the number of parallel secondary layers to 7 to approximate the total copper cross section of the 9 layers of ½ foil windings. This was to get more comparative data for the thermal aspects of the winding methods.

In the window area of the transformer, there was left an area capable of 3 more parallel secondary windings. This was filled with Teflon and ceramic.

A Teflon fixture was built to aid in winding the coils and inserting the inter-winding insulation. Each interface was coated thinned RTV prior to assembly. The method of winding the laminated copper strips was a 45 degree fold at the corners. The folds were made in alternating directions so that there was not a buildup of stretched material in the outer layers.

The Teflon fixture was machined to have a window approximately 0.06 inch smaller than both the core window dimension. The windings were compressed in the fixture and allowed to cure for 3 days. All thinned silicone apparently cured. The three photos below are of the winding in the fixture with the connector to the transformer being attached. The external leads of the primary between the two sandwiched sections were extended to provide clearance for the secondary windings. The extra Kapton extending beyond the windings was trimmed after RTV cure.

Figure 43. The Winding in the Fixture with the Connector to the Transformer Being Attached

The open areas seen in the fixture were first filled with un-thinned RTV or
Durapot epoxy.   The RTV did not cure to depth in over a week's time, and the application of 300°C apparently inhibits further longer term cure. The RTV had extruded from the core showing that there was a problem with the RTV. The high temperature epoxy likewise developed stress cracks after a few 10's of hours operation, and is deemed unsuitable for long term operation.

This transformer was disassembled and no core cracking was found. Some of the deep section of silicone, which had not cured, was found in an almost liquid state, and apparently having been subjected to 300°C prevented subsequent cure even when opened. 59 hours had been accumulated on the transformer.

The existing set of silicone laminated winding was cleaned of all the epoxy and also of any uncured RTV, and any open edges or windings delaminated during cleaning were re-laminated with red hi-tem Loctite RTV silicone, which was allowed to cure for 4 days and cure verified visually and by touch. The winding appeared in good electrical condition. The winding is shown before cleaning at right.

This winding was then re-assembled into the same core using Durapot 810 thermally conductive ceramic vs. silicone. The extended windings at the end of the cores were also encased in silicone. This was baked for 8 hours at 250°C without power applied. With power applied, results were nearly identical to previous results: core saturation at near 307°C, only 8 degrees°C hotter than the aluminum plate on which it was mounted. As in previous transformers, an unfilled gap between the windings and the core was maintained.

Figure 44. Winding Before Cleaning

To more closely approximate the heat sink on a spacecraft, a liquid cooled type aluminum plate (not cooled for the testing except by the 300°C oven air) was used in the buildup vs. using the previously used finned heat sinks. The transformer core was enclosed in a ¼ inch thick aluminum cover. In a spacecraft application, this could be a heat pipe assembly to tie the side of the core away from the heat sink thermally to the heat sink. Additionally, this 'heat pipe simulator" was extended to cover the windings external to the ferrite core. The assembly was instrumented with thermocouples. The photo at right is after operation at 295°C ambient for 59 hours. Note the extreme oxidation of the

Figure 45. Transformer, After Operation at 295°C

unused liquid pipes thru the aluminum plate and that the fiberglass type K thermocouple wires are nearly the color of ash, as only the fiberglass itself is left on these leads. TFE type thermocouple wires had been tried earlier, but failed due to thermal flow of that insulation and gave erroneous readings (always low).

The photo below is another view. The extended leads of the primary that were used to allow the sandwich construction were also covered with ceramic but not with the "heat pipe simulator'.

Table 4. Steady Runs of the Oven (All Temperatures are in Degrees C)

Oven set	292	294	299
STATE	steady run	steady run	**sat**
far heat sink	294.3	299.2	303
top of HS	301.5	302.1	308
near heat sink	295.7	299	304.3
back winding	301.5	305.4	308.4
front winding	310.2	314.4	317.9
back rt core	301.5	305.4	308.4
front lft core	302.2	306.2	308.

