COMPACT GAS-INSULATED TRANSFORMER

DOE CONTRACT DE-AC02-79 ET 29071

FOURTEENTH QUARTERLY REPORT

AUGUST 1983

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PREPARED BY:

GENERAL ELECTRIC COMPANY
POWER TRANSFORMER DEPARTMENT
PITTSFIELD, MA.
FOR

THE U.S. DEPARTMENT OF ENERGY
WITH

THE EMPIRE STATE ELECTRIC ENERGY RESEARCH CORPORATION
THE NEW YORK STATE ENERGY RESEARCH DEVELOPMENT AUTHORITY
THE CONSOLIDATED EDISON COMPANY OF N.Y.
THE NIAGARA MOHAWK POWER CORPORATION OF N.Y. AND
THE BONNEVILLE POWER ADMINISTRATION

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DOE/ET/20971--T5

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DE83 017441

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FOREWARD

This report describes work performed February 1983 through June 1983, for the U.S. Department of Energy, Washington, D.C., under Contract No. DE-AC02-79ET-29071. The work was performed in the Power Transformer Department, Corporate Research and Development and the Large Transformer Technical Resources Operation of the General Electric Company. The work is under the technical cognizance of Messrs. K. W. Klein, Manager-Division of Electric Energy Systems, Department of Energy and P. A. Gnadt, Oak Ridge National Laboratory. Mr. Klein's and Mr. Gnadt's guidance is gratefully acknowledged.

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The contributors acknowledge the assistance of their colleagues in PTD, LTTR0, and in GE Corporate Research and Development.

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PATENT STATUS

This technical report is being transmitted in advance of DOE patent clearance and no further dissemination or publication shall be made of the report without prior approval of the DOE Patent Counsel.

TECHNICAL STATUS

This technical report is being transmitted in advance of DOE review and no further dissemination or publication shall be made of the report without prior approval of the DOE Project/Program Manager.

TRADEMARK NOTICE

Throughout this report, reference is made to Mylar film and Freon 113. Mylar and Freon are the registered trademarks of E.I. DuPont de Nemours for their polyethylene terephthalate film and Freon gases.

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Section 1.0
PROGRAM OBJECTIVE

The overall objective of this program is to develop new technologies for application in a radically new power transformer design. The specific objective lies in designing a transformer which is more efficient, more compact, lower in weight and audible sound, nonflammable, which does not rely upon mineral oil insulation, and which is compatible with the gas insulated electrical system of the future.

This program, which will last over three years, has as its goal the development of design and manufacturing technology. Design prototypes in the 50 MVA-345 kV range will be tested. In addition to the development of technologies, the program provides for economic, environmental, and systems application assessments of the emergent technologies.

Section 2.0 DESIGN CONCEPT

Gas insulated power transformers have been built for commercial service, generally to meet requirements of non-flammability. These have found application in mines and areas of high population density. The General Electric Company built and delivered a number of such units in the 1950's.

Generally, these transformers have been built similar to oil-filled transformers. The coils were wire wound, and cooling was accomplished by circulating the insulating gas through the windings and core. An intermediate heat exchange system was used in which fluorocarbon liquid carried heat from the gas to the outside. Because the insulation gas (SF_6) was a poorer coolant than the oil it replaced, these transformers were generally larger than the equivalent oil filled transformer.

In the present concept, the insulating fluid is high pressure gas. The coolant is a liquid, contained in a closed system. The design concept is shown schematically in the cross-sectional view of a coil in Figure 2.1.

This winding incorporates the following design features:

1. Full height sheet conductor.
2. Polymer film as insulation between turns.
3. High pressure gas insulation external to the coil.
4. Separate liquid cooling system consisting of thin, cylindrical annuli wound into the coil carrying a dielectric cooling liquid, which is carried to external heat exchangers via insulating tubing.

It should be noted that these four concepts are not independent, but form a consistent whole. Thus, for example.

1. Employment of high density gas (a poor medium for transferring heat) suggests the use of a different fluid for cooling. This, in turn, leads to the advantageous arrangement of completely separating the insulating and cooling mediums.
2. Sheet windings can lead to higher winding space factor than that attainable with wire windings, especially when winding current is very large (depending on the design and specific application). Furthermore, the simple cylindrical geometry of sheet windings makes possible a comparatively simple cooling duct design.
3. Use of sheet windings makes it possible to use polymer sheet as turn-to-turn insulation.
4. Gas insulation is compatible with a wide variety of polymers which would not be suitable for use with oil.

Figure 2.1 Cross Section of a Sheet-Wound Forced-Cooled Transformer

Section 3.0
SUMMARY OF PROGRESS DURING THE 14th QUARTER
FEBRUARY THROUGH JUNE, 1983

3.0 SUMMARY OF PROJECT MANAGEMENT AND PLANNING

During this quarter the failure of Short Circuit Model #7 at a low value suggested a program plan change be made to accommodate another short circuit model. After consultation with our DoE Technical Advisor "Paul Gnadt", we agreed to eliminate the Prototype Thermal Model which was designated Prototype #1 and have redesigned the arrangement of the windings to be a Prototype Short Circuit Model. Arrangement of windings to produce high forces dictate a simple low-high winding arrangement which would not be appropriate to heat run because of the excessive edge currents for this 56" size.

3.1 DESIGN STUDIES (TASK 1100)

During this period a study of the possible "early" cost reductions was made and these costs were included in the cost program logic. With these modifications in place parametric studies of sheet width and impedance variations were undertaken on a large auto (448 MVA-500KV) and a large GSU (500 MVA-500KV). The resulting curves are presented in the body of this report. The development of a satisfactory copper to copper (sheet to Litz wire) joint and manufacture of 8 leads for prototype #1 was accomplished in the Philadelphia Welding Lab.

At the time of our last review, Joe Slocik visited a company in California who make no-heat-shrink tubing (solvent expanded materials). Samples in neoprene (not conducting enough) indicate this would be a promising approach. We included these samples in the evaluation of molded rubber on leads. Our goal for cooling leads with conducting rubber is to minimize the loss that would occur in the "dielectrically required" large lead but to provide a surface that appears dielectrically like that large lead. Samples were molded and tested and compare favorably to the results published for the 1" diameter bare rod tests.

3.2 MECHANICAL STUDIES (TASK 1250)

Last quarter we reported the evaluation of the isolators which, as tested, were too much constrained. This period we evaluated isolation between the core and pedestals mounted in concrete and demonstrated a 28-30 dba isolation of core to pedestal. Based on this result we modified the tank base to provide a direct in-line (core to floor) supporting structure and built a concrete base

in the anechoic chamber. Two effects were noted: sound level reduced about 3 dba and sound pressure internal to the tank increased 8 to 10 dba. Installation of sound energy adsorbing material internal to the tank effects the externally measured sound only 1 to 2 dba while reducing the internal sound pressure to 84 dba indicating there is still a mechanical coupling to the tank dome which has not been interrupted. Designs to achieve this are presented.

3.3 DIELECTRIC STUDIES (TASK 1200)

Insulation development work is grouped into four basic areas.

1. Winding Insulation (Task 1221)
2. Coolant System dielectrics (Task 1222)
3. Major Insulation (Task 1223)
4. HVDC Applications (Task 1224)

During this period the following items were accomplished and reported in detail in the body of this report.

1. Lead model coil tests were completed
2. Impulse breakdowns were performed at elevated temperatures
3. Main gap models were tested and analyzed
4. Core shield tests were performed
5. In response to questions raised at the Thirteenth Quarterly Review, our data and other literature was reviewed to determine the effect of air voids in the coil
6. Lead test fixture was built and testing was completed
7. Coolant system dielectric tests continued
8. The 345 KV Disk Bushing successfully passed all tests with margin

3.4 SHORT CIRCUIT STUDIES (TASK 1230)

Model #7 was short circuit tested in the General Electric High Power Lab in Philadelphia. Prior to test extensive evaluation of pressure measuring techniques was undertaken to be able to evaluate the pressure surge that emanates from the panels during a short circuit. Testing was inconclusive in that the cooling panel headers failed at 33% of the intended test level.

These were an oven brazed design with several high stress locations compared to the welded design planned for the prototype. Considerable evaluation of a short circuit model from the parts of prototype #1 is described.

3.5 THERMAL TECHNOLOGY (TASK 1240)

During this period model #7 was completed. It was loss tested in 6 winding configurations by exciting different sections of the winding with other sections idle. These results were compared to EDDY56 (our initial analysis program) and KONRAD (the improved analysis program). Although KONRAD did not predict the impedances well it was very accurate for the losses. Later investigations found an extraneous factor which had effected the impedance prediction. The EDDY56 predictions were consistently low. Since the designer of EDDY56 has left the company, reasons for this discrepancy have not been investigated.

Thermal tests of model #7 were made at 0.866, 1.0, 1.1, 1.2, and 1.5 per unit loading. Tests were within 1°C of the prediction and during the overload testing, time constants for overloading were developed. Temperature results are included in the body of the report.

3.6 MATERIALS (TASK 1260)

Two areas of interest were pursued this period. 1st, the evaluation of the effects of moisture and voltage on aging with the possible use of power-factor measurements to monitor aging. The results are that power-factor is not effected by aging with or without moisture present. The moisture and voltage results conform to the curves previously presented. Continuous voltage aging at 100 V/mil stress had no effect on mylar materials.

At the last review concern was expressed about the effects of corona generated products on the transformer materials. A test tube was developed in that corona could be produced and preliminary testing was run. If breakdown occurs all materials are effected by the arc products. If corona is normal at a value less than 100 PC in this small volume damage was minimal in only SF₆ but excessive with freon present, indicating a large test program is needed to provide complete confidence in the results.

3.7 PROTOTYPE (TASK 1270)

During this period the prototype #1 parts; cooling panels, leads, cylinders, were finished. The decision not to make the #1 thermal model, but to build a short circuit model (#8) caused a redesign, rearrangement of parts which are presently being wound into the coil of the test model. Considerable evaluation and investigation into flexibility and strength of the prototype panel header design was undertaken and is reported.

3.8 ACCESSORIES

Sensitivity analysis of the characteristics of the gas separator were made to determine operating characteristics under different loading and temperature conditions. It was determined that a variable voltage control on the cycled heater will take care of all conditions. The detailed analysis is included in this report.

3.9 COMMERCIALIZATION (TASK 3000)

We covered several aspects of Commercialization during this period. We presented similar papers describing the CGITransformer at the Pacific Coast Electrical Association Meeting in Los Angeles March 18th, at the Southeastern Electrical Exchange Meeting in New Orleans April 19th and at the American Power Conference in Chicago on April 18th.

We developed a customer survey questionnaire and refined it with the help of Dave McLean of Corporate Marketing Services. We then visited three customers: Alabama Power, Southern Services Co. and Houston Light and Power. Results indicated considerable interest by the customers in the transformer designs and where the survey questions could be improved.

3.10 SYSTEM STUDIES (TASK 4000)

Tom Jauch has studied the characteristics of the autotransformer we provided with the help of TNA experts and reports effects on system operation are less than the variation seen with different commercial offerings. A discussion is included in this report.

Section 4.0
PLANS AND SCHEDULES FOR THE 15th QTR
BEGINNING JULY 1983

1. Prototype #1 has been changed in design from a Thermal Prototype to a Short Circuit model. We are in the process of winding the coil. This is only a short circuit model so all the controls and thermocouples for a thermal test are not needed. The tank modifications are being made so that assembly can be achieved in September and test in SF₆ in Philadelphia will occur in October.
2. Prototype #2 parts are being made. The limiting cooling panels only need the replacements used from the short circuit prototype. It's design is still an interleaved design depending upon satisfactory development of a main gap design to be viable. A decision could be made late in September to build the dielectric prototype as an autotransformer without a main gap to investigate all the other possible problems.
3. The Thermal Design procedure will be documented in the next period.
4. Design studies will include parametric studies of a 500 MVA 500 KV GSU design.
5. Dielectric investigations will include designing, building and testing new designs of main gap and core shield models. Completion of high temperature dielectric tests at CRD at temperatures of 150°C for Mylar will be achieved shortly vs 100° and 125°C test are being included in this report.

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AGENDA
 COMPACT GAS-INSULATED TRANSFORMER PROJECT
 14TH QUARTER REVIEW PITTSFIELD, MASSACHUSETTS

AUGUST 10, 1983

8:30 A.M.	WELCOME	GE - DOE
8:45 A.M.	REVIEW PROGRAM	BILL RATHBUN
9:00 A.M.	PROJECT STATUS	BILL RATHBUN
9:45 A.M.	POST PHASE I PROPOSALS	
11:00 A.M.	REVIEW OF 13 TH QTR. CRITIQUE	BILL RATHBUN
12:00 NOON	LUNCH	
1:00 P.M.	DESIGN STUDIES	JOE SLOCIK
1:45 P.M.	DIELECTRIC STUDIES CLIVE REED HERMAN SCHNEIDER	BILL KENNEDY
3:20 P.M.	BREAK	
3:30 P.M.	SHORT CIRCUIT (MODEL 7 TEST)	JIM MCIVER
EVENING	TO BE ANNOUNCED	

AUGUST 11, 1983

8:30 A.M.	THERMAL STUDIES (MODEL #7 TESTS)	WERNER BACH STEVE FOSS
9:30 A.M.	MECHANICAL STUDIES	BILL RATHBUN
9:45 A.M.	MATERIALS	BILL FESSLER
10:00 A.M.	ORNL STUDIES	CHUCK BRINKMAN
10:30 A.M.	BREAK	
10:40 A.M.	ACCESSORIES	STEVE FOSS
12:00 NOON	LUNCH	
12:45 P.M.	CGIT SHOP TOUR	TEAM
2:10 P.M.	COMMERCIALIZATION	BILL RATHBUN JIM DELLEA
2:30 P.M.	SYSTEMS	TOM JAUCH
2:50 P.M.	BREAK	
3:00 P.M.	REVIEWERS CRITIQUE	REVIEWERS
4:00 P.M.	REVIEWER'S CRITIQUE W/TEAM	TEAM

CHART 0.1

PROGRAM SCHEDULE JULY 1983

\$691,895.-

SPENT TO DATE

\$468,102.-

TO GO

OAK RIDGE NATIONAL LABORATORY

OPERATED BY
UNION CARBIDE CORPORATION
NUCLEAR DIVISION

POST OFFICE BOX X
OAK RIDGE, TENNESSEE 37830

April 18, 1983

Mr. W. H. Rathbun
Manager, CGIT Program
Power Transformer Department
General Electric Company
100 Woodlawn Avenue
Pittsfield, MA 01201

413

Dear Bill:

CGIT Meeting
March 14-15, 1983
Palo Alto, California

The subject review meeting was well handled by the CGIT project team. The review committee, as usual, was very complimentary about the information presented and the professional manner in which it was presented. The quality of the research and development is excellent and reflects the technical expertise and dedication of the project members.

The project review committee still feels that review meetings should be scheduled for a minimum of one and one-half days. As you know the tentative dates for the next meeting are the 10th and 11th of August. We suggest the meeting be held in Oak Ridge or in Pittsfield.

There are a number of things about the project that need consideration based on the comments made in the project review meeting. These items are listed below.

1. Overload heat runs should be made on one of the prototypes in order to establish the short-time (30 min.) and long-time (4 hr) overload capability. Loading prior to the overload run should be at least 75% of rated load.
2. The effects of partial discharge in SF-6 should be examined to determine if the by-products of partial discharge have a damaging effect on materials of construction and what level of partial discharge should be of concern.

3. The Freon electrification problem continues to be an important concern. We feel GE should be doing more fundamental work to learn about Freon compatibility in the CGIT. The question of chlorine interaction with zinc or some other metals in the transformer should be explored. GE should also investigate the effect of the ac magnetic field on the Freon dielectric behavior.
4. Since the cooling panels are compressible, it is evident that Freon may be forced into the manifold header hose section during short circuit conditions. Specific studies are needed to establish that the hoses and support system will withstand the forces produced during a short circuit.
5. The review committee is still not convinced that air bubbles will not be trapped during the winding process. You should establish what size air bubbles will result in a significant dielectric problem in the transformer. Another alternative is to design the winding process so that only SF-6 can be trapped in the windings.
6. A Freon leak detection system is required to give an early indication of a coolant leak into the SF-6 environment. The device should be sensitive enough to detect a leak before the coolant contamination level reaches the danger point. The review committee does not feel that the installation of a cold finger is sufficient to serve as a warning device, although it may be satisfactory to trap small amounts of Freon.
7. The significance of Mylar sticking to the aluminum has not been established. Since local adhesion of the Mylar to the aluminum will probably occur, the short term and/or long term effects should be investigated. It appears that the difference in thermal expansion of the Mylar and aluminum when they are joined could produce adverse dielectric effects.
8. More design effort is required to minimize eddy currents in the winding. A suggestion was made to add slits at the edge of the winding in an effort to reduce the eddy currents. Has this suggestion been fully investigated?
9. The effect of Freon boiling on the dielectric strength should be investigated further.
10. The copper to aluminum weld should be subjected to thermal cycling tests to verify the design.
11. The committee feels that you should continue to investigate the design stress due to the effect of pin holes and flaws in the Mylar. This should help to establish the design stress criteria and define the safety margin.

There are several additional items which were mentioned in conjunction with the demonstration unit and they are listed below for your information.

1. It is obvious that the utility companies represented are in favor of proceeding with the development of the CGIT concept. It is apparent, however, that before proceeding to the post Phase I studies, the CGIT must be shown to compare favorably in total evaluated cost to the new high- efficiency conventional models.
2. Studies should continue through Phase I to develop methods of reducing cost. It is still apparent that a major contributor to the cost is the present design of the cooling system.
3. The demonstration unit should be provided with a no-load tap changer.
4. Edge contouring of the winding should be addressed for the demonstration unit.
5. The possible application of the CGIT as a generator transformer is recognized. Design efforts should include investigations into the applications for lower voltages and higher currents.
6. We realize that the preliminary studies showed that the present design of the CGIT was not suitable for use as a converter transformer. We would hope that you will continue to look at alternate designs for this application, even though there is some concern that the harmonics created during this application will create excessive losses.
7. The General Electric Company should continue to study the commercialization aspects of the transformer concept. The committee would like to see more positive indication from GE that they support the commercialization of the new design.

We should reiterate that if all the answers to the technical problems have not been fully addressed at the end of the present funding for the Phase I effort, the committee would propose a period of time, possible one year, to address the remaining issues before embarking on the design and construction of a demonstration unit. Those items which cannot be addressed and fully answered within the available funding level should be specified early in calendar year 1984.

This letter should not be construed to change the contract in scope, price, terms or conditions; only the DOE Contracting Officer is authorized to make such changes.

Sincerely,

Paul A. Gnadt

PAG:bks

LARGE TRANSFORMER

BUSINESS DIVISIC

POWER TRANSFORMER
DEPARTMENT

GENERAL ELECTRIC COMPANY, 100 WOODLAWN AVE., PITTSFIELD, MASS. 01201

413 494-2335

SUBJECT: COMMENTS ON THE 13th QTR. CRITIQUE

May 23, 1983

Mr. P. A. Gnadt
Union Carbide Corp.
Bldg. 9108 Mail Stop 2
PO Box Y
Oakridge, TN 37830

Dear Paul:

Thank you for your excellent summary critique of the 13th Quarterly Review. We recognize and accept the recommended date change you recorded, as requested by ESEERCO, and request the meeting be held in Pittsfield. We should have hardware available for review and will be able to incorporate more contributing individuals into the review program. I hesitate to push the start of our meeting before 10:00 am to allow arrival of New York, Syracuse and Albany people on the starting day. The local airline arrives here from LaGuardia at 9:30 am.

We are going to address those comments listed in your letter at the Review. The following comments indicate how we will proceed.

1. Overload Tests - We have been able to run a 141% load test on Model #7 and will report these results at the 14th Quarterly Review. We plan to run a 150% load test on the prototype over a 75% steady state condition as described. We recognize this procedure is from the new loading guides. We expect to present these results at the 15th Quarterly Review.
2. We will examine a few tubes with all materials present in SF₆ only with a corona source, along with the composite tubes suggested in the next paragraph where Freon is also included. We have found from literature search results that satisfactory field performance has been demonstrated by SF₆ devices with equivalent stress levels. Other search results will be presented at the review.

3. This is a Multifactored Comment.

- a. We will present summary reports of the compatibility tests made for freon and our materials for the two-phase cooled transformer. Tests we had deemed unnecessary to repeat.
- b. Corona generated chlorine will be considered along with the SF₆ data above.
- c. One would expect magnetic effects on current electron flow would be as described in literature for vacuum Electron tubes where an axial field would cause electrons to spiral and cross fields would turn the electrons into the adjacent tube walls as suggested by the right hand rule. The exception in our case is that the flow speed is so slow vs. the speed of electrons in metal that there is no effect. This aspect will be discussed at the Review.
- d. Magnetic effects on dielectric strength are felt to be nonexistent based on discussions with the many dielectric design engineers and scientists we've contacted. If a surprise is to happen it will occur on the prototype heat run next fall.

4. The Pressure Surges in the Panel Feed Pipes. We are making a strong effort to record the pressure surges that occur during the Model #7 short-circuit test. We will have the Freon cooling system connected and Freon flowing during these tests, with pressure transducers in the coolant pipes at the exit/entrance to several panels. The small system has all the critical components including a pressurizer which operates like our equalizer. These tests will be reported at the 14th Quarterly Review. We plan also to monitor these pressures during the short-circuit test of the prototype.

5. Air Bubbles Wound Into the Winding - There are several aspects of this concern that have been addressed by previous reports but published separately. We will pull them all together to put this concern to rest at the next review.

6. Freon leak detection is easy if one has means of sampling the insulating gas and transporting the sample to a laboratory. A laboratory that is equipped to detect amounts of chlorine atoms by gas chromatography, infrared spectrography, or X-ray defraction devices. As far as we know nobody has a device to separate chlorine and fluorine halogens in a field type of instrument. Literature and vendor searches will be made for devices of this type. A report of these findings will be included at the 14th Quarterly Review.

7. Significance of Mylar Sticking - An analysis that considers the expansion characteristics of the materials over the maximum temperature range indicates that the stresses would be sufficiently low to be well within the stress capability range of the materials and thus no ill effects from sticking would be encountered. Concern for thinning of the dielectric is being addressed by hot dielectric tests currently underway at CRD. Results will be presented at the next review.

8. Minimize Eddy Currents - Add slits to the winding. When I came aboard the project I inherited a pile of folded and slit paper models that had been generated by everybody on the team especially Andy. We studied these and other ideas, and concluded that there is no transposition or slitting technique that we had found that significantly reduced losses. Each folding technique drastically decreased space factor. It is a fact of life that since the flux is to be controlled as it will be in a sheet winding there will be edge eddy currents to cause this to happen. Interleaving windings reduces the flux MVA per winding and helps reduce the local eddy currents. We will review these efforts and effects at the 14th Quarterly Review.
9. The effect of Freon Boiling on Dielectric Strength. To accept the answer to this concern one must first understand our freon system and the positive effect of the pressure equalizer. This device causes the pressure in the Freon to be at the relatively high pressure of the SF₆ under all conditions. The dielectric strength of high pressure Freon vapor is as good as SF₆. We will review this and the back up dielectric data at the Quarterly Review.
10. Copper to Aluminum Weld-Thermal Cycled - We presented integrity tests and discussion on this joint in the 6th and 7th quarterly reports. We have recently reviewed the evaluation techniques with metallurgists at ORNL and GE, and will cover the report at the next review to allay this concern.
11. Pinhole and Flaw Stresses - As a result of the excellent presentation by Clive Reed on our pinhole question we need to wrap that up with the "safety" margin for the design stresses. This will put it into perspective at the next review.

Post Phase I

1. We recognize the negative effect the improvements to, and accuracy confirmation of the loss calculation techniques have had on our loss prediction levels. We are also proud of the strides made in reducing losses in conventional transformer designs in this short time period. More parametric design studies will be made to identify possible areas of loss improvement and these results will be presented at the next review.
2. Cost Reduction Ideas - We have already recognized several things that will improve with production; the panel manufacture, the cooler manufacture, "standard coolers" where sound is not specified, tank manufacturing costs, Mylar in quantity, manufacture of step blocks, box clamps are less expensive than T shaped (no fiberglass machining). We will hold "Idea Sessions" during this period with the results to be discussed at the next review.
3. During the discussion I thought it was suggested that the third prototype was to have a NLTC as well as the Demonstration Unit. Systems evaluation to date have suggested that NLTC is a requirement not a luxury for GSU's and autotransformers and this device must be included in most designs.

4. Thicknesses for the conductor for the proposed Demonstration Units are close enough to the prototype to say we would not need to contour the edges. Design studies for GSU's and other high current applications have suggested that the winding will consist of parallel sheets with size limiting leads so that edge contouring is not presently anticipated as necessary.
5. GSU lead and winding design will be discussed at the next review. In short, when leads are placed in a cross flux field, the lead size is limited and thus parallel winding sheets are attractive. Techniques and limitations will be discussed at the next review.
6. We do not believe Harmonics in Converter Transformers is a problem for the CGIT as the MVA at higher frequencies is low. The dielectric distribution of voltage controlled by the electrostatic field for AC and controlled by the resistive component for DC was the concern displayed at the last review. If the AC solutions to the main gap problem are successful as predicted, the DC distribution and techniques for improvement will be reviewed.
7. Commercialization by Customer Survey is to be presented at the next review.

We have been as responsive as possible to unanticipated and undefined surprises that have occurred during this project but are not able to spend much further effort on anything not directly included in the cost plan unless there are other funds identified for that purpose.

See you in August.

W. H. Rathbun
Manager-CGIT Project

ids/0145E

5.1 DESIGN STUDIES (TASK 1100)

PARAMETRIC DESIGN STUDIES (TASK 1110)

Parametric design studies were conducted on a 10-448 MVA-525000 GRY- 241500 GRY-34500 CGIT to determine the effect of conductor width and percent impedance on the total evaluated cost (TEC) of a transformer. Our computer design program (CDP) logic was based on eddy losses as calculated by the EDDY56 program. We made a series of design runs using the CDP results, then hand extrapolated them to an estimated KONRAD value. This proved to be a somewhat tedious and inaccurate process. We therefore made KONRAD runs of 17 designs and used these values in a regression analysis to give us new estimating logic for the CDP. The new logic was incorporated into the CDP and several hundred computer designs were generated to give the required information on TEC versus percent impedance (%IX) and conductor width. Chart 1.1 shows the series of curves that were generated from the mass of computer runs used to get TEC versus % IX. Each curve represents the TEC as a function of %IX while holding constant core size and 1000 amps./in² current density.

From this information we can generate the curves of Chart 1.2 which show TEC versus %IX for a 60" winding conductor width limit and no conductor width limit. Also we included the effect of an evaluation for lower impedance of \$18,000/%IX.

The plotted data revealed that for this particular CGIT rating, the optimum design (lowest TEC) with no winding conductor width limit was at approximately 4.3% impedance. With a 60" conductor width limit the optimum design shifted upwards to approximately 5.4%. Also the TEC comparing optimum designs showed an increase of approximately 6.3% when restricting the conductor width to 60". This shows the cost benefit of utilizing wider conductor sheets in the future.

If we take into account the BPA evaluation of \$18,000/% impedance lower than spec, the optimum impedance for a 60" conductor limit shifts from 5.4% to 4.4% while the no conductor width limit optimum impedance shifts from 4.3% to 3.6%. Meanwhile the TEC decreased 2.4% and 3.2% respectively.

We also wanted to pursue further the effect of conductor width on TEC for varied current densities. Chart 1.3 shows curves of TEC versus conductor width for a 7.8% IX design of this rating at 600, 800 and 1000 amps/in² current densities. The per unit TEC for this chart is on the same basis as the previous two charts. This study showed a TEC advantage when utilizing current densities lower than 1000 a/in² if the conductor width is not limited. However with the conductor width limited to 60", the TEC decreases slightly with 800 a/in² current density but increases when designing with 600 a/in².

We began a parametric study on a 1Ø -500 MVA-500000 GRY-22500 GSU. This size unit would be built on a two or four leg core. Initial design runs were made of a 250 MVA unit to come up with an optimum design to use for the 500 MVA unit. Chart 1.4 shows that the lowest TEC designs on a per unit basis were 1.0, 1.01, 1.07, and 1.13 for 400, 600, 800 and 1000 a/in² current density respectively. They yielded conductor widths of 140, 125, 118, and 112 in. respectively. If we are limited to 60" wide conductor, TEC increases 10% over the lowest TEC at a 140" wide conductor.

A conventional transformer and CGIT optimum design will be generated and cost compared during the next quarter.

PHYSICAL DESIGN STUDIES (TASK 1120)

Leads

The technique of ultrasonically welding a copper sheet to the copper Litz wire to replace brazing has been developed. Successful samples as shown in Chart 1.5 were produced in the Philadelphia Welding Lab and evaluated in our Materials Lab. The "sun burst" pattern had been designed to give good mechanical and electrical contact.

Once the weld was developed, we proceeded with determining the frequency of ultrasonic spot welds required to assure us that all strands will be welded to the copper sheet. On a 5" section of 25 strand (5 groups of 5 strands) flattened lead as shown in chart 1.6, we determined that a 1" weld spot spacing should yield sufficient contact to every strand.

Three full scale leads as shown in chart 1.7 were built for use in our full scale model, SC Coil #8. Electrostatic contouring material uncured conductive EPDM rubber, was applied to these leads using heat shrink tubing with an over-wrap of heat shrinkable Mylar tape in the application process. Four lead contouring test models were made and tested to determine the integrity of the EPDM contouring material. The test results are reported in the dielectrics section of this report.

We also made up a test sample using No Heat Shrink Conductive Tubing provided by Insulation Systems, Inc. No Heat Shrink Tubing utilizes a solvent expansion process of a previously extruded tubing. As the solvent is allowed to evaporate after the tubing is installed, it shrinks back to its original state. This lead model tested similar to the EPDM models however since we only had small sections to test, we ran into problems of testing in the joint regions. Again the test results are in the dielectrics section. We found that we were able to apply a small section of No Heat Shrink Tubing in the lead transition area as long as the copper sheet was not attached to the flattened Litz cable, chart 1.8. Once fully cured the material is easily shaped with a razor and sandpaper. From the tests performed on the lead contour test models, we theorize that a small joint or seam may not have a dramatic effect on the withstand KV. This would lead us to believe that we

may be able to apply the contouring in two pieces. The transition region could be contoured first before the copper sheet is ultrasonically welded to the Litz cable, with the remainder of the lead contoured after the winding is finished and ready for installation onto the core. We will be obtaining more No Heat Shrink Tubing and perform more tests. Our intent would be to get away from applying the uncured EPDM rubber which is a very tedious process and poses definite bending problems for manufacturing during the winding operation especially when considering large contour diameters.

CGIT DESIGN STUDIES

TEC VS IMPEDANCE

TEC VS CONDUCTOR WIDTH

LEAD ULTRASONIC WELDING

LEAD CONTOURING

CHART 1.0

% IMPEDANCE

5.1 - 6

CHART 1.2

ULTRASONIC SPOT WELD OF COPPER SHEET TO LITZ CABLE

3/8" DIAMETER U/S SPOTS ON 1" CENTERS

	SPOT NUMBER					
	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>
STRAND CONTACTED	E3	A5	C2	E1	A1	B3
	E4	B1	C3	E2	A2	C1
	E5	B2	C4	E3	A3	C2
	A1	B3	D1	E5	B3	C4
	A2	B4	D2	A2	B4	C5
	A3	C1	D4	A3	B5	D1
	A5	C3	D5	A4	C1	D2
	B3	C4	E2	A5	C2	D3
	B4	C5	E3			D4
	B5		E4

5 GROUPS (A, B, C, D, E) OF
5 STRANDS (1, 2, 3, 4, 5)

ULTRASONIC SPOT FREQUENCY DETERMINATION

CHART 1.6

FULL SCALE LEADS

CHART 1.7

NO HEAT SHRINK CONDUCTIVE CONTOURING

CHART 1.8

5.2 MECHANICAL DEVELOPMENT

The original concept of the gas insulated transformer was envisaged to provide the double wall (gas space) concept of sound reduction within the transformer. To accomplish this we expected to isolate the core from the tank using known vibration isolation techniques and then with the compressible gas would provide its adsorbing characteristic, the unit would be only as noisy as its equivalent double wall conventional unit.

Our experience has been one of frustration as in the first design of isolator the rubber was confined in such a way as to be ineffective. The transfer car used for the anechoic chamber has been modified over the years and presently has a laminated platform which in reality is quite soft when compared to tank dome stiffness. These two factors contributed to the level of the initial test.

Initial test of CGIT 1 ft. measurement.....63 dba

Sound pressure measured inside tank95 dba

Conventional Transformer calculated on its larger circle 66 dba

Since the center support was only mounted on the tank dome the rubbers were removed to effectively remove the support from the system.

Test of CGIT with Center Support Removed 1 ft. measurement ...65 dba

The question of whether the sound was being transmitted through the mounting or through the gas was answered by installing fiberglass bats inside the tank to adsorb the gas transmitted energy.

Test of CGIT with internal fiberglass bats 1 ft. measurement...65 dba

Internal sound pressure with internal fiberglass bats82 dba

At this time we built a set of pedestals (6" pipe) mounted on a 1" steel platform to evaluate the redesigned isolators. We found that the unevenness of the floor allowed the 1" plate to be quite soft nullifying the isolation of the rubber mounts. The pedestals were then removed from the large plate and each individually set in Porroc concrete on the floor. This provided stiffness to demonstrate better than 27 dba separation between the core mounting (lifting beams) and the mounting pedestals. Having demonstrated this we modified the bottom dome of the tank to provide direct in-line support as shown in Chart 2.3, from the isolator mounting; to the tank; to the pedestal to the floor. The unit was assembled in the anechoic chamber on a newly poured concrete between the rails. The unit was set on a thin layer of Porroc so that all the legs would provide equal positive support. The isolation between core and base was again checked with 30 db separation being demonstrated.

Sound level measured 1 ft. from the tank.....62 dba

Sound level inside.....103 dba

We added fiberglass sound bats to the internal structure and the levels reduced:

External sound with fiberglass bats.....59 dba

Internal sound with fiberglass bats88 dba

As a result of these tests we have concluded that separate mounting of the core to the ground must be achieved from the tank mounting. Sketches of possible inexpensive solutions are shown on Chart 2.4.

Analysis of the two tests would suggest that the addition of sound adsorbing material reduced the gas conducted sound to well below mounting conducted sound. If the mounting contribution to the 62 dba measurement was the 59 dba then the gas born sound was 58.4 dba. Thus the reduction achieved through the tank was $103 - 58.4 = 44$ dba. Separate mounting of the core and tank will achieve greater than 15 dba of mounting conducted sound energy, but a block of adsorber material in a flexible bag with filtered breathing capability is needed to control the internal sound build up so as to achieve the 15 dba or better reduction this design is capable of.

CHART 2.1

Prototype in Anechoic Chamber as prepared
for Sound Tests and Core Heat Run Tests.

CONVENTIONAL 50 MVA 345 KV Autotransformer

NEMA Sound prediction with coolers. 78 dba

NEMA Sound prediction on equivalent OA Rate 75 dba

CGIT

Initial Sound Test External Measurement 63 dba

Internal Measurement 95 dba

Removed Center Support Ext. 65 dba

Added Fiberglass Ext. 65 dba

Int. 82 dba

CHART 2.2

Core on Pedistals in Building 100.
Tests achieved 27dba Isolation.

CHART 2.3

5.2 - 6

CHART 2.4

CGIT Sound Test Results:

Modified Tank Bottom	Ext.	62 dba
	Int.	103 dba
Added Fiberglass Adsorbers	Ext.	59 dba
	Int.	88 dba

Tank Isolation for Airborne Sound is Approximately 44 dba.

CHART 2.5

Mounting Improvement Ideas

CHART 2.6

DIELECTRICS TECHNOLOGY DEVELOPMENT (TASK 1220)

Insulation development work for the CGIT can be grouped into four basic areas:

1. Winding Internal Insulation (Task 1221)
2. Coolant System Dielectrics (Task 1222)
3. Major Insulation (Task 1223)
4. HVDC Application (Task 1224)

These areas are illustrated in Chart 3.1 which presents a cross section of the gas insulated transformer. The overall schedule is presented in Chart 3.2.

During this quarter the following work items were accomplished:

1. Lead model coil tests were completed
2. Impulse breakdowns were performed at elevated temperatures
3. Main gap models were tested and analyzed
4. Core shield tests were performed
5. In response to questions raised at the Thirteenth Quarterly Review, our data and other literature was reviewed to determine the effect of air voids in the coil
6. Lead test fixture was built and testing was completed
7. Coolant system dielectric tests continued
8. The 345 KV Disk Bushing successfully passed all tests with margin.

Because of the emphasis placed on the main gap models this quarter no additional work was performed on HVDC applications. It is expected that a redesign of the main gap will be better suited to converter transformers than the initial design was.

WINDING INTERNAL INSULATION (TASK 1221)

Lead Model Studies: Concluding Measurements

In the Thirteenth Quarterly Report, results were presented for a proposed optimum construction for insulating the leads in a sheet winding. The optimum construction is comprised of three parts:

- o a solid wedge (to fill the gas wedge and give structural support to the overlaying layers)
- o additional Mylar films over the copper sheet in the area of the gas wedge
- o additional Mylar film over the entire lead structure

A schematic view of this construction is shown in Chart 3.3. By selectively adding or removing different parts of this construction it was shown that all three parts were essential to achieve the desired discharge and breakdown performance and that additional insulation at any one of the locations does not lead to further improvement. In the last quarterly report, partial discharge inception and extinction measurements were presented for a coil (lead coil #7) built with 6 specimens of this construction, using Textolite as the material for the solid wedges. The present report covers the concluding breakdown tests on these 6 specimens using different rates of voltage increase: 100 Vrms/day (2 specimens), 100 Vrms/hour (2 specimens), and 100 Vrms/day (2 specimens). The results presented below provide additional verification of the desirable electrical performance of this proposed lead insulation construction.

A detailed description of the construction of lead coil #7 was given in the previous quarterly report; all six models were insulated in identical manner and were mounted in pairs to produce a smoother contour for wrapping the two sheets of Mylar turn-to-turn insulation and the overlaying conductor. Tests were conducted in SF₆ gas at a pressure of 400 kPa following prior evacuation. In the previously-reported tests, partial discharge inception and extinction measurements were made using a Biddle discharge detector operating in the balanced mode. The procedure was that typically used for such measurements: the voltage was quickly raised to 500 Vrms and then increased in 100 V rms/1 min steps until discharge inception was registered and then, at the same rate, for an additional 1000 Vrms above inception; the voltage was then lowered at the same rate until the discharge extinction voltage was reached. This procedure was used for each of the six lead specimens in succession. Upon completion of all discharge measurements, breakdown tests were carried out on each specimen in turn. The rate of voltage increase was varied for each pair of lead models; for the first pair it was 100 Vrms/min, for the second pair 100 Vrms/hour, and for the final pair 100 Vrms/day. At the completion of all tests, the coil was removed from the pressure vessel and post mortems performed on each of the six lead models.

In Table 5.3-1 the previous discharge data and the new breakdown data are reported together.

Discussion and Conclusions

As can be seen in the data of Table 5.3-1, the proposed optimum lead insulation structure has continued to exhibit very good performance: the discharge inception and extinction and breakdown stresses are considerably above those of the proposed turn-to-turn insulation.