Figure 46. Transformer, After Operation at 295°C

After approximately 150 hours running time at 295°C, the oven was left on overnight and the output had drooped to 24 V out at 53.6 amps. The input current waveform *did not* indicate
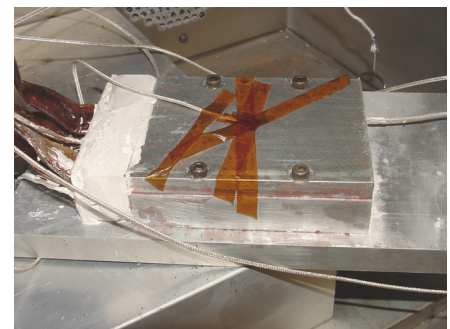
saturation, but was operating at a reduced duty cycle. All temperature data above was taken June 2nd, 2004 to attempt to answer why the reduced output voltage occurred, as partial core saturation was expected but not observed. The input voltage has remained constant at 270 Vdc during all observed operational time, so the flux level due to the primary winding should have remained constant. The flux level does drop as the pulse width narrowed and reduced the output voltage to 24 Vdc. As seen in the data above, core saturation temperature remains at 307°C. This rules out any ferrite annealing phenomena. Also suspected was a possible insulation delamination that would cause a higher temperature differential from core to the heat sink. In hindsight, after transformer disassembly, this was found to be the cause. Insulation deterioration apparently started at about this time. Core to heat sink temperature difference remained about 10°C, similar to beginning of test data.

The power supply 270 Vdc is supplied from a power factor correction circuit (PFC) in the Kepco commercial supply. This supply was designed to operate at 380 Vdc output, and was revised for the Hi-temp magnetics program to put out 270 Vdc, lowering the efficiency of the PFC circuit. The power supply is fed thru a marginally sized isolation transformer for safety, and the nominal output of the isolation transformer is 107 Vac under full load. The probably explanation for the power supply going into a low output voltage mode is that a power line anomaly or local load dropped the ac line voltage low enough so that the PFC circuit went into current limit, causing the 270 Vdc output to drop and increasing the input current to the transformer. The output continued to deliver the 53.6 A set on the electronic load, and latched onto a reduced output voltage mode of operation. An additional test showed that the supply recovered to 28 Vdc with a 1 second power off reset of for a chamber temperature drop of 2-3°C. These appears consistent with the latching condition for the over current condition for the PFC circuit. The reset is obvious, the 2-3°C drop may allow lower core and copper losses with just enough reduction in PFC circuit output to reset.
There is no evidence from the test data that there has not been any change in core saturation capability or transformer thermal transfer parameters other than core delamination.
The external lead of the transformer are of the same construction as the windings, and show no delamination or damage, but do operate at near oven ambient, 10 to 20°C cooler than the hot spots.

During the week of June 21-25, the transformer was run nearly continuously 24 hours per day and was shut down the evening of the 25th. It was successfully started at room temperature on June 28th, but failed during the first hour of operation as the temperature was climbing to 300°C.
The first photo is the exterior, the most obvious features are the crack between the aluminum housing and the ceramic covering of the windings, and the good condition of the Kapton and RTV laminate insulation on the copper conductors. The copper conductors had no oxidation, whereas a bare copper sample in the oven (a part of the heat sink plate used) had flaking copper oxide.
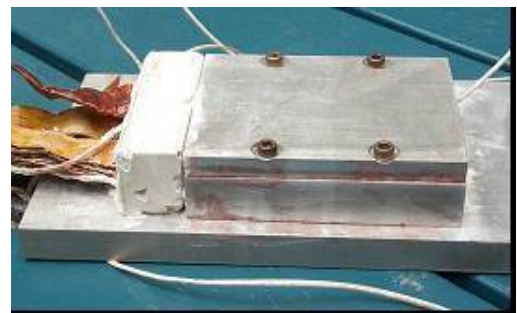
Figure 47. The Transformer After Running for Nearly Five Consecutive Days

The transformer that failed June 28th was disassembled and analyzed. Cause of failure was extensive insulation damage due to internal temperatures in excess of 320°C. There were no internal thermocouples, as in previous testing cores had cracked wherever a thermocouple touched the inside winding window of the core. The core was cracked along the center leg and the

red silicone had crystallized into small hard (approximately same hardness as rock salt) grains. The internal ceramic was also cracked.

The table shows rounded hours of operation, temperatures, and anomalies. Note that this chart shows both the initial transformer with Red High Temp RTV fill and the later Ceramic fill transformer. The coil windings from the RTV fill transformer were re-used for the ceramic fill transformer.