The purpose of the longer times of voltage application was to examine the possibility that more severe deterioration due to discharges or other degradative phenomena such as tracking might occur in the somewhat unusual structures around the insulating wedges or in the thin gas spaces adjacent to the wedge itself. To assess this possibility, in Chart 3.4 the breakdown data has been plotted as a function of time to breakdown. For reference, typical 50% data for the turn-to-turn insulation is shown. While it is recognized that the data presented is limited, the fairly linear relation between breakdown voltage and $\log(\text{time})$ is interpreted as indicative of two points: 1) that deterioration will occur at a linear rate if the lead structure is subjected to an over-voltage test and 2) that the proposed lead insulation structure is not prone to dramatic breakdown. This is considered as additional assurance for good performance by the proposed design. Post mortems on each of the models revealed no evidence for tracking or widespread discharge damage.

Regarding the choice of materials for the wedge, it was discussed at the last quarterly review that Textolite is not considered an optimum choice but that for the present tests it was used for demonstration purposes because of its ready availability and its machinability to the desired wedge shape. A preferred material would be one with as low a dielectric constant as possible (e.g. polypropylene) and one that will readily conform to the prevailing curvature of the winding (e.g. a silicone rubber).

Conclusions:

- o The final tests on the proposed optimum lead insulation structure have provided additional evidence for its very good 60 Hz discharge and breakdown performance.
- o The breakdown performance with different times of voltage application has not shown any indications of unusual discharge or tracking phenomena occurring in the SF₆ gas wedges around the lead. Thus the tests do not indicate potential problems in a full-size winding built with this construction.
- o The solid Textolite insulating wedges were used specifically for demonstration purposes. Preferred wedge materials include moldable polyester, polypropylene, or silicone rubber. The conforming qualities of a silicone rubber make it one of the more attractive candidates.

TABLE 5.3-1

DISCHARGE INCEPTION VOLTAGE (DIV), DISCHARGE
EXTINCTION VOLTAGE (DEV), AND BREAKDOWN VOLTAGE
FOR LEAD COIL #7 (SF₆ GAS PRESSURE = 40 kPa)

Lead	DIV (Vrms)	DEV (Vrms)	Breakdown (Vrms)	Rate of Rise for Breakdown
1	1630	(Noise)	6320	100 V/min
2	1819	1740	6430	"
3	1819	1860	4100	100 V/hr
4	1700	1760	4500	"
5	1800	1700	2700	100 V/day
6	1820	1790	3000	"

Reference: 2 x 0.92 mil Mylar turn-to-turn insulation
(50% values)

DIV (Vrms)

878

Breakdown (Vrms)

3400 (100 V/min)

Impulse Breakdown Studies at Elevated Temperatures

In previous work on the transient performance of the sheet winding construction, the two major findings have been: 1) low voltage transient analysis studies on an instrumented coil have shown that a sheet winding has an inherently (favorable) uniform internal electric stress distribution when subjected to transient voltages; 2) in tests conducted on model sheet windings at room temperature, the lightning impulse (1.5 x 50 microsecond) breakdown was very high and, unexpectedly, the (longer-rise-time) switching impulse (250 x 2500 microsecond) breakdown performance was even higher. The very favorable impulse breakdown performance was attributed to the excellent dielectric strength of the polymer film; the higher switching impulse breakdown (vs. lightning impulse breakdown) was attributed to space charge effects.

In a continuation of work on transient breakdown performance, breakdown measurements have been performed at 100 and 125°C as part of the experimental program to establish the upper operating temperature capability of a sheet winding construction incorporating Mylar film as the turn-to-turn insulation. These measurements have also permitted us to further evaluate the mechanism responsible for the higher breakdown that occurs with the longer-rise-time impulse waves.

Measurements have been made on the usual concentrically-wound 10-sample coils where individual capacitor samples were constructed with 2 sheets of 0.92 mil thick x 6.5 in wide Mylar film and 3 mil thick x 6 in wide electrical grade aluminum conductor. Other details of design and winding methods have been given in previous quarterly reports; in particular, the usual stringent precautions to remove and exclude particles during winding were observed. Tests were conducted at an SF₆ gas pressure of 400 kPa after evacuation of the pressure vessel to 30 um.

Based on prior experience, it was decided to conduct both lightning (1.5 x 50 microsecond) and switching (250 x 2500 microsecond) measurements on a single coil, selecting 5 capacitor specimens for tests with one waveform and 5 specimens for tests with the other waveform. By doing this, we are able to obtain results for the two waveforms on specimens that are constructed and prepared for testing (evacuation+impregnation with SF₆ gas+temperature equilibration) in an identical manner. From prior experience, we know that, as a result of the cushioning action of the intervening pad of Mylar film between specimens, transient breakdown in individual capacitor specimens does not adversely affect adjacent samples. Hence this procedure is considered as quite legitimate, and tests with the two different waveforms should have no affect upon one another. (Post mortems carried out following the tests presented below have verified this to be the case.)

In the first 10-sample coil tested at 100°C it was, however, found to be impossible to achieve the desired lightning impulse (1.5 x 50 microsecond) waveshape with the 0.25 uF capacitor specimens. In previous tests with such capacitance specimens there was no problem, but with the additional inductance of the leads from the generator to the test oven, attempts to adjust the test circuitry to obtain a clean 1.5 x 50 μs waveshape were unsuccessful. As a consequence, tests were conducted with the closest clean waveshape, a 5 x 50 microsecond impulse wave; the switching impulse waveshape (250 x 2500 microsecond) did not present a problem.

Testing was started with impulses of around 5 kV peak, (i.e., around 50% of the impulse strength previously measured at room temperature) and voltage was increased in roughly 10% increments (~ 500V). Three separate negative impulses were applied at each level, followed by three separate positive impulses, before proceeding to the next level. The criteria for determining breakdown voltage were 1) the specimen should have survived at least four shots at that voltage (i.e., 3 negative and 1 positive) before breakdown occurred -- if not, breakdown was considered to have occurred at the previous, lower voltage level --, and 2) that breakdown be quoted as the prospective crest value determined from the impulse waves survived. In each case, breakdown occurred on the front of the wave, mainly near the crest but sometimes on the rising portion of the wave; in no instance did breakdown occur on the tail, as can happen in an oil-paper system. Following the completion of the tests with 5 x 50 microsecond waves on the innermost 5 specimens, tests were conducted using a 250 x 2500 microsecond waveshape on the outermost 5 specimens. Results are plotted in Chart 3.5 in comparison with prior data at room temperature. We

note that the 100°C results for the two rise times are very close to one another; they appear to fall a little below the previous room temperature lightning impulse breakdown data and distinctly below the prior room temperature switching surge data.

To achieve a waveshape more representative of a lightning impulse, an additional coil was built with several different, lower capacitance specimens. A comparison of the shapes achievable for each of the different capacitors showed that 0.025 uF (i.e., roughly 1/10 the capacitance normally tested) gave the desired (1.5 x 50 microsecond) waveshape (Chart 3.6). Consequently a number of coils have been built with this capacitance for testing.

To-date results have been obtained at 100 and 125°C on two separate 10-sample coils with 0.025 uF capacitance specimens. In each coil, 5 samples were tested with the shorter (1.5 microsecond) and 5 with the longer (250 microsecond) rise time. Tests were again conducted at an SF₆ gas pressure of 400 kPa, using the same test procedure (starting with 5 kV peak waves) and the same criteria for assessing breakdown. Results are plotted in Chart 3.7 in comparison with the results obtained at 100°C with the 0.25 uF specimens.

Discussion and Conclusions

In the preliminary measurements at 100°C (Chart 3.5) it is apparent that the two waveshapes, with rise times varying by a factor of 50, show essentially the same breakdown behavior; no longer do we see the much higher breakdown with longer rise time found previously at room temperature. A preliminary interpretation of this change is that space charge effects are losing their effectiveness in inhibiting electron injection that is the precursor for breakdown.

In the second set of tests at 100°C (Chart 3.6) we again note that breakdown is essentially the same for the two rise times; in this case the lightning impulse has a slightly shorter rise time (1.5 microsecond). However, a striking difference between the two sets of data at 100°C is noted: the magnitude of the breakdown is markedly higher for the smaller capacitance specimens (test area - 1/10 that of higher capacitance). Hence, since it is our view that breakdown is triggered by very small, chance particles wound into the winding, the differences in breakdown are provisionally ascribed to an area effect, resulting in a greater chance for adventitious particles to occur in the winding with larger area. Roughly, we note that the better samples (highest breakdown) with the higher capacitance specimens have similar breakdown to the poorer samples (lowest breakdown) with the smaller capacitance. Our view that particles are the triggering force for breakdown in these measurements is considered to be supported by 1) the steeper distribution of breakdown values found at 100°C compared to room temperature -- previous measurements with deliberately-added particles have shown a similar, steeper distribution -- and 2) the post mortem finding that the majority of the breakdowns are internal.

In the measurements at 125°C we note that breakdowns for the two waveshapes are again very similar and that the values are somewhat higher than at 100°C. (Unfortunately, three of the lightning impulse specimens were broken down in preliminary testing to get the correct waveshape; while we do not have breakdown values for these samples obtained by the correct testing protocol they were in the same range as the two good measurements.) This result is significant in terms of the possible operation of the Mylar-insulated sheet winding at 125°C during overload situations. In future tests, measurements will be extended to 150°C in order to help to establish the upper temperature capability of the winding when subjected to transient voltages.

Conclusions:

- o Lightning and switching impulse breakdown of the Mylar-insulated sheet winding are very comparable to one another at both 100 and 125°C. Breakdown is a little higher at 125°C.
- o Transient breakdown measurements carried out at 100°C using samples varying in area by a factor of 10 show a substantial area effect.
- o The distribution of breakdowns for measurements at 100° and 125°C suggest that particles are the dominating factor in breakdown.

Edge Finish of Conductor

In the previous quarter, preliminary work was begun on the effect upon 60 Hz performance of using a contour finish to the aluminum conductor vs. a precision slit finish as used in all previous six inch model tests. Results were presented in the last quarterly report for separate coils built with "contour-polished" and precision slit aluminum: very little difference was observed in either discharge or breakdown performance. However, optical examination of the two conductor edges revealed that there was very little difference in the shape of the two edges, thus it was concluded that the results can be considered to be as expected.

Since contour polishing did not achieve the desired hemispherical edge to the conductor, which would be expected to produce an improvement in discharge inception performance, both 10 and 20 mil thick aluminum was submitted to Gibbs Wire and Steel Inc. (Gibbs) of Southington, Connecticut, in an effort to see if they could provide hemispherical (#1 rounded) edges, as claimed. For reference, we also asked Gibbs to provide precision slit 10 and 20 mil aluminum. In Chart 3.8 cross-sections of the edges of Gibbs #1 rounded and Gibbs precision slit 20 mil thick aluminum are shown. The features of note are the contours of the edges; the markings on the aluminum come from the cutting and polishing process and should be ignored.

End-on scans of the rolls of #1 rounded and precision slit aluminum from Gibbs revealed a high degree of uniformity for both the 10 and 20 mil thick material, indicating that the quality seen in Chart 3.8 can be obtained with consistency.

Clearly, the rounded material achieved by Gibbs in this case has a superior finish to the contour polished aluminum shown in the previous quarterly report (Chart 3.5).

At this time it is not planned to do further evaluation of conductor edge finish. Precision slit material has provided very satisfactory performance in the many six inch size that coils evaluated during the past three years and, providing the precision slitting of the thicker conductors is performed in as clean a manner as indicated in Chart 3.8, problems are not anticipated. At some point, however, hemispherical rounding or even contour polishing could be reconsidered as in situ methods during coil fabrication to provide additional insurance against imperfect edges or chance slivers arising from the slitting process.

Main Gap Models

The basic design of the main gap models has been described in previous reports. It consists of two coils, each with radial builds of 0.5", separated by a 0.2" gap. Extra turns of aluminum were wound over the outer winding to insure a snug fit for the 9" diameter high voltage shield. Each coil uses 0.004" x 5.0" aluminum conductor interwound with (2) 0.001" x 6.0" Mylar sheets. The coils were wound on 6" fiberglass cylinders. Samples were assembled as shown in Chart 3.9. Electrical connections were accomplished with .004 x .250 aluminum strips between the first turn of the inner winding through a hole in the center of the cylinder to the bottom metallic clamp, with a second strip from the metallic ground shield to the bottom clamp. A third strip from the aluminum conductor of the outer winding was passed through a hole at the center of the outer shield and attached to its out- side surface using conductive epoxy.

Three basic types of models were constructed. The control group had 90° edges on the windings at the main gap. Another group had tapered edges at the gap formed by cutting a rectangular slit in the center of each conductor which extended five turns from the gap into the winding. The top and bottom of the conductor were then bent slightly so that they touched at the end of the coil. Two tapers were built: .030" x .060" and .030" x .250". The third group of samples used the 90° edge on the coils but included a series of eleven equalizers in the main gap to reduce the stress off the winding edges. Two types of construction were also used for these samples. On one type the equalizers were formed from Steinerfilm (aluminum vapor-deposited on Mylar) while the other type used separate equalizers made from .004" aluminum conductor. One additional sample was made with two miniring shields on either side of a 1.2" Mylar pad. While not a true main gap sample, this test piece was used to examine the corona behavior of the test fixture itself. The different main gap constructions are illustrated in Chart 3.10.

Most samples were tested four at a time in the fixture used for the insulation/pressure tests and the end ring/setback models. Two 90° edge samples were used for each run, initially with two tapered gap coils and later with two equalizer samples. For every test a vacuum of about 180 microns was held for a minimum of 24 hours, which was followed by at least 24 hours of SF₆ impregnation at 45 psig. Test results are summarized in Chart 3.11.

Main gap samples 13 and 14 were not taken to breakdown but were held at fairly high levels of partial discharge for several hours. The purpose of this test was to determine if the source of the corona was the same as the breakdown. The aluminum equalizer sample (coil 14) was held at 35 KV for one hour and achieved a partial discharge level of 50 - 100 pc, while the Steinerfilm sample (coil 15) was subjected to 45 KV for 1.5 hours with discharges between 600 and 800 pc. No damage was found on either sample when post mortems were performed on the coils which indicated that higher levels of partial discharge are necessary to cause tracking on the Mylar.

Analysis of the performance of the main gap models is summarized in Chart 3.12. In part (a) the maximum local stresses at an arbitrary potential of 100 KV are compared for the proposed gap of the prototype transformer and the main gap model. It is interesting to note that the performance with the equalizers should be quite similar to that of the .030 x .060 taper in the main gap model, but that the equalizers are less effective in the actual prototype.

Part (b) of the chart gives the mean voltages for corona inception and breakdown for the samples. The tests show good improvement in corona inception voltage for the .030 x .060 tapered sample, followed by the Steinerfilm gap coils. Breakdown levels are approximately the same for the 90° edge coils and the bevel samples, with the equalizer coils roughly 20% higher.

The final section of the chart presents the stresses for the different samples at corona inception and breakdown. With the exception of the aluminum equalizer coils there is good agreement between the samples at corona inception. The low stresses exhibited by the aluminum equalizer sample was due to the very poor alignment of the equalizers in the gap. When one of the coils was vacuum potted in epoxy and sectioned, the equalizers were found to be randomly displaced up to .125" in the gap.

Although the tapered coil edge and equalized main gap designs do offer improvement in dielectric performance as compared to the 90° edge, they do not appear to provide sufficient margin over test and operating voltages. Chart 3.13 shows the expected peak ac corona inception and breakdown voltages for the prototype gap based on the results of the main gap models. Several other concepts are presently under study including more equalizers in the gap and potted shields. These alternatives will be reviewed for manufacturability and additional main gap samples will be constructed and tested.

Main Gap Models - Conclusions

- 1) Experimental results agree well with performance calculated with field program
- 2) Main gap taper and equalizer placement critical to design
- 3) Additional work required to develop practical main gap design

Core Shield Models

The purpose of these tests is to establish a design for the ground shield adjacent to the core cylinder for the CGIT. Three designs have been built and tested; they are illustrated in Chart 3.14. All samples were wound on 6" OD x 8" long fiberglass cylinders with .25" walls. On the two initial designs the core shield was bonded to the inside of the cylinder. The first four models included a simulated neutral end of a winding using the same .030 x .060 taper as several of the main gap models. The radial build of the winding was 0.45", and was made with 75 turns of 4" x .004" aluminum and (2) sheets of 5" x .001" Mylar. Twenty turns of conductor were wound over the coil; these turns were removed as necessary to fit the outer shield. For the second and third series of coils the simulated winding was removed and a miniring shield was added over the Mylar pad. On the third group the shield was moved to the outside of the cylinder.

The samples were tested in the same fixture as used for the main gap samples. The first two designs had four samples each built and tested, while two samples were tested from the third group. All samples were subjected to a minimum of 24 hours vacuum followed by an additional 24 hours of impregnation by SF₆.

Test results are summarized in Chart 3.15. All breakdowns went from the beginning of the winding along the surface of the cylinder to the clamping plate. Note the low corona inception voltage of the initial models. Because these tests were performed before the tapered main gap models it was thought that the corona may have originated at the taper. When the data from the main gap models was later analyzed and compared to field plots for the core shield samples the stresses in the latter were found to be about half that required for corona inception.

The breakdown performance of the second group of samples (without the simulated winding) was improved. Samples 5-7 failed from the sharp edge of the filler foil under the outer shield to the clamping plate. Sample 8 contained no filler foil and failed from the miniring to the clamping plate at a slightly higher voltage. The corona inception voltage was still lower than expected. When examined under a microscope the winding cylinders were found to have many voids wound in them in the 4-10 mil size range. These are at the minimum of the Paschen curve and are the probable source of corona. Tracking was found between trails of bubbles in the cylinder, and several voids were totally blackened.

Because of these voids it was found that placing the shield under the cylinder was impractical. Consequently, the last two models had the shield on the outside. Because of concern about the gas wedge formed at the start of the miniring shield, on sample 16 this area was filled with a stepped assembly of Mylar covered with a sheet of Steinerfilm butted up against the aluminum shield. These test pieces were similar to those used for the insulation/pressure study except that the original pieces used a continuous sheet of aluminum for the ground plane covered with (2) 1 mil sheets of Mylar. The performance

of the core shield models was considerably poorer than the insulation/pressure models. Corona inception averaged 10 KV and 70 KV, respectively, while breakdowns were 100 KV vs. 140 KV. Only one of the core shield models (#16) was tested to breakdown, the other was held at 90 KV for 2 hours (#17). Discharge activity for #17 was in the 1000-2000 pC range with spits to 5000. A post mortem of the coil showed considerable tracking on the Mylar around the outer miniring, with only one burned spot on the core shield. Coil #16 exhibited multiple breakdowns across the gap and the Steinerfilm at the end of the shield was vaporized (Chart 3.16).

In comparing last group of core shield models with the insulation/pressure tests, it would appear that the poor performance of the core shield tests is caused either by the bare aluminum used in the shield or by the gaps between the ribs. Two additional models are being wound using insulation over the shield; they will be discussed in the next report.

Core Shield Models - Conclusions

- 1) Because of voids in the fiberglass the core shield must be placed on the outside of the cylinder
- 2) Bare metal on the shield must be covered with either Mylar or epoxy as insulation

Air Voids in Winding

At the last several reviews concern has been expressed regarding the behavior of small air voids which might be created in the coil during the winding process. Information relating to this situation has been reported throughout this project; the purpose of this analysis is to summarize the available data in one location.

In order to insure that the dielectric performance of coils wound on the small winding machine would be satisfactory, ten single sample coils were built and tested in air shortly after the machine was completed. These results were originally presented in the report "Evaluation of Advanced Technologies for Power Transformers - Final Report Part 2." The primary objective was to examine the ability of the winding machine to exclude particles from the coil, and it was performed in air as a quick test to avoid the vacuum and SF₆ impregnation procedures usually applied. (Five of these coils were subsequently tested in SF₆ at 6 atm to investigate any deterioration of the coils which might have occurred during the tests in air - no evidence of a reduction in strength was found.) The coils were similar to those used by CR&D prior to their multiple sample coils. Specifications are given on Chart 3.17.

The coils were tested by applying a 100 Vrms/1 minute slowly rising voltage up to 3000 Vrms, then reducing the voltage at the same rate back to zero. The discharge inception voltage is the initial value measured; the discharge extinction voltage is the value measured after the sample had withstood the 3000V rms level. Results are shown in Chart 3.18.

As reported in the earlier paper, significant conclusions of these tests included:

- . The high value of withstand voltage achieved by eight of the ten samples and the high breakdown values of the two that failed, provide an indication that the coils are of high quality.
- . Despite the fact that high levels of discharges (2000 - 6000 pC) had been sustained, the measured discharge extinction voltages showed little difference from the original discharge inception voltages. This indicates that little change (improvement or degradation) has occurred insofar as the origination of discharges is concerned; such behavior when noted in other experiments will be referred to as "a lack of conditioning."

The most important result of the test for this report is the fact that the corona inception for all coils is well above the operating turn to turn voltage of the prototype (120 v/turn - 60 v/mil) and its induced test voltage.

In Quarterly Reports 11 and 12 results were presented for Paschen curve measurements in SF₆ gas 1) between hemispherical metal electrodes at the small gap sizes encountered in the turn to turn insulation and around leads of the transformer sheet winding and 2) in similar small gaps between Mylar film surfaces where the gaps were produced by deliberately punching 40 mil holes in a sheet of Mylar film. In the 13th Quarterly Report these results were extended to measure the discharge inception voltage in 40 mil size voids and fine "pinholes", both in atmospheric air and in SF₆ gas over the pressure range 100 - 400 kPa. These tests showed that the classical Paschen curves for air and SF₆ can be applied to the geometry used in the CGIT. (Chart 3.19).

Also in the 13th Quarterly Report, peak breakdown voltage at 4 atm was tabulated for 11 gas gap sizes between .1 and 2.0 mils. For a parallel plate electrode system the total voltage across the electrodes is given by a simplified version of the equation presented in the Twelfth Quarterly Report:

$$V_{tot} = \frac{V_g}{t_g} \times \left(\frac{\epsilon_g t_m}{\epsilon_m} + t_g \right) \quad (1)$$

where

V_{tot}	=	applied voltage
V_g	=	voltage across gas gap
t_g	=	thickness of gas gap (mils)
t_m	=	thickness of Mylar insulation (mils)
ϵ_g	=	dielectric constant of SF ₆ = 1
ϵ_m	=	dielectric constant of Mylar = 3.2

In a gas-Mylar system, partial discharges will begin when the gas gap breaks down. Using equation 1, the corona starting voltage was calculated for several different Mylar thicknesses up to 4 mils. With no Mylar, the data follow the classical Paschen curve. With insulation added a minimum voltage occurs at a gas gap between .5 and .9 mils. This critical gas gap increases with Mylar thickness.

The same analysis can be performed for air and SF₆ at different pressures. Chart 3.20 gives the corona inception voltage as a function of gas gap for parallel plate electrodes with 2 mils of Mylar insulation at 1 and 4 atm pressure. The calculated minimum corona inception for air at 1 atm of 730 peak volts (516 volts rms) is in excellent agreement with the 521 Vrms obtained in the tests. (Chart 3.18.)

When the coil is pressurized it would be expected that the pressure within any voids would increase above 1 atm. According to the Paschen curve this would raise the corona inception voltage above the experimental values recorded in Chart 3.18. An estimate of the pressure within a void can be obtained from the impregnation tests described in the First Annual Report. These coils had a single 40 mil hole punched out of one of the two sheets of Mylar film used for turn insulation. The hole was located 27.6" from the start of the conductor at the center of the sheet. Two single sample and one ten sample coil were tested; the ten sample coil contained 6 samples with voids and 4 without.

In each single coil, the pressure vessel was evacuated to around 30 um, at which point it was pressurized with SF₆ gas to 6 atm and discharge inception measurements were begun immediately. The sixty-hertz test voltage was increased in steps of 100 volts (1 minute) up to discharge inception and a further 500 volts above inception (to establish that the discharges were persisting); then the voltage was decreased in 100-volt steps until discharge extinction was reached and recorded. As a check on the measurements, a repeat of the above procedure was made after the coil had been at 0 volt for 5 minutes. The above procedure was then followed as a function of time. The resulting discharge function inception and extinction measurements are plotted in Chart 3.21. The sensitivity of the discharge measurements was 1-2 pC.

The data plotted in Chart 3.21 shows a steady increase in discharge inception and extinction voltages over a period of roughly 80 hours and a subsequent very slow increase through 170 hours. After 173 hours, the sample was tested to breakdown by increasing the voltage in 1 minute, 100-volt steps. Breakdown occurred at 3270 volts. A post-mortem revealed that breakdown had occurred in the deliberately-added hole.

Chart 3.22 tabulates the theoretical corona inception voltage for 1 mil Mylar and 1 mil gas for air and SF₆ at 1 and 6 atm. The actual corona inception at 0 hours of 560 Vrms is greater than the calculated value for air at 1 atm indicating higher pressure in the void. In fact, an applied voltage of 560 Vrms across the gap would give 428 Vrms across the void, or 605 Vpeak. From the Paschen curve for air, this corresponds to a spacing pressure product of 0.045 bar mm, or a pressure of approximately 1.8 atm.

Lead Tests

The lead tests are performed using a modification of the fixture designed for the divergent field tests and described in the First Annual Report. In this experiment the coated leads were wrapped around a 20" diameter disk which was machined with a groove around the edge to hold the lead.

This was positioned perpendicular to a 25" diameter ground plane with radiused edge as illustrated in Chart 3.23. The disk could be rotated from outside the test vessel so that several segments of the disk can be tested on each filling of the test vessel. Also, the ground plane was mounted on a rack and pinion so that the spacing between the plane and disk could be changed from outside the tank. A geared drive system with minimal backlash was used so that a pointer and scale outside the tank could be used to set the spacing accurately.

Four sets of coated cable have been tested, three with EPDM conductive rubber around the copper cable and one using a "no heat shrink" tubing. Results are presented in Chart 3.24, which show the cable to perform similarly to the 1" bare diameter electrode from the earlier tests. The results from sample 3 are subject to further study as many of the breakdowns involved joints between the sleeving. This indicates that the EPDM rubber does indeed act as a conductor, and the material should be more than adequate for use in the CGIT.

COOLANT SYSTEM DIELECTRICS (TASK 1222.1)

During this period, dielectric tests on the insulating pipes for the coolant system were performed on Teflon tubing that did not contain carbon. Results presented in the last quarterly report indicated that the breakdown voltage of carbon-loaded Teflon pipe was affected either by contamination, the crystal structure resulting from the cooling process in the manufacture of the pipe, or the carbon contained in the material. For isolating this effect, the same type of Teflon pipe was obtained without the carbon loading. To reduce testing time tests were performed with SF_6 on both the outside and inside of the tubes using lightning impulses, switching impulses, and 60 Hz voltages. With 15 cm length test samples, the standard length used in these tests, no breakdowns which involved the coolant pipe samples occurred and the test voltages were limited by external flashovers of the test setup. The tests were then repeated with SF_6 on the outside and flowing Freon on the inside of the tubes. The Freon contained sufficient Mobil DCA 48 additive to produce a conductivity of about 10^{-10} mho cm^{-1} . Again, breakdown involving the test samples did not occur as is shown in Chart 3.25. All tests were performed with SF_6 at 45 psig, and when Freon was used inside the tubes, the pressure was 45 psig, the temperature 25°C , and the flow rate 5 gallons per minute corresponding to a velocity of 3.6 ft/sec.

To obtain breakdown data on this coolant pipe material, the length of the test samples was shortened from 15 to 10 cm. The sequence of tests performed with the carbon free Teflon tubing was as follows:

1. No tubing present - for obtaining shield/shield strength in SF_6 .
2. 10 cm sample tubes - SF_6 inside and outside.
3. 10 cm sample tubes - SF_6 on the outside of the tube and flowing Freon on the inside.
4. 10 cm sample tubes - SF_6 on the outside of the tubes and Freon vapor on the inside of the tubes (to address the question of dielectric strength when fluid level is down).

Details of the test parameters and the test results are given in Chart 3.27 and a comparison between tests with Freon liquid and Freon vapor inside the test samples is shown in Chart 3.26.

In tests made on the carbon-free Teflon tubes, breakdowns across the samples at the higher voltages produced more damage to the material than was found on the carbon-loaded Teflon tubes. In one test with a negative impulse of 955 kV (across a 10 cm tube), the damage penetrated the material and resulted in the mixing of the SF_6 and the Freon.

Some testing also has been performed on other types and shapes of pipes with a 10 cm length. These include Tefzel (one type of material used at the EPRI/Con Ed/GE Astoria HVDC Project) and corrugated flexible Teflon.

The commercially available Tefzel tubing has a smaller diameter than the Teflon, with a 1/2 inch O.D. and 3/8 inch I.D. Tests were made with SF₆ at 45 psig on the outside of the tubes and flowing Freon on the inside. The temperature was 25°C, the pressure 45 psig, and the flow rate 5 gpm. Since this tubing had a smaller diameter, the velocity through the tubes was about 14.5 ft. sec. The additive Mobil DCA 48 was used for all tests in concentrations to achieve conductivities of approximately 10^{-10} mho-cm⁻¹. Again, the tube samples withstood the full test voltages as limited by external flashovers of the test setup.

In the absence of breakdowns on the Tefzel tubes, it was decided to make tests which would purposely cause breakdowns along the pipe to assess the damage produced. This type of test was accomplished by adding metal sleeves at each end of the test sample to increase the voltage gradient across the sample in two ways: length was decreased slightly and the shield effectiveness was reduced. These tests were made with SF₆ on the outside of the tubes and flowing Freon on the inside under the same conditions as the first test with Tefzel. Negative lightning impulse voltages were used for the test and breakdowns did occur at different voltage levels depending on the length of the sleeves that were added. The highest breakdown voltage was 881 kV and, like the other breakdowns across the Tefzel, the only damage was a discoloration giving the surface a smokey appearance along the path of the breakdown. This occurred on the outside of the tube in SF₆ and there were no other marks on the tubes.

A corrugated Teflon tube similar in size to the original Teflon samples was tested with SF₆ both inside and outside of the tube for lengths of 15 and 10 cm. There were no breakdowns across this sample. This material has the advantage of being flexible and thus would not require pre-forming.

The next series of tests will be made with SF₆ on the outside and flowing Freon on the inside of the corrugated tubes. If breakdowns do not occur across the test sample, then a series of damage tests with the added sleeves will be performed to investigate the effects of breakdowns on the corrugated tube material.

GAS DIELECTRIC TECHNOLOGY

CHART 3.1

DIELECTRICS DEVELOPMENT

SCHEDULE

	1983												1984	
	J	F	M	A	M	J	J	A	S	O	N	D	J	F
MAIN GAP MODELS	XXX	XXX	XXX	XXX			XXX	XXX	XXX	XXX	XXX			
LEAD MODELS				XXX	XXX	XXX								
PASCHEN CURVE TESTS	XXX	XXX	XXX	XXX										
CONDUCTOR EDGE STUDY					XXX	XXX								
COOLANT PIPE STUDY		XXX	XXX	XXX	XXX	XXX		XXX						
LTC DESIGN										XXX	XXX			
DC STUDIES		XXX							XXX	XXX				

CHART 3.2

- A 1 SHEET 2.0 MIL MYLAR
- B TEXTOLITE WEDGE
- C LEAD
- D 0.25 MIL MYLAR
- E 0.5 MIL MYLAR
- F 0.25 MIL MYLAR
- G COPPER SHEET

3.3 Schematic Cross-Section of Proposed Optimum Lead Insulation Structure.

3.4 Plot of Breakdown Voltage in Excess of Partial Discharge Inception Voltage as a Function of Time to Breakdown for Proposed Optimum Lead Insulation Structures.

3.5 Preliminary Measurements of Lightning and Switching Impulse Breakdown of Turn-to-Turn Insulation at 100°C.

3.6 Lightning Impulse Waveshape Used in Tests on
0.025 μ F Turn-to-Turn Insulation Models.
Time Scale = 2 μ s/cm

CHART 3.6

3.7 Measurements of Lightning and Switching Impulse Breakdown of Turn-to-Turn Insulation at 100 and 125°C. Measurements at 100°C made for Two Different Test Areas.

3.8 Profiles of Edges of a) Precision Slit and
b) Contoured (#1 Rounded) 20 mil thick Aluminum.
Slitting and Contouring Performed by Gibbs Wire
and Steel Inc.

1221.5B
MAIN GAP MODELS

MAIN GAP MODEL - DETAIL OF WDG. EDGE
CHART 2 10

MAIN GAP MODELS
TEST RESULTS

TYPE OF SAMPLE	SAMPLE NO.	CORONA INCEPTION KV RMS	BREAKDOWN KV RMS
90° EDGE	95	8	60
	96	12	62
	99	12	60
	100	6	65
	101	8	60
	11	15	70
	12	15	70
030 X 060 TAPER	1	18	68
030 X 250 TAPER	2	15	67
	3	14	65
STEINERFILM EQUALIZER	9	15	80
	14		CORONA SAMPLE
ALUMINUM EQUALIZER	10	10	80
	13		CORONA SAMPLE
ALL MYLAR SAMPLE	15	35	CORONA SAMPLE

CHART 3.11

ANALYSIS OF MAIN GAP

A) STRESSES PROTOTYPE AND MODEL @ 100 KV

	90°	EDGE	030x250 TAPER		030x060 TAPER		STEINERFILM		ALUMINUM	
	MYLAR	SF ₆	MYLAR	SF ₆	MYLAR	SF ₆	EQUALIZER	MYLAR	SF ₆	
							MYLAR	SF ₆		
PROTOTYPE	1192	395	--	--	95.8	87.6	167	139	--	--
MODEL	5490	4260	4385	3400	31130	2740	3770	2940	2790	2540

B) CORONA INCEPTION AND BREAKDOWN VOLTAGES OF MODELS

CORONA INCEPTION	15.4	20.5	25.5	21.2	14.
BREAKDOWN	90.4	93.3	96.2	113	113

C) CORONA INCEPTION AND BREAKDOWN STRESS OF MODELS

CORONA INCEPTION	856	656	899	698	875	699	798	623	390	350
BREAKDOWN	1960	3850	4090	3170	3300	2630	4265	3330	3160	2840

- NOTE: 1) ALL VOLTAGES ARE PEAK AC
 2) ALL STRESSES ARE PEAK V/MIL

CHART 3.12

EXPECTED PERFORMANCE OF
PROTOTYPE MAIN GAP (PEAK AC VOLTAGE)

	90° EDGE	030 X 060 TAPER	STEINERFILM EQUALIZERS
CORONA INCEPTION	170	790	445
BREAKDOWN	995	2982	2373

ACTUAL TEST VOLTAGES

IMPULSE: 1050 BIL

1 MINUTE 60 HZ: $460 \times \sqrt{2} = 650 \text{ KV PEAK}$

CHART 3.13

a) INNER SHIELD WITH SIMULATED WINDING

b) INNER SHIELD WITH MINIRING

c) OUTER SHIELD WITH MINIRING

CORE SHIELD MODELS

CHART 3.14

CORE SHIELD MODELS
TEST RESULTS

TYPE OF SAMPLE	SAMPLE NO.	CORONA INCEPTION KV RMS	BREAKDOWN KV RMS
INNER SHIELD WITH SIMULATED WINDING	1	8	28
	2	4	28
	3	8	28
	4	12	28
INNER SHIELD NO WINDING	5	24	150
	6	30	120
	7	40	140
	8	40	160
OUTER SHIELD NO WINDING	16	30	100
	17	30	CORONA SAMPLE

CHART 3.15

STRIP SHIELDED CYLINDER

CHART 3.16

TYPICAL SIX-INCH COIL SPECIFICATIONS

ALUMINUM WIDTH	6 IN. (15.2 CM)
ALUMINUM THICKNESS	0.003 IN. (0.076 MM)
POLYMER FILM WIDTH	6.5 IN. (16.5 CM)
POLYMER FILM THICKNESS	2 X 0.00092 IN. (2. X 0.0233 MM)
TEST AREA	0.55 M ²
SAMPLE CAPACITANCE	0.25 μ F
CYLINDER DIMENSIONS	6.0" OD X 8.0" LONG
LEAD DIMENSIONS	0.625" X .003" STRIPS

CHART 3.17

STEP 1
(100 V/1 min steps)

- Measure discharge inception voltage
- Measure discharge extinction voltage

STEP 2
(100 V/1 min steps)

- Measure discharge inception voltage
- Measure discharge extinction voltage

(a) TEST PROCEDURE

CHART 3.18

PARTIAL DISCHARGE INCEPTION AND BREAKDOWN MEASUREMENTS ON TEN 0.25- μ F CAPACITOR COILS
IN AIR AT 1 ATMOSPHERE

DISCHARGE INCEPTION (V RMS) (2-10 pC)	DISCHARGE INCEPTION STRESS (KV PEAK/MM)	WITHSTAND (V RMS)*	WITHSTAND (KV/MM)	BREAKDOWN (V RMS)	BREAKDOWN (KV PEAK/MM)	DISCHARGE EXTINCTION (V RMS) (2-10 pC)	DISCHARGE EXTINCTION STRESS (KV PEAK/MM)
600	19.2	3000	90.8	2800**	84.7	570	17.2
560	16.9	3000	90.8			480	14.5
500	15.1	3000	90.8			490	14.8
500	15.1						
450	13.6	3000	90.8	2900**	87.7	420	12.7
430	13.0						
480	14.5	3000	90.8			630	19.1
550	16.6	3000	90.8			560	16.9
540	16.3	3000	90.8			540	16.3
600	18.2	3000	90.8			540	16.3

* TYPICAL DISCHARGE MAGNITUDE AT 3000 V = 2000 pC to 6000 pC.

** BREAKDOWN OCCURRED AT SITES REMOTE FROM CONDUCTOR EDGES.

(b) TEST RESULTS

CHART 3.18

FIGURE 131

Courbe de Paschen pour le SF₆ en échelles logarithmiques. Température 25 °C.

Paschen Curve for SF₆ in log-log scale. Temperature 25 °C.

CHART 3.19

From "Breakdown of Gases in Uniform Fields Paschen Curves for Nitrogen, Air, and Sulfur Hexafluoride" Electra, No. 32 pp. 61-82.

CHART 3.20

Change in Discharge Inception Voltage and Discharge Extinction Voltage with Time Following Introduction of SF₆ Gas at 6 Atm. for a Single Sample Test Coil with Deliberately-Added 1-mm Diameter Circular Hole in One of the Sheets of Polymer Film

From 1st Annual Report

IMPREGNATION MODELS
CALCULATED CORONA INCEPTION VOLTAGE

	ACROSS 1 MIL GAS PEAK V	ACROSS 1 MIL GAS AND 1 MIL MYLAR PEAK V RMS V
SF ₆ @ 1 ATM	800	1050 740
@ 6 ATM	2000	2620 1850
AIR @ 1 ATM	450	590 420
@ 6 ATM	1150	1510 1065

CHART 3.22

LEAD CONTOURING DIELECTRIC TEST SETUP

CHART 3.23

LEAD TESTS

	SAMPLE NO.	TEST	NO. OF BREAKDOWN	$\bar{X}$ (KV PEAK)	(KV)	BARE ROD
EPDM	1	60 HZ	5	410	17	400
	2	NEG IMP	3	470	22	450
		POS. IMP	2	536	12	530
	4	NEG SS	3	400	26	420
		POS SS	2	400	18	575
NO HEAT SHRINK	3	60 HZ-THICK SECTION	1	354	-	
		NEG IMP " "	1	603	-	
		60 HZ-INTERMEDIATE	1	348	-	
		NEG IMP	1	543	-	
		60 HZ-THIN SECTION	1	540	-	

CHART 3.24

CHART 3.25

Comparison of Teflon Tubing with and without Carbon Loading.
 SF₆ on the Outside and Flowing Freon with Additive
 on the Inside of Pipes - Sample Length, 15 CM

CHART 3.26

Comparison Test of Freon Vapor vs Liquid Freon Flowing
in Coolant Pipe Test Samples.