Table 5. Testing of Transformer

date	1=Sun day	hours	event	notes						
12-Apr	2	5		295°C ambient						
13-Apr	3	9								
14-Apr	4	9								
15-Apr	5	9								
16-Apr	6	9								
17-Apr	7	0								
18-Apr	1	0								
19-Apr	2	9								
20-Apr	3	9	**59**	total hours on RTV filled windings.						
21-Apr	4	0		redone in ceramic, same winding						
22-Apr	5	9		295°C ambient oven set						
23-Apr	6	9								
24-Apr	7	9								
25-Apr	1	9								
26-Apr	2	9								
27-Apr	3	9								
28-Apr	4	9								
29-Apr	5	9								
30-Apr	6	0								
1-May	7	0								
2-May	1	0								
3-May	2	9								
4-May	3	9								
5-May	4	9								
6-May	5	9								
7-May	6	9								
8-May	7	0								
9-May	1	0								
10-May	2	18		on overnight						
11-May	3	15								
12-May	4	9								
13-May	5	9								
14-May	6	0								
15-May	7	0								
16-May	1	0								
17-May	2	9								
18-May	3	9		on overnight						
19-May	4	9								
20-May	5	11								
21-May	6	0		out of town, no testing						
22-May	7	0		out of town, no testing						
23-May	1	0		out of town, no testing						

31

Date		Hrs		Notes
24-May	2	0		out of town, no testing
25-May	3	0		out of town, no testing
26-May	4	0		out of town, no testing
27-May	5	0		out of town, no testing
28-May	6	0		out of town, no testing
29-May	7	0		out of town, no testing
30-May	1	0		out of town, no testing
31-May	2	0		Memorial day
1-Jun	3	15		195 hours of ceramic time
2-Jun	4	18	A	**24 volt anomaly noted (A)**
3-Jun	5	24		reset oven to 293°C
4-Jun	6	15		
5-Jun	7	0		
6-Jun	1	0		
7-Jun	2	9		
8-Jun	3	18		
9-Jun	4	24		
10-Jun	5	16		
11-Jun	6	0		
12-Jun	7	0		
13-Jun	1	18		
14-Jun	2	24		

All temperatures in degrees C, data from June 2

				4-Jun
Oven set	292	294	299	ok, 293C
STATE	OK	OK	sat	
back winding	301.5	305.4	308.4	316
near heat sk	295.7	299	304.3	299
far heat sink	294.3	299.2	303	297.6
top of HS	301.5	302.1	308	302.4
back rt core	301.5	305.4	308.4	304.3
front lft core	302.2	306.2	308.6	306.2
front winding	310.2	314.4	317.9	317.3

Date		Hrs		Notes
15-Jun	3	24		
16-Jun	4	15	A	**voltage drop to 24 vdc @1pm, 28V after 15 sec power recycle**
17-Jun	5	9		reset oven to 290°C **further 24 v anomalies**
18-Jun	6	9		
19-Jun	7	0		
20-Jun	1	0		
21-Jun	2	18		
22-Jun	3	24	A	
23-Jun	4	24	A	
24-Jun	5	24	A	
25-Jun	6	14	A	
26-Jun	7	0		
27-Jun	1	0		

All temperatures in degrees C, data typical for 290C oven set

date	18-Jun	22-Jun	25-Jun	4-Jun	292C
STATE	28 v	24.5 v	23.5 v	ok, 293C	OK, June 2
back winding	317	317.6	317	316	301.5
near heat sk	297	297	296	299	295.7
far heat sink	295	295	295	297.6	294.3
top of HS	298	298	295	302.4	301.5
back rt core	302	302	302	304.3	301.5
front lft core	305	305	305	306.2	302.2
front winding	320	320	320	317.3	310.2

Date		Hrs		Notes
28-Jun	2	1		**Secondary permanent short developed during 1st hour running during temperature ramp up.**
total hours run		608		

The major event that was a precursor to the insulation failure was the voltage drop of the output, denoted in the table by "A", for anomaly. The cause of this output voltage drop to 24 v dc from 28 Vdc (current remained at 53.6 amps) had been estimated to be due to overnight power transients that latched an input current limit on the 270 Vdc input power supply. Disassembly showed that the true cause was likely a temporary short between transformer turns that latched the current limit. The current limit was discussed in last months report.