SF₆ Outside Test Samples - Sample Length, 10 CM

CHART 3.27

Test Results - 10 CM Length Test Samples
Carbon-Free Teflon Tubes

Description	Gas/Liquid		Sample Breakdowns (B.D.) or Test Set-Up Limitations (T.S.L.) - kV									
	Outside Sample	Inside Sample	Switching Impulse				Lightning Impulse				60 Hz	
			Negative		Positive		Negative		Positive		R.M.S.	
			T.S.L.	B.D.	T.S.L.	B.D.	T.S.L.	B.D.	T.S.L.	B.D.	T.S.L.	B.D.
Shields only, no test sample	SF ₆ 45 psig	SF ₆ 45 psig		887	693		998		825		440	
Carbon-free Teflon O.D. ~3.2cm I.D. ~1.9cm	SF ₆ 45 psig	SF ₆ 45 psig	887		711		1005 <u>1st Test</u> Breakdown appeared external in air <u>2nd Test</u> Across sample in SF ₆	1005	819		440 Breakdown in two locations; external in air and across test sample in SF ₆	
Carbon-free Teflon O.D. ~ 3.2cm I.D. ~ 1.9cm	SF ₆ 45 psig	Freon liquid 45 psig, 25°C Flow rate 5 gpm (3.6 ft/sec.) Conductivity 1.17x10 ⁻¹⁰ to 1.61x10 ⁻¹⁰ Mho-cm ⁻¹		887	711		Across sample in SF ₆	955	800		440 Across sample in SF ₆	
Carbon-free Teflon O.D. ~3.2cm I.D. ~1.9cm	SF ₆ 45 psig	Freon vapor vacuum, 12 to 0 in. Hg.		517		671	<u>1st Test</u> 793 Across sample in SF ₆ <u>2nd Test</u> 842 Across sample in Freon vapor		622 Across sample in Freon vapor		440 <u>1st Test</u> Breakdown in air, SF ₆ , and Freon vapor <u>2nd Test</u> No breakdowns	440

S.3 - 44

CHART 3.27

Chart 3.27

5.4 SHORT CIRCUIT TECHNOLOGY DEVELOPMENT (TASK 1320)

The short circuit test of model 7 was conducted during this quarter in the Philadelphia High Power Laboratory. Teardown and analysis of the model indicated a need for further testing of the cooling panel header design. The model 7 and prototype header designs were tested to establish their relative strengths. As a result of the model 7 test, a new short circuit design was conceived. Short circuit model 8 will utilize 56" high windings and the prototype cooling panel design to establish short circuit impact pressure withstand levels.

Short Circuit Model 7 Test

This model contained 24" high windings with stranded copper leads on the inner and outer LV windings and aluminum bar leads on the middle HV winding. Cooling panels from the model 6 design were reused on this model. The winding arrangement is shown in chart 4.1. While designed in an interleaved XHX configuration for thermal testing, a tap lead within the H winding allowed short circuit testing in an XH configuration to maximize short circuit forces. The radial build of the coil (in inches) was:

10.000	Core cylinder inner radius
<u>.375</u>	Core cylinder
1.500	Xi winding, 60 turns (.020 Al + .002 Myl)
11.875	
<u>.125</u>	Mylar gap
12.000	
<u>.900</u>	H winding, 100 turns (.006 Al + .002 Myl)
12.900	
<u>1.790</u>	H winding (idle)
14.690	
<u>.500</u>	Mylar gap
15.190	
<u>1.040</u>	Xo winding (idle)
16.230	
<u>.500</u>	Fiberglass band
16.730	

The model was tested in air with the freon coolant circulating during 10 cycle short circuit tests. The inner X winding was energized with the 100 turn H winding pre-shorted. The winding configuration in the short circuit test cell is shown in Chart 4.2. Closeups of the high current leads external to the winding are shown in Chart 4.3. Due to the small radial build of the Xi winding, considerable effort was spent to assure an adequate air gap existed between the low-voltage leads. Short circuit impact pressures generated within the panels were of primary interest, so instrumentation was devised to measure the pressure surge as it entered the coolant tubing. Two Kistler Model 601B Pressure Sensors were used to detect freon system pressures, as shown in Chart 4.4. Panels 1 and 4 were instrumented, since they had maximum pressures transmitted to them. While the panel 4 transducer did not operate due to freon leakage into its coupling, the other device gave good output signals.

The effect of the pressure surges on the coolant hoses external to the panels was investigated analytically, and provisions were made for evaluation of alternative hoses during the short circuit test. While rigid Teflon tubing was originally planned for the prototype design, high impact pressures require a thick-walled hose to keep Teflon tensile stresses reasonable. The tubing concept shown in Chart 4.5 is being considered as an alternative. Although short circuit pressures are high, the amount of freon displaced is small. Therefore, a resilient, corrugated tube may possibly absorb the pulse and result in acceptable stresses in a thin-walled design. Hydraulic calculations indicate this approach could reduce the prototype's hose wall thickness from 1/4" to 1/16", thereby simplifying coil assembly considerably. It was planned to compare the corrugated hose and thick-walled hose performances at rated current during the short circuit test, but the model failed before reaching this level.

Failure of the model was at an unexpectedly low level and was caused by rupture of the cooling panel headers. The tests achieved are shown in Chart 4.6. The 850 psi generated pressure achieved compares to the 50 MVA prototype's maximum generated pressure of 2175 psi. Since the header failures at 31 KVA did not damage the winding, temporary header repairs were made in an attempt to achieve higher test levels. Panel leakage was widespread even after repair, and the loss of freon reduced panel impact strength on the last test. While the final failure of the coil is classified as a turn-to-turn electrical failure, the header ruptures on the previous shot are the root cause of failure.

Model 7 Failure Analysis

Teardown of the model revealed that both the conductor and lead concepts performed well. This was expected, due to the excellent short circuit stability witnessed in early models. However, the model's cooling panels showed evidence of mechanical distortion at points both external and internal to the winding. Chart 4.7 shows the ruptured outlet header of cooling panel 4. This is typical of the external damage present in all four of the innermost panels. The riser and seam with filler piece is visibly bulged, as is the seam between the riser wall and the cylindrical header. All oven-brazed joints in the header riser assembly showed some degree of freon leakage following the test.

Since the prototype header design differs significantly from that shown in Chart 4.7, much comparative analysis and testing has been done on the two designs. The prototype design uses TIG welding and therefore is substantially stronger than the model 7 design. Also, the model 7 header assembly is much stiffer than the new design, and thus cannot absorb pressure surges within the header. Predicted pressures on the model 7 test were based on hydraulic calculations with inelastic boundaries, so the riser's stiffness is validated by the good agreement with measured values. In contrast, the predicted elastic behavior of the prototype header may reduce the pressures seen by the Teflon tubing. This work is discussed more fully in the Prototype Manufacturing and Development section.

Internal panel damage was also present, as evidenced by the pictures of panel 1 in Chart 4.8. The outlet header was the site of the ultimate electrical failure, but there was also axial buckling along the panel's outlet manifold. The combination of inward manifold buckling and outward riser bulging sheared the mylar at the point shown in Chart 4.8 and failed the coil electrically. The internal panel damage is not of concern because: 1) the manifold design on the prototype has been strengthened, and 2) freon loss prior to the electrical failure substantially reduced buckling strength.

Design of Short Circuit Model 8

Following teardown of model 7, it was apparent that increases in panel strength would be required for adequate short circuit performance. It was also felt that the numerous design changes already implemented on the prototype cooling panels have resulted in a stronger panel. To determine the actual short circuit strength of the larger cooling panels, it was decided to utilize prototype 1 parts in the construction of a 56" high short circuit model 8.

The model 8 design is shown in Chart 4.9 and is a non-interleaved design of reduced impedance and MVA. As such, it can develop short circuit forces in excess of those expected in the interleaved 50 MVA prototype design. Chart 4.10 shows the short circuit pressures developed in all models containing cooling panels, as well as representative values for larger units. It is seen that model 8 will generate higher uniform pressures than the prototype, and non-uniform edge pressures will be approximately the same. (Uniform pressures determine cooling system behavior and edge pressures determine supporting cylinder behavior.) It is also seen that short circuit pressures in the larger MVA, higher KV unit are considerably lower than those of model 8 and the prototype. Short circuit forces are strongly dependent on the impedance and degree of interleaving, and these factors decrease forces in the single phase 78 MVA unit, which is a conceptual design for Con Edison.

Mylar/Aluminum Sticking

Concern was expressed at the Thirteenth Quarterly Review about the possible tearing of mylar due to thermal expansion mismatches at elevated temperatures. This was investigated for one dimensional circumferential expansion. Assume an aluminum layer and a mylar layer are bonded such that they must be at the same length at 110°C as they were at 0°C. The strains thereby induced in the materials can be determined by the relationships

$$\Delta(AL) = L \alpha_A \Delta T = L (23 \times 10^{-6}) \Delta T \text{ for aluminum}$$

and

$$\Delta(MY) = L \alpha_M \Delta T = L (16 \times 10^{-6}) \Delta T \text{ for mylar.}$$

Since material strain is given by $\epsilon = \Delta/L$, the two equations can be solved for total strain, mylar strain and aluminum strain. Using this analysis, the mylar strain is found to be only 770×10^{-6} inch/inch, indicating no mylar tearing can be expected.

MODEL 7 WINDING ARRANGEMENT

A: INTERLEAVED POWER TRANSFORMER, THERMAL CONNECTION.

B: AUTOTRANSFORMER, SHORT CIRCUIT CONNECTION

VIEW OF LV FRONT
SHORT-CIRCUIT TEST OF MODEL 7

VIEW OF HV FRONT
SHORT-CIRCUIT TEST OF MODEL 7

CHART 4.2

SPACER BLOCKS BETWEEN LEADS
OF LV WINDING

LV LEAD SUPPORT STRUCTURE

CHART 4.3

PRESSURE TRANSDUCER AT OUTLET
HEADER OF PANEL 1

PRESSURE TRANSDUCER AT INLET
HEADER OF PANEL 4

CHART 4.4

CORROGATED THIN-WALL TEFLON
TUBING ALTERNATIVE

CHART 4.5

<u>I Input, LV (Peak KA)</u>	<u>LV Winding (Mean PSI)</u>	<u>Radial Press. (Generated PSI)</u>	<u>Transducer Pressure Predicted/Measured</u>	<u>Comment</u>
10.3	875	95	40/14	Calibration shot
14.3	1675	175	75/18	
31.0	7910	850	375/330**	Mechanical Failure- burst panel headers
34.5*	9800	1050	465/485	Electrical Failure- turn-to-turn

* 51 KA attempted; coil failed before first peak.

** Approximate - amplifier output clipped before peak.

SHORT CIRCUIT TEST RESULTS FOR MODEL 7

CHART 4.6

SPLIT OVEN-BRAZED
SEAMS

BULGED RISER PLATE

RUPTURED OUTLET HEADER ASSEMBLY
FROM PANEL 4

CHART 4.7

SITE OF TURN-TO-TURN
ELECTRIC FAILURE

OUTLET HEADER ASSEMBLY
FROM PANEL 1

BUCKLE

AXIAL MANIFOLD BUCKLE ON
PANEL 1

CHART 4.8

MODEL 8

22.4 MVA (OUT) 62 KV/124 KV

% IX = 1.42%

50 MVA PROTOTYPE

50 MVA (OUT) 138 KV/345 KV

% IX = 5.8%

TOTAL RADIAL PRESSURE

(GENERATED PRESSURE PER WINDING)

	P _R (PSI) UNIFORM DISTRIBUTION	NON-UNIFORM FORCE MULTIPLIER	P _R (PSI) NON-UNIFORM DISTRIBUTION	CYLINDER THICKNESS (INCHES)
MODEL 6 (ELEC. FAILURE)	1125	1.74	1960	.375
MODEL 7 (HEADER FAILURE)	850	1.10	940	.375
MODEL 8 (PLANNED MAXIMUM)	2640	1.25*	3300	.570
50 MVA PROTOTYPE (XHX)	2175	1.47	3200	.570
78 MVA DESIGN STUDY (XHXH)	715	1.20*	860	1.350

*Assumed value, pending further analysis

CHART 4.10

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5.5 THERMAL DEVELOPMENT (TASK 1240)

LEGEND

1. Test Coil #7
 - a) Design characteristics, loss analysis & comparison of interleaved vs. non interleaved wdg. arrangement.
 - b) Additional loss test comparisons Eddy56/Konrad vs. test.
 - c) Heat run
 - d) Heat run analysis
2. Overload Studies
 - a) Transient winding rise profile for random loading
 - b) Transient winding rise profile for a two-load cyclic loading.
 - c) Equivalent continuous winding rise due to a) or b)
 - d) Loss of life

1. Test Coil #7

- a) Design characteristics, loss analysis and comparison of interleaved vs. non-interleaved winding arrangements.

The need for test coil #7 arose from the fact, that coil #6 failed short circuit test as well as the fact that it showed considerable discrepancies between calculated and tested losses. At this point we obtained permission of the use of a new electromagnetic analysis program referred to as the "Konrad" program. It predicted the losses of test coil #6 much closer to tested losses. To give us another test point, we needed another test coil.

Another reason for a new test coil was to prove the drastic reduction in losses expected for the interleaved winding design. We designed the new coil with the designation of test coil #7. The design and loss comparisons are shown in chart 5.510. The results show the great reduction in the eddy losses and edge loss density of the interleaved over the non-interleaved winding design. Chart 5.511 shows the edge loss densities plotted for the interleaved and non interleaved designs respectively.

- b) Additional loss test comparison Eddy56/Konrad vs. test.

In order to expand the cases for comparison of the loss predictions by Konrad vs. Eddy56, further connections were selected and tests made. The results are shown per chart 5.512.

These loss tests clearly show that the Konrad program predicts the eddy losses most accurately. All future analysis will therefore be made exclusively with the Konrad program.

- c) Heat Runs

The coil was prepared for the heat runs with thermocouples and cooling panels located per chart 5.520 and 5.521. The method of staggering the cooling panels was not feasible for the split X winding. We placed (2) cooling panels in each X winding in symmetrical fashion, (4) cooling panels in the H winding in staggered fashion. The cooling system was the same used for test coil #6. The thermal data was collected by a computerized Fluke system. A sample output is shown per chart 5.522. Heat runs were made at .866, 1.0, 1.2 and 1.47 PU load. The transient winding temperatures vs. time for the maximum hot spot were plotted reference charts 5.523 to 5.526. Also plotted were the steady state hot spot temperatures at 1.0 PU load across the radial build for the H-winding, reference chart 5.527 to 5.530. In the overload study of transformers the time constant of the winding plays an important part, as will be seen later. This value can be derived from the transient winding rise curve, by solving the transient winding rise equation for m , where $m = 1/B$. B being designated as the time constant.

$$\theta_t = \theta_u (1 - e^{-mt})$$

$$m = \frac{1}{B} = \frac{\ln\left(\frac{\theta_u}{\theta_u - \theta_t}\right)}{t}$$

In the case of the heat runs conducted with coil #7 the initial rise of the winding was the ambient air temperature. The freon was cooled by a freon-to-water heat exchanger. The initial rise of the coil was the effective water temperature. The time to get from that temperature to the air ambient therefore was an unknown quantity. To derive the time constant, the system of equation had to be expanded. Ref. Appendix 5.531. Equation (7) was used to calculate the time constants.

In the case of the 1.47 PU heat run the ultimate rise θ_u was not known, since the heat run was not conducted beyond the 150°C temperature of the winding to prevent possible damage. In this case the ultimate rise was calculated, ref. charts 5.532 and 5.533.

d) Heat run analysis

The H-winding had (4) cooling panels arranged in staggered fashion suitable for the analysis as shown in previous reports. The analysis is performed with the new 2-dimensional solution heat transfer program COIL2*D by Dr. S. Foss. The program incorporates the stagger geometry, and the peripheral spread correction and thus is a quasi-three-dimensional solution, which compares well with the three-dimensional solution program THTD.

The analysis of the H-winding is shown per charts 5.534 and 5.535. The agreement with the test result is remarkably good, the average rise 42.7° vs. 42.7° tested, the hot spot rise 45.5° vs. 46.7° tested for TC #49, 50.

The X-winding due to interleaving was not suitable for staggering the cooling panels. The before mentioned program cannot be used. An additional obstacle to the analysis are the boundary conditions of these split windings. These boundary conditions, i.e. the gap between the inner X winding and the H winding is .125 thick mylar, designed for low impedance for reason of low short circuit power requirements. Analysis of thermocouple 1 and 2 show a calc. rise of 15.0° vs. 12.9° test for the average and a 16.8° vs. 16.7° respectively for the hot spot. Reference chart 5.535. Thermocouples 19 and 20 tested 16.9° vs 15.8° calc and 18.0° vs. 16.4° calc, ref. chart 5.536. Here the boundary condition, a non-adiabatic boundary to the H winding, shows the impact of heat flux flowing from the H winding toward the X-winding. The outer X winding was not suitable at all for any analysis except for a three dimensional analysis which was not performed at this time.

The coolant incremental rise checks out as follows:

		T°C	
	GPM	Calc	Test
Freon	23.2	$10.63 \left(\frac{11.3}{23.2} \right) = 5.2^{\circ}\text{C}$	5.2°C

For Ref. Heat Run Data See Chart 5.522

The water incremental rise was as follows:

		T°C	
	GPM	Calc	Test
Water	5	$3.794 \left(\frac{11.3}{5} \right) = 8.6^{\circ}$	11.0°

The discrepancy of the water rise is due to the losses contributed by the pump.

2. Overload Studies

a) Transient winding rise for random loading

The transient thermal behavior of a winding under load can be expressed in the differential form:

$$\frac{d\theta}{dt} = m (\theta_u - \theta) \quad \begin{array}{l} \theta = \text{winding rise} \\ \theta_u = \text{ultimate wdg. rise} \end{array} \quad (1)$$

i.e. the temperature gradient is proportionate to the difference of rise to ultimate rise. By separating the variables we have

$$\frac{-d\theta}{\theta_u - \theta} = -m dt \quad (2)$$

The solution of this equation with the substitute method is:

$$\theta_u - \theta = c e^{-mt} \quad \begin{array}{l} c = \text{integration constant} \\ m = \frac{1}{T} \\ T = \text{time constant} \end{array} \quad (3)$$

The value of the integration constant can be found by the initial condition: @ t = 0, $\theta = \theta_0$ and $c = \theta_u - \theta_0$ then:

$$\begin{aligned} \theta_u - \theta &= (\theta_u - \theta_0) e^{-mt} \\ \theta &= \theta_u - (\theta_u - \theta_0) e^{-mt} \end{aligned} \quad (4)$$

For the condition of $\Theta_0 = 0$ we have the more familiar version:

$$\Theta = \Theta_u (1 - e^{-mt}) \quad (5)$$

In the case of different levels of loading following each other randomly we can express the end point Θ_1 at $t = t_1$ of the first loading period with an ultimate winding rise Θ_{u1} corresponding to the level of loading m_1 as follows:

$$\Theta_1 = \Theta_{u1} - (\Theta_{u1} - \Theta_0)e^{-m_1 \Delta t_1} \quad (6)$$

At this point Δt_1 the loading changes to a new loading. The initial condition for $t = 0$ are $\Theta = \Theta_1$ and the integration constant, equation (3) is

$C = \Theta_u - \Theta_1$. Equation (3) takes the form:

$$\begin{aligned} \Theta_u - \Theta &= (\Theta_u - \Theta_1)e^{-mt} \\ \Theta &= \Theta_u - (\Theta_u - \Theta_1)e^{-mt} \end{aligned} \quad (7)$$

For the new loading period 2 with Θ_{u2} , Δt_2 and m_2 we have

$$\Theta_2 = \Theta_{u2} - (\Theta_{u2} - \Theta_1)e^{-m_2 \Delta t_2} \quad (8)$$

This is now continued for each new loading so that we may write as a general equation:

$$\Theta_n = \Theta_{un} - (\Theta_{un} - \Theta_{n-1})e^{-m_n \Delta t_n} \quad (9)$$

The loading may indeed be a no-load. The winding will then cool off at a rate

$$-\frac{d\Theta}{dt} = m\Theta \quad (10)$$

This equation has the solution:

$$\Theta = ce^{-mt} \quad (11)$$

To find the value of the integration constant c we set at $t = 0$ $\Theta = \Theta_i$. Then

$$\Theta = \Theta_i e^{-mt} \quad \begin{array}{l} \Theta_i = \text{initial winding} \\ \text{rise} \end{array} \quad (12)$$

The initial rise could be any rise Θ_n during the loading periods.

With this set of equations we can now accurately describe the temperature profile of the random loading of the transformer. Such a loading profile is graphically shown in chart 5.540.

b) Transient winding rise for cyclic loading of 2 loads

For the special case of a cyclic loading consisting of 2 repetitive loads load₁ on for t = t₁, load 2, on for t = t₂, we can write equation (9) as follows:

$$\Theta_{2n+1} = \Theta_{u1} - (\Theta_{u1} - \Theta_{2n})e^{-m_1 \Delta t_1} \quad \text{odd cycle} \quad (13)$$

$$\Theta_{2n} = \Theta_{u2} - (\Theta_{u2} - \Theta_{2n-1})e^{-m_2 \Delta t_2} \quad \text{even cycle} \quad (14)$$

For n the following condition exists:

$$\Theta_{2n+1} = \Theta_{2n-1} = \Theta_{f1} \quad \Theta_{f1} = \text{final rise at load}_1 \quad (15)$$

and

$$\Theta_{2n} = \Theta_{2n+2} = \Theta_{f2} \quad \Theta_{f2} = \text{final rise at load}_2 \quad (16)$$

Equation (13) with substitution from (14) and (15) can now be written as follows:

$$\Theta_{f1} = \Theta_{u1} - \left\{ \Theta_{u1} - [\Theta_{u2} - (\Theta_{u2} - \Theta_{f1})e^{-m_2 \Delta t_2}] \right\} e^{-m_1 \Delta t_1} \quad (16A)$$

If we substitute $A_1 = e^{-m_1 \Delta t_1}$, $A_2 = e^{-m_2 \Delta t_2}$,

$$A_1 * A_2 = A_3 = e^{-(m_1 \Delta t_1 + m_2 \Delta t_2)}$$

and simplify and rearrange equation (16A) we get (Ref. appendix 5.541)

$$\Theta_{f1} = \Theta_{u1} * \frac{1 - A_1}{1 - A_3} + \Theta_{u2} * \frac{A_1 - A_3}{1 - A_3} \quad (17)$$

This is the upper winding rise limit the winding will experience under this loading condition. Of interest is also the lower winding rise limit. Rewriting equation (14) with substitution from (16) and (13) we have:

$$\Theta_{f2} = \Theta_{u2} - \left\{ \Theta_{u2} - [\Theta_{u1} - \Theta_{u2} - \Theta_{f2}]e^{m_1 \Delta t_1} \right\} e^{-m_2 \Delta t_2} \quad (18)$$

This equation with substitutions as before reverts to:

$$\Theta_{f2} = \Theta_{u2} * \frac{1 - A_2}{1 - A_3} + \Theta_{u1} * \frac{A_2 - A_3}{1 - A_3} \quad (19)$$

A cyclic loading consisting of an on-load and off-load period can be derived in similar fashion. The expression for the upper winding rise limit, the on-load period, is the following:

$$\theta_{f1} = \theta_u \frac{1-A1}{1-A3} \quad (20)$$

and similarly for the off-load period we get:

$$\theta_{f2} = \theta_u \frac{1-A1}{1-A3} * A2 \quad (21)$$

c) Equivalent Continuous Winding Rise

Of equal importance to the hot spot rise calculation is the temperature time exposure of a winding under overload conditions, since it reflects on the life loss of the transformer insulation. The task is to find the temperature time area under the load temperature profile. This can be done by integration of the respective equations.

To find the temperature-time product under the loading condition of equation (4) we integrate with respect to t:

$$\theta_t = \theta_{ut} - (\theta_u - \theta_o) \int_{t=0}^{t=t} e^{-mt} dt \quad (22)$$

$$\theta_t = \theta_{ut} - \frac{1}{m} (\theta_u - \theta_o) (1 - e^{-mt}) \quad \text{Ref. Appendix 5.542} \quad (23)$$

$$\bar{\theta} = \theta_u - \frac{1}{tm} (\theta_u - \theta_o) (1 - e^{-mt}) \quad \bar{\theta} = \text{Avg. Wdg. Rise} \quad (24)$$

Integration of equation (12) with respect to t results in

$$\theta_t = \theta_i \int_{t=0}^{t=t} e^{-mt} \quad (25)$$

$$\theta_t = \theta_i \left(\frac{1}{m} \right) (1 - e^{-mt}) \quad (26)$$

$$\bar{\theta} = \theta_i \left(\frac{1}{tm} \right) (1 - e^{-mt})$$

In the case of th 2 load cyclic loading and neglecting the periods prior to reaching f_1 and f_2 , the temperatures time product can be expressed as follows: (Ref Fig.)

$$A_{L1} = \theta_{2n+1} t_1 = \theta_{u1} t_1 - \frac{1}{m_1} (\theta_{u1} - \theta_{f2}) (1 - e^{-m_1 \Delta t_1}) \quad (27)$$

$$A_{L2} = \theta_{2n} t_2 = \theta_{u2} t_2 - \frac{1}{m_2} (\theta_{u2} - \theta_{f1}) (1 - e^{-m_2 \Delta t_2})$$

$$\bar{\theta} = \frac{A_{L1} + A_{L2}}{t_1 + t_2} \quad (28)$$

A numerical example of a cyclic loading, CGIT Coil #7

$$\text{Loading 1 147\% } \Delta t_1 = 60 \text{ min. } \theta_{u1} = 152^\circ\text{C, } m_1 = \frac{1}{t_1} = .0279$$

$$\text{Loading 2 100\% } \Delta t_2 = 180 \text{ min. } \theta_{u2} = 70^\circ\text{C, } m_2 = \frac{1}{t_2} = .0422$$

$$A_1 = e^{-m_1 \Delta t_1} = .187$$

$$A_2 = e^{-m_2 \Delta t_2} = .000503$$

$$A_3 = A_1 A_2 = .0000941$$

$$\theta_{f1} = 152 \frac{1-A_1}{1-A_3} + 70 \frac{A_1-A_3}{1-A_3} = 136.7^\circ\text{C}$$

$$\theta_{f2} = 70 \frac{1-A_2}{1-A_3} + 150 \frac{A_2-A_3}{1-A_3} = 70^\circ\text{C}$$

$$A_{L1} = 152 * 60 - 35.8 (150-70)(1-A_1) = 6792 (^\circ\text{C min}) \quad \theta_1 = 113.2^\circ\text{C}$$

$$A_{L2} = 70 * 180 - 23.7(70-136.7)(1-A_2) = 14181 (^\circ\text{C min}) \quad \theta_2 = 78.8^\circ\text{C}$$

$$\bar{\theta} = \frac{6792 + 14181}{240} = 87.4^\circ\text{C}$$

$$\bar{T} = 87.4 + \text{Ambient} = 87.4 + 14.3^\circ = 101.7 (95^\circ)$$

d) Loss of Life

Under the assumption that Mylar has the same loss of life characteristics as 55°C paper insulation system the loss of life for each cyclic loading period (4 hours) would be the following:

$$P_{ct} = 100 T_m / 10(B/T-A)$$

$$T_m = \text{load time in hrs}$$

$$P_{ct} = 100 * 4/10$$

$$T = \text{absolute temperature}$$

$$P_{ct} = .01342 \%$$

$$B = 6972.15 \text{ for transf.}$$

$$A = 14.133 \text{ for } 55^\circ\text{C} \\ \text{Input system.}$$

The equation for the winding rise ϑ_{t_1} at t_1 and ϑ_{t_2} at t_2 are:

$$\vartheta_{t_1} = \vartheta_{\mu}(1 - e^{-mt_1}) \quad (1) \quad m = \frac{1}{B} \quad B = \text{Time constant}$$

$$\vartheta_{t_2} = \vartheta_{\mu}(1 - e^{-mt_2}) \quad (2)$$

$$m, t_1 \text{ and } t_2 \text{ are unknown. By setting } t_2 - t_1 = a \\ t_2 = a + t_1 \quad (3)$$

we have:

$$\vartheta_{t_2} = \vartheta_{\mu}(1 - e^{-m(a+t_1)}) \quad (4)$$

$$= \vartheta_{\mu}(1 - e^{(-ma - mt_1)})$$

$$= \vartheta_{\mu}(1 - e^{-ma} e^{-mt_1}) \quad (5)$$

From (1) we derive

$$e^{-mt_1} = \frac{\vartheta_{\mu} - \vartheta_{t_1}}{\vartheta_{\mu}} \quad (6)$$

Substituting (6) into (5):

$$\vartheta_{t_2} = \vartheta_{\mu} \left(1 - \frac{\vartheta_{\mu} - \vartheta_{t_1}}{\vartheta_{\mu}} e^{-ma} \right)$$

$$= \vartheta_{\mu} - (\vartheta_{\mu} - \vartheta_{t_1}) e^{-ma}$$

$$e^{-ma} = \frac{\vartheta_{\mu} - \vartheta_{t_1}}{\vartheta_{\mu} - \vartheta_{t_2}}$$

$$m = \frac{1}{a} \ln \frac{\vartheta_{\mu} - \vartheta_{t_1}}{\vartheta_{\mu} - \vartheta_{t_2}} \quad (7)$$

PROOF OF EQ. (17) AND ()

$$\begin{aligned}
 v_{f_1} &= v_{\mu_1} - \{v_{\mu_1} - [v_{\mu_2} - (v_{\mu_2} - v_{f_1}) A_2]\} A_1 \\
 &= v_{\mu_1} - \{v_{\mu_1} - [v_{\mu_2} - v_{\mu_2} A_2 + v_{f_1} A_2]\} A_1 \\
 &= v_{\mu_1} - \{v_{\mu_1} - v_{\mu_2} + v_{\mu_2} A_2 - v_{f_1} A_2\} A_1 \\
 &= v_{\mu_1} - v_{\mu_1} A_1 + v_{\mu_2} A_1 - v_{\mu_2} A_1 A_2 + v_{f_1} A_1 A_2
 \end{aligned}$$

$$v_{f_1} (1 - A_1 A_2) = v_{\mu_1} (1 - A_1) + v_{\mu_2} (A_1 - A_1 A_2)$$

$$\underline{v_{f_1} = v_{\mu_1} \frac{1 - A_1}{1 - A_3} + v_{\mu_2} \frac{A_1 - A_3}{1 - A_3} \quad \text{EQ. (17)}}$$

$$\begin{aligned}
 v_{f_2} &= v_{\mu_2} - \{v_{\mu_2} - [v_{\mu_1} - (v_{\mu_1} - v_{f_2}) A_1]\} A_2 \\
 &= v_{\mu_2} - \{v_{\mu_2} - [v_{\mu_1} - v_{\mu_1} A_1 + v_{f_2} A_1]\} A_2 \\
 &= v_{\mu_2} - \{v_{\mu_2} - v_{\mu_1} + v_{\mu_1} A_1 - v_{f_2} A_1\} A_2 \\
 &= v_{\mu_2} - v_{\mu_2} A_2 + v_{\mu_1} A_2 - v_{\mu_1} A_1 A_2 + v_{f_2} A_1 A_2
 \end{aligned}$$

$$v_{f_2} (1 - A_1 A_2) = v_{\mu_2} (1 - A_2) + v_{\mu_1} (A_2 - A_1 A_2)$$

$$\underline{v_{f_2} = v_{\mu_2} \frac{1 - A_2}{1 - A_3} + v_{\mu_1} \frac{A_2 - A_3}{1 - A_3} \quad \text{EQ.}}$$

PROOF OF EQ.(23).

$$\bar{v} = \bar{v}_u - (\bar{v}_u - \bar{v}_0)e^{-mt} \quad \text{EQ. (4)}$$

$$\bar{v} dt = \bar{v}_u dt - (\bar{v}_u - \bar{v}_0)e^{-mt} dt$$

$$\bar{v}t = \bar{v}_u t - (\bar{v}_u - \bar{v}_0) \int_0^t e^{-mt} dt$$

$$\bar{v}t = \bar{v}_u t + \frac{1}{m}(\bar{v}_u - \bar{v}_0) \left[e^{-mt} \right]_0^t$$

$$\bar{v}t = \bar{v}_u t + \frac{1}{m}(\bar{v}_u - \bar{v}_0)(e^{-mt} - 1)$$

$$\bar{v}t = \bar{v}_u t - \frac{1}{m}(\bar{v}_u - \bar{v}_0)(1 - e^{-mt}) \quad \text{EQ. (23)}$$

5.5 Thermal Development (Task 1240)

Core Thermal Model

A steady state three dimensional thermal model was developed to serve as a design aid for predicting the temperature distribution within the core of the gas insulated transformers. The core model is flexible permitting the user to examine a number of alternative coolant materials and core cooling panel arrangements. The program permits material substitutions based on the temperature dependent physical properties of the dielectric coolant, core material and dielectric gas. The user can select the mode of cooling desired. The loss distribution within the core can be altered with relative ease if desired.

The method of finite differences was selected as the system solver. The core model was coded in HPL, a Hewlett Packard language, for the HP 9825B desk top computer. Predictions by the model are in good agreement with the observed heat run data.

A Technical Information Series Report Number 83PTD100 was written documenting this effort.

Chart 550 illustrates the yoke/leg corner section analyzed in this study. Chart 551, listed in the Sixth Quarterly Report, lists the core corner loss distribution as a function of spatial position. Chart 552 defines the boundary faces of the core considered in the thermal model. Chart 553 is a sketch of the three dimensional nodal layout selected to describe the heat conduction within the core corner. Chart 554 list typical input data for the core model based on a R113 forced convection cooling mode. Charts 555 and 556 list the predictions of core temperature based on Chart 554 example inputs.

ALTERNATIVE GAS COOLING CONCEPT

On December 13, 1982, the alternative cooling concept of SF₆ gas cooling of the gas insulated transformer was reviewed with Mr. Paul Gnadt. The alternative cooling mechanism was reviewed in light of thermal considerations only and are summarized in a graph illustrating the hot spot temperature of the GIT coil as a function of the number of concentric cooling ducts within the coil. The transformer analyzed was the 50 MVA prototype coil.

Chart 557 defines the coil hot spot temperature in terms of four characteristics rises and the ambient air temperature. Chart 558 provides a relation for the coil hot spot temperature rise over duct wall temperature. The equation is based on the envisioned 40°C coil rise using seven 360 degree cooling ducts. Chart 560 provides a relation for the cooling duct rise over coolant. The equation is dependent on the properties of the fluid (gas or liquid) and the spacing within the cooling ducts. Chart 561 provides a relation for the temperature rise of the coolant within the coolant duct. The heat exchanger size is assumed constant irrespective of cooling medium. For liquid/forced air cooling, a heat exchanger duty of 25°C is assumed. For the case of gas/forced air cooling, a heat exchanger duty of 40°C is estimated. Chart 562 provides a relation showing the pressure loss experienced within the coil as a function of the coolant flow rate, duct spacing and the number of cooling ducts. Chart 563 lists physical properties of the two cooling mediums (SF₆ gas and R113 liquid). Chart 564 lists characteristics of the 50 MVA prototype important in the analysis. Chart 565 illustrates the coil hot spot temperature as a function of the number of cooling ducts utilized within the coil. From Chart 565, it is not feasible to use SF₆ gas to maintain the hot spot temperature of the coil below 120°C.

TRANSIENT ANALYSES OF COMPACT GAS TRANSFORMER

The purpose for performing a transient thermal analysis is to predict the thermal behavior of transformer when deviations from normal operating conditions occur. Two types of transients are of interest. The first type is if the cooling system fails while the transformer is operating under full load. The second type is when the transformer is overloaded. Knowledge of transient thermal behavior under these operating conditions is necessary for the safety margin design.

To avoid the complexity of the system, a microscopic model, which assumes uniform coil properties was developed to describe the transient thermal behavior of the coil. For the cooling system failure transient, the absence of convection heat dissipation results in an increase of the coil temperature. Eq. (1), Chart 566, is the transient microscopic energy balance from the coil under this situation. This equation defines a steady increase in coil temperature of $1.45^{\circ}\text{C}/\text{min}$ which results from coil losses.

For the cases of overload transient, heat removal by the coolant exists. Based on the time duration of the overload, a new steady state coil hot spot temperature may eventually be established. The new steady state coil hot spot and coolant temperatures can be determined from Eqs. (2) and (3) (Chart 566).

It may be noted that the temperatures listed in Eqs. (2) and (3) have to be calculated by an iterative scheme because of temperature dependence in the loss term. Chart 567 lists temperature rise predictions as a function of load. Chart 568 displays the increase in coil hot spot temperature as a function of load.

Another aspect is the time for the coil hot spot temperature to reach the maximum tolerance as a function of load. The time can be determined from Eq. (4) in Chart 566. Note that T_{coil} in this equation represents the desired maximum hot spot temperature which can be equal to or less than the new steady state hot spot temperature. Chart 569 shows the computed results. For a known overload and a maximum limit of hot spot temperature, the time to shut off the power can be conveniently determined from this figure.

Design & Loss Comparison Test Coil #6 and 7

Rating: FFW-60-3000-19350-6450

Design Comparison

Loss Comparison (Test)

	<u>Non-Interleaved</u>
DC Loss	10330 W
Eddies+Strays	3300 W
Load Loss	13630 W
% IX	6.3
Max. Edge	
Loss Density	11.5 W/in ³

Interleaved

10731 W
653 W
11384 W
1.9

Interleaved Non Interleaved

.2
.83
.54

Chart 5.510

EDGE LOSS DENSITY INTERLEAVED VS.
NON INTERLEAVED
TEST COIL #6,7

CHAPT 5.511

LOSS COMPARISONS BETWEEN TEST, EDDY56 AND KONRAD

Winding Configuration Test Coil #7

LOSSES

	<u>EDDY56</u>	<u>KONRAD</u>	<u>TEST</u>	<u>K/T</u>
1. INTERLEAVED X-H CONN. X_2-X_3				
LOAD LOSS	10915 W	11325 W	11384 W	.995
EDDIES	253 W	669 W	653 W	1.025
2. NONINTERLEAVED X_1-H				
LOAD LOSS	13662 W	14436 W	14459 W	.998
EDDIES	850 W	1636 W	1478 W	1.107
3. NONINTERLEAVED X_1-H_{200}				
LOAD LOSS	17142 W	18270 W	18500 W	.988
EDDIES	1207 W	2340 W	2350 W	.996
4. NONINTERLEAVED X_1-X_0				
LOAD LOSS	25050 W	27229 W	27667 W	.984
EDDIES	2865 W	5050 W	5629*)	.897
5. NONINTERLEAVED X_0-H				
LOAD LOSS	21850 W	23038 W	22876 W	1.007
EDDIES	1095 W	2288 W	2298 W	.996

*) THIS CONNECTION (WIDE MAIN GAP) GENERATES STRAY LOSSES IN CORE CLAMPS.