There are 2 embedded temperature charts in the table above, the first, on the previous page, shows that between June 2nd and June 4th, the internal thermal conductivity deteriorated as evidenced by higher winding temperatures. As previously discussed, there were no internal thermocouples inside the core due to causing core cracking, so hot spot temperatures were surely above 320°C. On the previous page, the embedded chart shows that whether the input current limit had latched or not, the transformer temperatures were constant from June 18-25th.

Transformer current remained constant at 53.6 A, one reading of 52.7A was seen. The highlighted June 4th and June 2nd columns further illustrate that there had been internal thermal degradation.

There is no evidence from the test data that there has been any change in core saturation capability, but transformer thermal transfer parameters definitely changed with time due to electrical insulation degradation.

The external lead of the transformer are of the same construction as the windings, and show no delamination or damage, but do operate at near oven ambient, over 30°C cooler than the probably internal hot spots.

Disassembly details

The degree of internal deterioration of the insulation was not expected. Data sheets from last January listed Red High Temp RTV as 340°C, the current Loctite web site show these characteristics and are included for reference. This material had shown no degradation as part of the transformer windings or embrittlement during the first 59 hours of operation, at which time the first transformer was dis-assembled.

Superflex® Red High Temp RTV	59630 59675	80 ml tube 300 ml cartridge	Red	-	-	-75° to 600°F (-59° to 316°C)

http://www.loctite.com/int_henkel/loctite_us/binarydata/pdf/LT3355v4_MROgasketingsealing.pdf

Dupont data remains the same as it was last year.
The graphs show the retained Dielectric Strength at 325°C (617°F) for 25 µm (1 mil) Film. http://www.dupont.com/kapton/general/spaging.html

In our application the Kapton was stressed to only 30 V/mil. 30 V/mil is only 0.4% of the 100% rating.
Many applications use a combination of RTV and Kapton. A short literature search on RTV and Kapton reactions at 300°C plus found no data. Dupont lists 2 big 'killers' of Kapton; DMF after 1 day at 152°C , zero properties remain; and Dow Silicone Varnish 1402, after 48 hours at 250°C Kapton decomposes.

Figure 48. Dielectric Strength Retained Vs. Time

In the air at about 500°C (932°F), Kapton® polyimide film decomposes and completely disappears after 12 hours, while in a vacuum or in an inert atmosphere 60 to 65 percent of the film remains after prolonged aging at temperatures as high as 1000°C, but no strength remains.

Figure 49. Core Halves

From the disassembly photos and notes, which follow, there obviously is some type of reaction at 320°C between materials used. No chemical analysis or research have been done or are anticipated, as a conclusion is that future efforts would need to concentrate on ceramic high voltage techniques.

This set of 3 photos show both core halves, the lower left the top core half which did crack along the center leg. There were no electrical signatures that could be attributed to a crack during operation, but there was neither crack heard nor force required during removal of the aluminum top. It is assumed the core cracked sometime during the 500+ hours of operation without significantly effecting operation. The treeing patterns on both sides of the core appear only on the outer core surfaces, none were seen on the inner window of the core against the winding. The surface with the treeing was in contact (thin layer of RTV for thermal conductivity) with the grounded heatsink. The points of origin of the trees roughly correspond to the location of the edges of the primary windings, but there is no evidence of the pattern on the edges of the cores. The treeing phenomenon remains unsolved, as there is no measurable effect on core performance.

Figure 50. Ceramic Encased Winding

This set of 3 photos is the ceramic encased winding with the cracked core removed. Some of the ceramic cracking was due to adhesion and happened during disassembly, but other cracks were existing.

A close examination of all 6 of these photos show a red powder at the edges, This is remnants of Red RTV used for a thermally conductive paste between the core and the aluminum housing. The red RTV reverted to a grainy crystalline type structure. Again, no chemical analysis was performed.

A surprise came when the ceramic was removed. Where the external leads laminated with red RTV and Kapton showed no signs of oxidation, the internal copper was badly oxidized, on all layers. This indicates that a few hundred hours (at least a few tens of hours) prior to transformer failure the lamination failed internal to the windings allowing air entry.

Figure 51. Badly Oxidized Internal Copper

34

The four photos on the left hand column are views of the winding fanned out. The Kapton has totally deteriorated, with many decomposed holes and flaky particles.