ENGINEERING SKETCH

WS
RATING ()

PO

SH

OF

SHEETS

PREPARED BY W. BACH 10/16/82

CHECKED BY

TEST COIL #7

THERMOCOUPLE LOCATIONS

H-W
PLAN VIEW

ELEVATION

ENGINEERING SKETCH

WS
RATING ()
PREPARED BY

PO

SH

OF

SHEETS

CHECKED BY

TEST COIL # 7

THERMAL COUPLE LOCATIONS

PLAN VIEW

ELEVATION

X0 - W

PLAN VIEW

CHART 5.521

GENERAL ELECTRIC COMPANY -- POWER TRANSFORMER DEPARTMENT -- GAS INSULATED TRANSFORMER -- THERMAL TESTS, MODEL COIL 7

TEST CONDITIONS: 11.3KW TO STABILITY THEN MAX AVAILABLE I TO 150C, 2.9GPM FREON

5.0 GPM WATER TO HEAT EXCHANGER - 4 PSIG ON AIR BAG

DATE: 4-MAY-83 TIME: 11:15 START: 8:15: MIN. ELAPSED: 180.0 TAPE K361 FILE NO 16

AMPS: 474.6 VOLTS: 115.1 KW: 11.214 KVA: 54.624 AMB TEMP C: 25.4(26.2 25.0 25.9 24.4) 2.0000 50.2

TEMPERATURE, C											
HIGH VOLTAGE WINDING											
DEGREES											
66 126 198 280 350											
M T M T M T M T M T											
TURN	THERMOCOUPLE NO										
0	63.1	63.9	999.9	999.9	38.0	43.4	41.9	46.1	63.4	65.0	31,32,33,34,25,26,27,28,29,30
50	61.2	65.2							60.3	64.9	37,38,35,36
75											39,40
100	44.2	56.8	70.2	74.2	77.5	80.3			42.1	54.7	45,46,47,48,41,42,43,44
150							80.3	84.3			49,50
200	81.4	85.7	41.4	54.1	42.6	49.2			80.5	85.2	55,56,57,58,51,52,53,54
225							72.7	76.2			59,60
250			69.8	73.7	63.2	999.9					63,64,61,62
300	78.9	80.7	73.1	999.9	67.5	69.3	26.0	999.9	36.6	47.5	71,72,73,74,65,66,67,68,69,70

TEST COIL #7

INNER LOW VOLTAGE WINDING											
DEGREES											
136 316 0 90											
M T M T M T M T											
TURN	THERMOCOUPLE NO										
0	50.5	54.3	42.3	45.4	52.6	54.9	45.9	47.9	1,2,3,4,80,81,82,83		
10			48.5	52.2	54.0	55.9	45.0	999.9	5,6,84,85,86,87		
20	48.5	52.2	39.8	42.7	999.9	56.2	38.3	42.3	7,8,9,10,88,89,90,91		
30					53.8	999.9	41.4	44.2	92,93,94,95		
40	39.9	42.4	51.2	52.5	52.9	55.2	42.0	999.9	11,12,13,14,96,97,98,99		
50			45.0	46.8					15,16		
60	48.0	49.7	54.3	999.9					17,18,19,20		

MISCELLANEOUS TEMPERATURES, C

POSITION:	1	2	3	4	5	6	7	8	9
COOLING PANEL IN:	34.9	35.0	35.0	35.0	35.0	35.0	34.9	34.9	34.9
OUT:	39.7	39.9	39.3	42.1	42.4	39.0	39.7	39.1	39.1
RISE:	4.8	4.9	4.3	7.1	7.4	4.0	4.8	4.2	4.2
LEAD:	52.1	999.9	999.9	53.4	999.9	999.9	999.9	999.9	50.7

$$\bar{T}_{EFF FR} = \frac{40.15 + 34.96}{2} = 37.6^{\circ}C$$

$$\Delta T_{FR} = 40.15 - 34.96 = 5.2^{\circ}C$$

HEAT EXCHANGER: WATER IN: 8.8 WATER OUT: 19.8 FREON IN: 39.8 FREON OUT: 32.5 MANIFOLD TOP: 40.5 BOTTOM: 35.1

STRAIN GAUGE DATA (Ver = 1.0169 VOLTS)

LOCATION:	ICT (220)	ICA (220)	ICT (310)	ICA (310)	OCT (220)	OCA (220)	OCT (310)	OCA (310)
TEMPERATURE, C	41.8	41.8	39.6	39.6	38.0	38.0	38.2	38.2
MICROSTRAIN	109.9	-316.4	106.1	-553.3	15.1	605.5	-53.8	436.5

CHART 5.522

.066 PU HEAT RUN

$$m = \frac{1}{B} = \frac{1}{a} \ln \frac{T_u - T_{u1}}{T_u - T_{u2}}$$

$$m = .0416$$

$$B = 24 \text{ min}$$

$$T_u = 57.3 + 10.5 + 44.5 = 112.3$$

$$T_{u1} = 55.0^\circ\text{C}$$

$$T_{u2} = 41.0^\circ\text{C}$$

$$a = 20 \text{ min}$$

$$a = t_u - t_1$$

$$B = \text{TIME CONSTANT}$$

T °C

100

80

60

40

20

0

$T_c = 50$ EDGE

$T_c = 49$ MIDPOINT

$T_{amb} = 10.0$
°C

t min

20

40

60

80

100

120

140

160

t min

10 PU HEATRUN

$$RT = \frac{1}{a} \ln \frac{P_{\infty} - P_{\infty_1}}{P_{\infty} - P_{\infty_2}}$$

$$m = 0.0422$$

$$B = 23.7 \text{ min}$$

$$S_{\infty_1} = 84.3 - 14.3 = 70.0$$

$$S_{\infty_2} = 53.6 - 14.3 = 39.3$$

$$S_{\infty_3} = 68.0 - 14.3 = 53.7$$

$$a = 15 = t_2 - t_1$$

T °C

80

60

40

20

-4.5 min.

50

20

40

60

80

100

120

140

160

t min

#50, EDGE

#49, MID POINT

T_{AMB} = 14.3 °C

1.2 PU HEAT RUN

T °C

120

80

60

40

20

-10 min

TC #50 EDGE

TC #49 MID POINT

$$M = \frac{1}{B} = \frac{1}{12} \ln \frac{S_{100} - S_{\infty}}{S_{10} - S_{\infty}}$$

$$M = 0.033$$

$$B = 30.1 \text{ min}$$

$$S_{100} = 112.1 - 15.1 = 97.0$$

$$S_{10} = 112.1 - 15.1 = 97.0$$

$$S_{10} = 57.5 - 15.1 = 42.4$$

$$12 = 20 + 42 - 61$$

T_{AMB} = 15.1 °C

20

40

60

80

100

120

140

160

t min

T °C

147PU HEAT RUN

meas. 131.6

EDGE

MIDJOINT

140

120

100

80

60

40

20

0

$$m = \frac{1}{B} = \frac{1}{2} \ln \frac{T_u - T_{u1}}{T_u - T_{u2}}$$

$$m = 0.022788$$

$$B = 35.8 \text{ min}$$

$$T_{u1} = 130.5 - 13.4 = 117.1$$

$$T_{u2} = 81.1 - 13.4 = 67.7$$

$$T_{u2} = 133.1 - 13.4 = 119.7$$

$$a = 20 = t_2 - t_1$$

$$t_1 = \frac{1}{m} \ln \frac{T_u - T_{u1}}{T_u - T_{u2}}$$

$$t_1 = 22.14^\circ\text{C}$$

$$T_{AMB} = 16.4^\circ\text{C}$$

t min

160

180

5.5 - 25

CHART 5.526

TEMPERATURE PROFILE H-W (198°)
10 PH LOAD

TEMPERATURE PROFILE MW (350°) LOCAL LOAD

YAC 80

70

#30

#36

#29

#35

#44

#54

#58

50

#70

40

AVG TEMPERATURE = 37.6°C

#43

#68

30

20°

12

13

14

15° RADIAL BUILD "

/COIL2*D

H-W 1.47 PU LOAD

ENTER OVERALL HEAT TRANSFER COEFFICIENT (WATTS/IN/IN/C) ? .293

ENTER EDGE HEATING PENETRATION DISTANCE, INCHES ? 1.0

ENTER THERMAL CONDUCTIVITY OF INSULATION (W/IN/C) ? .0029

ENTER FRACTION CONDUCTOR ? .765

ENTER COIL EFFECTIVE HEATING HEIGHT, INCHES ? 24.0

ENTER COIL WIDTH, INCHES ? 2.35

ENTER COIL WIDTH BETWEEN FIRST AND LAST PANEL ? 2.35

ENTER RADIAL SPACING BETWEEN PANEL STEPS ? .78

ENTER MEAN COIL DIAMETER, INCHES ? 26.69

ENTER PANEL LENGTH, INCHES ? 34.5

ENTER PANEL + GAP LENGTH, INCHES ? 34.5

ENTER NUMBER OF COOLING PANELS ? 4.0

ENTER COEFFICIENT OF A TERM ? 0.0

ENTER COEFFICIENT OR A**2 TERM ? 0.0

ENTER VALUE OF KILOWATTS DISSIPATED ? 13.15

ENTER RATIO OF SKIN HEATING TO BULK HEATING ? 6.75

$$\Delta T_{EFF FR} = 1.47^2 \times (37.6 - 14.3) = 50.35^\circ C$$

$$\frac{T_{WATER}}{T_{FREON}} = \frac{18.4}{68.75^\circ C}$$

$$\Delta T_{INCR W} = 3.8 \times \frac{26.124}{5} = 19.85^\circ C$$

$$\frac{T_{WATER OUT}}{T_{WATER IN}} = \frac{8.5}{23.35}$$

$$\frac{T_{AMB}}{T_{WATER IN}} = \frac{8.5}{18.4^\circ C}$$

TWO-DIMENSIONAL RADIAL/AXIAL TEMP. DISTRIBUTION
AND RADIAL COOLING DUCT HEAT FLUX

** INSULATION PROPERTIES **

UNITS[=1 WATTS/IN/C)

THERMAL CONDUCTIVITIES : KMYLAR = 0.0029 KAL = 5.6192

** EFFECTIVE COIL PROPERTIES **

FRACTION INSULATION = 0.235

RADIAL EFFECTIVE K = 0.012 WATTS/IN/C

AXIAL EFFECTIVE K = 4.3

EFFECTIVE FILM COEFFICIENT = 0.2930 WATTS/IN/IN/C

** TRANSFORMER CHARACTERISTICS **

KWATTS GENERATED = 13.1

SE/BULK (WATTS/IN**3) = 1.88

PENETRATION DISTANCE = 1.0

MEAN RATIO SKIN HEATING TO BULK HEATING = 6.75

PARABOLIC EDGE HEATING COEFFICIENTS AO= 0.000A1= 0.000

CONSECUTIVE PARALLEL PANEL TO PANEL WIDTH = 1.90 IN

COIL WIDTH = 2.35 IN

COIL HEIGHT = 2.0 FT

MEAN COIL DIAMETER = 26.7 IN

PANEL LENGTH = 34.5 IN

PANEL GAP = 0.0 IN

NUMBER OF PANELS = 4.

NUMBER OF EFFECTIVE CONCENTRIC PANELS = 1.65

PANEL STEP SPACING DISTANCE = 0.78 IN

EFFECTIVE FRXN OF WIDTH PANEL SPACING = 0.07

DUCT THICKNESS = 25 MILS

MEAN PANEL VELOCITY = 0.67 FPS

BIOT NUMBER = 22.5

* CONCENTRIC STEP STAGGER/GAP SPACING FACTOR *

KSTGL HOT SPOT = 0.859

KGAPL HOT SPOT = 1.000

KAVG/HOT = 0.900

KSTGL AVERAGE = 0.773

Z (IN.)	COIL RISE OVER MEAN COOLANT (C)			(W/IN**2)	
	HOT SPOT/CONC	HOT SPOT/STGD	WALL RISE	Q/WALL	
0.0	103.4	88.9	157.6 6.64	2.39	
1.2	103.5	89.0	6.64	2.39	
2.4	104.0	89.4	6.65	2.41	
3.6	104.7	90.0	6.67	2.43	
4.8	105.7	90.9	6.69	2.47	
6.0	107.1	92.0	6.72	2.52	
7.2	108.7	93.4	6.77	2.58	
8.4	110.6	95.1	6.82	2.68	
9.6	112.9	97.0	6.89	2.81	
10.8	115.5	99.2	6.97	3.00	
12.0	118.4	101.8	7.09	3.30	

AVERAGE COIL TEMPERATURE = 57.6C

PROGRAM STOP AT 2400

READY
DVE

$$T_{\text{HOT}} = 101.8 + 68.7 = 170.5$$

5.5-31

CHART 5.533

HHHH
U# = NBT60066, WIDGET, 699WB

H-W TC # 49,50

TERMINAL 3323051081600

INPUT

READY
/COIL2*D

ENTER OVERALL HEAT TRANSFER COEFFICIENT (WATTS/IN/IN/C) ?2.293

ENTER EDGE HEATING PENETRATION DISTANCE, INCHES ?1.0

ENTER THERMAL CONDUCTIVITY OF INSULATION (W/IN/C) ?0.0029

ENTER FRACTION CONDUCTOR ?0.765

ENTER COIL EFFECTIVE HEATING HEIGHT, INCHES ?24.0

ENTER COIL WIDTH, INCHES ?2.35

ENTER COIL WIDTH BETWEEN FIRST AND LAST PANEL ?2.35

ENTER RADIAL SPACING BETWEEN PANEL STEPS ?0.78

ENTER MEAN COIL DIAMETER, INCHES ?26.69

ENTER PANEL LENGTH, INCHES ?34.5

ENTER PANEL + GAP LENGTH, INCHES ?34.5

ENTER NUMBER OF COOLING PANELS ?4.0

ENTER COEFFICIENT OF R TERM ?0.0

ENTER COEFFICIENT OF R**2 TERM ?0.0

ENTER VALUE OF KILOWATTS DISSIPATED ?6.1

ENTER RATIO OF SKIN HEATING TO BULK HEATING ?3.13

TWO-DIMENSIONAL RADIAL/AXIAL TEMP. DISTRIBUTION
AND RADIAL COOLING DUCT HEAT FLUX

** INSULATION PROPERTIES **

UNITS [=] WATTS/IN/C)

THERMAL CONDUCTIVITIES : KMYLAR = 0.0029 KAL = 5.6192

** EFFECTIVE COIL PROPERTIES **

FRACTION INSULATION = 0.235

RADIAL EFFECTIVE K = 0.012 WATTS/IN/C

AXIAL EFFECTIVE K = 4.3

EFFECTIVE FILM COEFFICIENT = 0.2930 WATTS/IN/IN/C

** TRANSFORMER CHARACTERISTICS **

KWATTS GENERATED = 6.1

SE/BULK (WATTS/IN**3) = 1.10

PENETRATION DISTANCE = 1.0

MEAN RATIO SKIN HEATING TO BULK HEATING = 3.13

PARABOLIC EDGE HEATING COEFFICIENTS A0 = 0.000A1 = 0.000

CONSECUTIVE PARALLEL PANEL TO PANEL WIDTH = 1.90 IN

COIL WIDTH = 2.35 IN

COIL HEIGHT = 2.0 FT

MEAN COIL DIAMETER = 26.7 IN

PANEL LENGTH = 34.5 IN

PANEL GAP = 0.0 IN

NUMBER OF PANELS = 4.

NUMBER OF EFFECTIVE CONCENTRIC PANELS = 1.65

PANEL STEP SPACING DISTANCE = 0.78 IN

EFFECTIVE FRXN OF WIDTH PANEL SPACING = 0.07

DUCT THICKNESS = 25 MILS

MEAN PANEL VELOCITY = 0.67 FPS

BIOT NUMBER = 22.5

 $T_{HS \# 50} = 84.3^{\circ}C$ $T_{COOL.} = 37.6^{\circ}C$ $\theta_{HS} = 46.7^{\circ}C$ $T_{AVG \# 49} = 30.3^{\circ}C$ $T_{COOL.} = 37.6^{\circ}C$ $\theta_{AVG} = 42.7^{\circ}C$

* CONCENTRIC STEP STAGGER/GAP SPACING FACTOR *

KSTGL HOT SPOT = 0.859

KGAPL HOT SPOT = 1.000

KAVG/HOT = 0.900

KSTGL AVERAGE = 0.773

TEST

Z (IN)	COIL RISE OVER MEAN COOLANT (C)			(W/IN**2)	
	HOT SPOT/CONC	HOT SPOT/STGD	WALL RISE	Q/WALL	
0.0	49.7	42.7	3.67	1.17	
1.2	49.7	42.7	3.67	1.17	
2.4	49.8	42.8	3.67	1.17	
3.6	50.0	43.0	3.67	1.18	
4.8	50.2	43.2	3.68	1.19	
6.0	50.5	43.4	3.69	1.20	
7.2	50.8	43.7	3.69	1.21	
8.4	51.3	44.1	3.71	1.23	
9.6	51.8	44.5	3.72	1.26	
10.8	52.3	45.0	3.74	1.30	
12.0	53.0	45.5	3.76	1.37	

AVERAGE COIL TEMPERATURE = 27.1C

PROGRAM STOP AT 2400

READY

RISEE*C

THIS PROGRAM WILL DETERMINE TEMPERATURE RISE IN DEG. C. OUTPUT WILL CONTAIN A LISTING OF RISES WITH AXIAL DISTANCE AT A RADIAL POSITION MIDWAY BETWEEN TWO DUCTS.
AN ENTRY OF ZERO IN INDICATED LINES WILL DEFAULT TO STD. VALUES AS NOTED.

ENTER DISTANCE BETWEEN DUCTS (IN) ?1.747

ENTER TOTAL COIL HEIGHT (IN) ?24

ENTER NUMBER OF DUCTS;MIN. IS 2 ?2

ENTER TOTAL ENERGY DISSIPATION (KW) ?3.53

ENTER MEAN COIL DIAMETER(IN) ?22.235

ENTER CONVECTION COEFF. IN W/IN**2/C (DEF 0.29307) ?

ENTER THICKNESS OF ALUMINUM, IN INCHES ?0.020

ENTER THICKNESS OF MYLAR, IN INCHES ?0.00184

ENTER THERMAL CONDUCTIVITY (W/IN/C) (DEF 0.00308)?0.00293

ENTER RATIO OF ENERGY DISTRIBUTION IN SKIN AREA TO BULK,R?3.76

$K_f = \frac{1}{1 + 135 \left(\frac{1.75}{22.235} \right)^2} = .92$	AXIAL POSITION	TEMPERATURE RISE	TEST
	INCHES	CENTIGRADE	
	0.00	16.3578 * .92 = 15.00C	12.9C
	2.00	16.4088	
	4.00	16.5649	
	6.00	16.8360	
	8.00	17.2369	
	10.00	17.7846	
	10.50	17.9468	
	11.00	18.1203	
	11.50	18.3061 * .92 = 16.8	16.7C
	12.00	18.5070	

X₂-W

TC # 19,30

EE*^c

S PROGRAM WILL DETERMINE TEMPERATURE RISE IN DEG. C. OUTPUT WILL CONTAIN A LISTING OF RISES WITH AXIAL DISTANCE AT A RADIAL POSITION MIDWAY BETWEEN TWO DUCTS.

N ENTRY OF ZERO IN INDICATED LINES WILL DEFAULT TO STD. VALUES AS NOTED.

ENTER DISTANCE BETWEEN DUCTS (IN) ?1.747

ENTER TOTAL COIL HEIGHT (IN) ?24

ENTER NUMBER OF DUCTS; MIN. IS 2 ?2

ENTER TOTAL ENERGY DISSIPATION (KW) ?3.53

ENTER MEAN COIL DIAMETER (IN) ?22.235

ENTER CONVECTION COEFF. IN W/IN**2/C (DEF 0.29307) ?