There is zero evidence that the Kapton had ever been laminated to the copper with RTV, just a gray glaze on the copper.

There were 6 layers of 1 mil Kapton between the primary and secondary windings, which are in much better shape (still recognizable Kapton) that can be seen at the ends of the arrows. Also seen in a large photo below.

The pictures below are of individual fragments of Kapton remaining between some turns. It is obvious from these samples that the final failure was due to inter-turn secondary short, and that the 24 Vdc anomalies were likely the result of intermittent short term shorts. The central photo is of Kapton dross left when windings were separated; the right hand photo is one of the larger fragments.
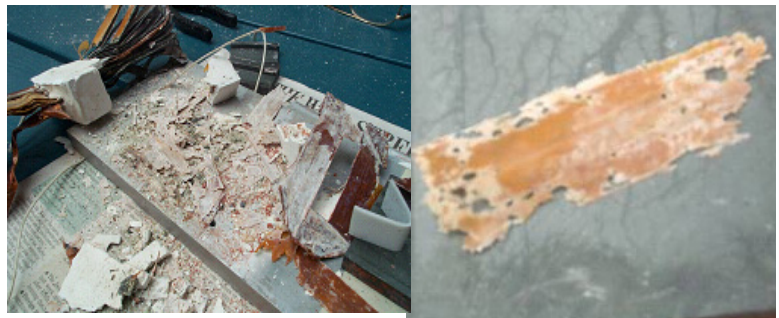

Figure 53. Fragments of Kapton Remaining Between Some Turns

The multiple layers of Kapton separating the primary and secondary are not totally disintegrated, but numerous holes are obvious. There does not appear to be any specific pattern to holes in the Kapton.

Figure 52. The Winding Fanned out

The space left by having only the same cross section of copper as previous transformers was filled with Teflon strips. Although the Teflon did not appear at first to have deteriorated, when bent it crazed and did not spring back. The photo to the right shows 2 strips of Teflon bent and retaining the exact shape into which they were bent.

Figure 54. Teflon Strips

This photo is of the input leads as they exited in the ceramic. These were at oven ambient temperature and showed little deterioration. The lower leads showed some delamination of the P221 Kapton tape added to the primary leads for additional voltage isolation. There was no delamination of the copper/RTV/Kapton sandwich for the leads at oven ambient (always < 300°C except for a few minutes).

Figure 55. Input Leads as They Existed in the Ceramic

3.3 Lessons Learned and Future Approach

The RTV/Kapton/ceramic approach for high dielectric capability coupled with long term 300°C plus temperature capability does not work.
Previously investigated commercial wire approaches using all ceramics, such as the following also have a limitation of being dependent on nickel for oxidation resistance.
http://www.ceramawire.com/ Limitation – 150 V dielectric withstand
http://www.gaumer.com/ProductList.pasp?cat=controlhightempwire&step1=High%20Temp%20Wire%20(450%20C) Limitation – 20 AWG is 0.108 inch dia
http://www.newportus.com/Products/Wire/HTMG.htm Limitation – 22 AWG is 0.104 inch dia
Also, numerous plasma ceramic spray onto foil, also limited by dielectric capability.

The commercial use of nickel also has a high frequency transformer problem with leakage inductance and losses due to the use of magnetic nickel, so a different oxidation protection metal would be required, such as gold or rhodium.

4.0 Paper submittals.

One of the expectations listed in the original request for proposal was that the work accomplished on the program be disseminated to industry through the use of technical papers.

5 papers have been prepared relative to this contract, the first 2 have been approved for release, and the final 3 listed are in the release review process. The probable final content of papers # 3 and #4 are included here, # 5 would be a hardware show and tell paper with some of the actual hardware of section 3.

1. New Ferrite Material for High Temperature Magnetics High Temperature Electronics Conference, June 2002
2. 300C Ferrite Material for High Temperature Magnetics, Power Electronics specialist Conference, June 2004.
3. 300C High Temperature Magnetics, digest submitted for the Applied Power Electronics Conference, March, 2005
4. Practical aspects of building a 300C ferrite planar transformer, digest submitted for the Applied Power Electronics Conference, March, 2005
5. Poster paper with hardware of #3, digest submitted for the Applied Power Electronics Conference, March, 2005