ENTER THICKNESS OF ALUMINUM, IN INCHES ?0.020

ENTER THICKNESS OF MYLAR, IN INCHES ?0.00184

ENTER THERMAL CONDUCTIVITY (W/IN/C) (DEF 0.00308) ?0.00293

ENTER RATIO OF ENERGY DISTRIBUTION IN SKIN AREA TO BULK, R ?1.12

AXIAL POSITION
INCHES

TEMPERATURE RISE
CENTIGRADE

TEST*)

$K_s = \frac{1}{1 + 1.25 \left(\frac{1.75}{22.235} \right)^2} \cdot 2.916 \cdot 0.84 \cdot .92$	0.00	17.2160	+.92 = 15.8°C	16.9°C
	2.00	17.2328		
	4.00	17.2844		
	6.00	17.3740		
	8.00	17.5065		
	10.00	17.6875		
	10.50	17.7411		
	11.00	17.7984		
	11.50	17.8599	+.92 = 16.40	18.0°C
	12.00	17.9262		

A) HEAT TRANSFER FROM H-W

TRANSIENT WINDING RISE PROFILE FOR RANDOM OR CYCLIC LOADING

CHART 5.540

FIGURE 1. CORE THERMAL MODEL - YOKE/LEG THERMAL ANALYSIS SECTION

FIGURE 3. YOKE LEG CORE SECTION BOUNDARY CONDITION FACE DEFINITION

FIGURE 5. NODAL GRID CONFIGURATION FOR YOKE/LEG REGION

TABLE IX

CORE THERMAL MODEL - HP INPUT

<u>HP Prompt</u>	<u>Notation</u>	<u>Prototype</u>
Gauss Seidel Iterations Desired?		100
System Pressure (psia)?	P	15
Core Loss (Watts)?		25,300
Core Loss (watts/in ³)?	Se	0.24
Core Space Factor?		1
Core Panel Height (in)?	L	97
k _p Parallel (Watt/in/C)?	k _p	13
k _d Perpendicular (Watt/in/C)?	k _d	0.5
Mean Coolant Temperature (C)?	T _f	36.5

Boundary Conditions

<u>Face No.</u>	<u>Boundary</u>	<u>Fluid</u>	<u>T_f (C)</u>	<u>Cooling</u>	<u>Flow (gpm)</u>	<u>No. Ducts</u>
1	Fluid	Air	41.7	Free	-	-
2	Fluid	Air	41.7	Free	-	-
3	Adiabatic	-	-	-	-	-
4	Fluid	R113	41.0	Forced	2.4	8
5	Fluid	R113	33.2	Forced	6.9	1
6	Adiabatic	-	-	-	-	-

Duct Information

<u>Face No.</u>	<u>Duct (in) Thickness</u>	<u>Duct Width (in)</u>	<u>Duct Aspect Ratio</u>	<u>Fraction Effective</u>
4	.048	11.5	.05	1
5	.076	21.0	.05	1

<u>HP Prompt</u>	<u>Notation</u>	<u>Prototype</u>
Leg Thickness to Duct Wall (in)?		11.5
Yoke Height (in)?		11.5
Yoke Width (in)?		3.625

CORE TEMPERATURE DISTRIBUTION - Finite Difference Solution
Gauss Seidel Iterations =100

TABLE X - HP OUTPUT

Fluid #4

PROPERTIES AND CHARACTERISTICS

Heat Generation	= 0.240 Watts/in ³
Total Core Loss	= 25300 Watts
Core Coolant Flow Rate	= 26.5 gal/min
Core Space Factor	= 1.000
k parallel	= 0.571 Watts/in/C
k perpendicular	= 0.022 Watts/in/C
Core Leg Thickness to Duct Wall	= 11.50 Inches
Core Yoke Height	= 11.50 Inches
Core Yoke Thickness to Symmetry	= 3.63 Inches
Average Coolant Temperature	= 36.5 C
Mean Coolant Core Top/Bot Rise	= 10.9 C

Fluid #	h(Watts/in ² /C)	Temp(C)	Fluid	Mode	Flow(gpm)
1	0.00918	41.7	AIR	Free	0.00
2	0.00164	41.7	AIR	Free	0.00
4	0.17002	41.0	R113	Forced	2.40
5	0.24305	33.2	R113	Forced	6.90

Core Nodal Heat Generations (Watt/in³)

0.240	0.240	0.216	0.308	0.400	0.492
0.240	0.240	0.225	0.317	0.464	0.446
0.240	0.240	0.234	0.436	0.418	0.400
0.240	0.240	0.243	0.390	0.372	0.354
0.240	0.240	0.252	0.344	0.326	0.308
			0.298	0.280	0.262
			0.252	0.234	0.216
			0.240	0.240	0.240
			0.240	0.240	0.240
			0.240	0.240	0.240

CHART 555

Radial Layer # 1

Core Nodal Temperatures (C)

79°C

TABLE X - Cont.

	63.3	63.4	63.4	63.4	60.2	51.1
	67.1	67.3	67.4	67.5	63.6	52.8
70°C	69.0	69.3	69.8	70.4	65.5	53.6
	69.2	69.6	70.5	71.6	66.2	53.7
70°C	67.5	68.0	69.2	71.8	66.2	53.4
				72.0	65.9	53.0
				71.8	65.4	52.6
				71.6	65.2	52.5
				71.5	65.1	52.4
				71.4	65.1	52.4
				70°C	66°C	54°C

PROTOTYPE CORE HEAT RUN

Radial Layer # 2

Core Nodal Temperatures (C)

60.1	60.3	60.6	61.0	58.7	50.6
63.3	63.6	64.2	64.8	61.9	52.1
64.9	65.4	66.4	67.8	63.9	52.9
65.1	65.7	67.2	69.3	64.8	53.1
63.7	64.4	66.3	70.0	65.1	52.9
			70.8	65.0	52.6
			71.0	64.8	52.5
			71.0	64.8	52.2
			71.0	64.8	52.2
			71.1	64.8	52.2

Radial Layer # 3

Core Nodal Temperatures (C)

51.6	51.9	52.4	53.6	53.3	49.2
53.2	53.7	54.7	56.5	56.2	50.4
54.1	54.8	56.6	59.9	59.8	51.4
54.3	55.3	58.3	63.9	62.0	51.9
53.6	54.9	59.7	66.4	63.1	52.1
			68.7	63.7	52.0
			69.7	64.0	51.9
			70.2	64.2	51.9
			70.5	64.4	52.0
			70.6	64.4	52.0

$$\max[\text{abs}(T_{1100} - T_{199})] = 0.022 \text{ C}$$

CHART 556

COIL HOT SPOT TEMPERATURE

$$T_{HS \text{ coil}} = \Delta T_{\text{coil}} + \Delta T_w + \Delta T_f/2 + \Delta T_{HX} + T_a$$

$T_{HS \text{ coil}}$ = DESIGN COIL HOT SPOT TEMPERATURE

ΔT_{coil} = COIL HOT SPOT RISE OVER DUCT WALL

ΔT_w = MEAN DUCT WALL RISE OVER MEAN COOLANT FLUID

ΔT_f = MEAN COOLANT RISE WITHIN DUCT

ΔT_{HX} = HEAT EXCHANGER DUTY OVER AMBIENT

T_a = AMBIENT DESIGN TEMPERATURE

50 MVA GIT COIL RISE OVER DUCT WALL

$$\Delta T_{\text{coil}} = 40^{\circ}\text{C} (7/n_d)^2$$

n_d = NUMBER OF EFFECTIVE 360° CONCENTRIC COOLING DUCTS.

COIL DUCT WALL RISE OVER COOLANT FLUID

$$\Delta T_w = \frac{2Xq_w}{a_1 k R_e^\alpha P_r^\beta}$$

X = DUCT RADIAL THICKNESS

q_w = MEAN DUCT WALL HEAT FLUX [=] WATTS PER IN²

k = COOLANT THERMAL CONDUCTIVITY

R_e = REYNOLDS NUMBER - DEFINED EARLIER

P_r = PRANDTL NUMBER $C_p \mu / k$

C_p = COOLANT SPECIFIC HEAT

μ = COOLANT VISCOSITY

a_1, α, β = FORCED CONVECTION PARAMETERS

- LAMINAR FLOW - $R_e \leq 2100$

$$a_1 = 3.66, \alpha = 0, \beta = 0$$

- TURBULENT FLOW - $R_e > 2100$

$$a_1 = 0.23, \alpha = 0.8, \beta = 0.4$$

COOLANT FLUID RISE WITHIN DUCT

$$\Delta T_f = \frac{2\pi D L q_w}{C_p \omega}$$

D = MEAN COIL DIAMETER

L = LENGTH OF COOLING DUCT

q_w = MEAN DUCT WALL HEAT FLUX

C_p = COOLANT SPECIFIC HEAT

ω = MEAN COOLANT FLUID MASS FLOW RATE WITHIN DUCT

CHART 560

HEAT EXCHANGER DUTY

- LIQUID TO FORCED AIR - 50 MVA PROTOTYPE

$$\Delta T_{HX} = 25^{\circ}\text{C}$$

- GAS TO FORCED AIR - 50 MVA PROTOTYPE (SAME SIZE AS LIQUID)

$$\Delta T_{HX} = 40^{\circ}\text{C}$$

TRANSFORMER COIL COOLING DUCT FRICTION LOSS

$$\phi_{\text{loss}} = n_d \frac{fL}{(\rho\pi D)^2} \left(\frac{\omega}{X}\right)^3$$

ϕ_{loss} = COIL DUCTS FRICTION LOSS [=] Kilo Watts

n_d = NUMBER OF EFFECTIVE 360° CONCENTRIC COOLING DUCTS

f = DARCY FRICTION FACTOR

$$f = \begin{cases} 24/Re & Re < 2100 \\ .119/Re^{.25} & Re \geq 2100 \end{cases}$$

Re = REYNOLDS NUMBER

$$Re = \frac{2\omega}{\pi D\mu}$$

L = LENGTH OF COOLING DUCT

D = MEAN COIL DIAMETER

X = DUCT RADIAL THICKNESS

ρ = COOLANT FLUID DENSITY

μ = COOLANT FLUID VISCOSITY

ω = MEAN COOLANT FLUID MASS FLOW RATE WITHIN DUCT

FLUID PHYSICAL PROPERTIES

- DENSITY

- R113 LIQUID - 1.57 g/cc
- SF₆ GAS - 0.02 g/cc

- SPECIFIC HEAT

- R113 LIQUID - 0.23 cal/g/C
- SF₆ GAS - 0.16 cal/g/C

- VISCOSITY

- R113 LIQUID - $1.87 \times 10^{-4} \exp(1053/(T+273))$ Poise
- SF₆ GAS - 1.6×10^{-4} Poise

- THERMAL CONDUCTIVITY

- R113 LIQUID - 1.4×10^{-4} cal/sec/cm/C
- SF₆ GAS - 3.5×10^{-5} cal/sec/cm/C

SF₆ GAS ALTERNATIVE COOLING CONCEPT

50 MVA PROTOTYPE TRANSFORMER

- DESIGN AIR TEMPERATURE - 40°C
- MEAN COIL DIAMETER - 43 IN.
- COIL HEIGHT - 56 IN.
- COIL POWER LOSS - 4.2 Kw
- HEAT EXCHANGER - 25°C LIQUID DUTY, 40°C GAS DUTY

Case A. Cooling Failure Transient

$$\frac{dT_{\text{coil}}}{dt} = \frac{Se}{\rho \text{ Cp}} \quad (1)$$

Case B. Overload Transient

$$T'_{\text{coil}} = T_{\text{am}} + L^2 (T_{\text{coil}} - T_{\text{am}}) \quad (2)$$

$$T'_{\text{freon}} = T_{\text{am}} + L^2 (T_{\text{freon}} - T_{\text{am}}) \quad (3)$$

$$L^2 = \frac{Se'}{Se} \left(0.7 \frac{225+T'_{\text{coil}}}{225+T_{\text{coil}}} + 0.3 \frac{225+T_{\text{coil}}}{225+T'_{\text{coil}}} \right)$$

$$t = - \frac{1}{\alpha} \ln \left(\frac{T'_{\text{coil}} - \frac{\beta}{\alpha}}{T_{\text{coil}} - \frac{\beta}{\alpha}} \right) \quad (4)$$

$$\alpha = \frac{Se}{\rho \text{ Cp} (T_{\text{coil}} - T_{\text{freon}})}$$

$$\beta = \frac{Se' + Se T'_{\text{freon}} / (T_{\text{coil}} - T_{\text{freon}})}{\rho \text{ Cp}}$$

Chart Equations for Different Transients

CHART 566

Chart Temperature Rises under Overload

Load, %	H.S./Freon, °C	Freon/Am, °C	H.S./Am, °C	H.S., °C
100	40.0	25.0	65.0	105.0
110	49.3	30.8	70.1	120.1
120	60.0	36.5	97.5	137.5
130	72.4	45.2	117.6	157.6
140	86.6	54.1	140.7	180.7
150	103.2	64.5	167.7	207.7

Ambient Temperature = 40°C

Chart Steady State Coil Hot Spot Temperature vs Percent Load

CHART 568

Chart Time to Reach Certain Maximum Coil Hot Spot
Temperature vs Percent Load

CHART 569

5.6 MATERIALS (TASK 1260)

The Mylar aging work during the past quarter has been directed to the continued evaluation of the electrical changes which can occur in the film during prolonged aging in SF_6 . In order to record the dissipation factor (DF) of the Mylar film, flat electrode test pieces were used in this work. A schematic drawing of these test pieces is shown in Chart 6.1. The DF of the Mylar film was measured as a function of time at the test temperature. The aging test conditions and the test results are shown in Chart 6.2.

As the data in Chart 6.2 show, no significant changes have been observed in the DF of the Mylar film under any of the test conditions. In each case, the time at the test temperature was sufficient for the physical properties (tensile and burst strength) of the film to have been reduced to 50% or less of their initial values. Forty days at 145°C is approximately the time required to reach 50% retention of the physical properties. The 40 day exposure is well beyond the time required for 50% loss at 160°C (approximately 20 days required) and at 175°C (approximately 4 days required). Neither electrical stress (100 v/mil) nor water (up to 1000 ppm of the film weight) appear to have an observable effect on the DF of the Mylar film. After forty days at 160°C , no significant changes have been observed in the DF of the Mylar film when aged at 100 VPM stress with either 100 or 1000 PPM water.

It appears that the aging of the Mylar film/ SF_6 insulation system results in physical degradation of the film well before any changes can be observed in the electrical properties as measured by DF. Thus the use of the physical changes to determine a limit for the application conditions, should provide an adequate safety margin for the electrical performance of the insulation system.

In an effort to determine if a low level corona would be detrimental to the aging characteristics of the Mylar film, sealed glass tubes as shown in the schematic drawing on Chart 6.3 were made. Each tube contains the following materials:

- 6 - 1/2" x 7" x .013" core steel strips
- 2 - 3/4" x 6" x .017" aluminum strips
- 1 - Aluminum shield and cap
- 1 - 1-1/4" x 11/16" x .090" tank steel pieces
- 1 - 1/4" x 4" x .025" stainless steel pieces
- 1 - 1" x .0403 dia. copper wire pieces
- 1 - 1/2" x 7/8" x .050 glass epoxy pieces
- 1 - 1/2" x 1/2" x .25 polymer concrete pieces
- 10 - 1/2" x 5" x .001 Mylar tensile strips
- 1 - 8" x 11-1/4" x .001 Mylar strip

After drying, four tubes were filled with 118 cm^3 of SF_6 and four tubes were filled with 118 cm^3 of SF_6 and 1.7 cm^3 of R-113 before sealing. One of each type of tube is being aged at 145°C under a stress of 17.50 KV with a corona level of 80-150 pico-coulombs. Identical control tubes (without corona) are being aged for the same time period (10 days).

CHART 6.1 TEST CELL FOR VOLTAGE STRESS TESTS
The whole assembly is held together by three
PEEWEE spring clips(not shown).

Chart 6.2

Change in Dissipation Factor Occurring in Mylar Film During Aging

Water (ppm)	Stress (v/mil)	Temperature (°C)	Total Time (days)	Dissipation Factor (%)		
				Initial	Final	Average
dry	0	175	40	4.5	6.0	5.2±1.0
dry	0	160	40	4.8	4.2	3.5±1.6
dry	0	145	40	1.8	4.0	3.9±1.1
dry	100	160	40	1.0	0.85	0.95±0.15
100	0	160	40	2.1	1.0	1.2±0.03
1000	0	160	40	2.1	1.0	1.2±0.03
100	100	160	40	3.0	0.8	1.05±0.55
1000	100	160	40	1.7	0.8	0.95±0.23

Corona Aging Tube

5.7 PROTOTYPE (TASK 1270)

A decision was made to build a full size short circuit model (SC #8) before proceeding with the prototype. However we will use the core, tank, disk bushings, cooling system and controls and accessories as planned for the prototype. This design will utilize a two winding coil in a low-high configuration.

Cooling Panel Headers

The short circuit tests on SC Coil #7 revealed some inadequacies in the header design. During a short circuit, high radial forces are generated which in turn create high cooling panel pressures in the range of 2000 PSI. During the SC Coil #7 tests, the oven brazes on the panel headers yielded as the header walls expanded allowing Freon to leak from the system. Concerned whether our full size panels would do likewise, we performed some static pressure tests and evaluation on the headers. We had already undertaken some analytic evaluation of pressure pulses due to a short circuit and their effect on the coolant pipes. These analytic calculations were undertaken to determine if flexible cooling pipes or a pulse absorber would be beneficial or necessary near our cooling panels. Calculations by our Fluids Engineers in the Materials Lab showed that if we assume a non-expanding header, the pressure seen at the outlet of the header would be approximately 45% of the generated internal panel pressure. In the case of a full size unit, panel pressure could be approximately 2500 PSI. Their calculations indicated that flow would increase from 11.4 gpm steady state to 12.2 gpm during the approximate 14 millisecond pulse. This converts to a volumetric increase of .04 in³. If this volume increase could be absorbed, the pressure pulse would be dissipated. This led us to conclude that a flexible pipe of some form or a pulse absorber would be most expedient. Further investigation was planned when the results of SC Coil #7 were revealed. Our immediate concern was to determine if header design problems existed on the panels presently being built. Our first test as shown in Chart 7.1 was intended to determine if the header as is could withstand a substantial volumetric increase and the types of pressures it took to expand the header. A sample as is header was TIG welded to a 1/16" stainless steel plate and hydraulically pressurized via the header pipe. The header showed dramatic expansion without any leaks. Chart 7.2 shows some header test specimens and test equipment used in our evaluation.

Chart 7.3 shows the results of an attempt to stiffen the header to prevent expansion. This showed that we could stiffen the header if necessary making it good for 1500 PSI with little expansion.

In carrying further the use of an absorber to dissipate the pressure pulse, we pursued the possibility of using the header itself as the absorber. Chart 7.4 shows the data of a test to determine the amount of expansion necessary to yield the material. According to our calculations we should be able to withstand a pressure pulse and fully recover without any harm to the header. We are therefore going ahead with using these TIG welded headers on our SC Coil #8 model.

To further substantiate our results we used the smaller oven brazed header off the SC Coil #7 in similar tests. The data in chart 7.5 shows very little expansion in the header before the seams start leaking. This header hasn't any appreciable pulse absorber capability and therefore ruptures.

Epoxy Disk Bushings

The 18", 345 KV epoxy disk bushing for the CGIT prototype has passed all 130% tests. The test setup used in our High Voltage Laboratory is shown in Chart 7.6. As reported in our 11th Quarterly Report the initial 18" Disk Bushing failed to meet the 130% voltage level. In performing the modifications as described in that report we found that we still had a slight offset between the outer ring electrode and the epoxy disk due to manufacturing tolerances. The offset was a fraction of the previous one but problems still existed. After lengthy discussions with the High Voltage Laboratory Engineers, we added a bead of epoxy in the corner, as shown on Chart 7.7, to eliminate any possible stress risers due to a sharp conductive edge left after machining. The test fixture was also modified to eliminate a possible high stress region.

Chart 7.8 summarizes the results of the 130% dielectric tests on the 18" disk bushing after these modifications were performed. Tests included 60 hz and positive and negative switching surge, full wave and 3 microsecond chopped wave at 100, 110, 120, 125 and 130% levels. Both sides of the disk bushing had SF₆ pressurized to 45 PSIG.

A spare 18" epoxy disk bushing is ready for test if needed. Meanwhile four more of the 12" epoxy disk bushings have been made and are ready for mechanical and electrical tests (one has already been tested as reported in the 6th Quarterly Report).

Cooling System, Controls and Accessories

The cooling system assembly as per sketches in the 13th Quarterly Report was started and is progressing well. We are continuing to pull together necessary accessories for the prototype and have had preliminary discussions on the design of the transformer controls. A system schematic was generated and reviewed by team members, see Chart 7.9. Several worthy suggestions were incorporated into the design. As a result of these discussions and further work we decided to use several different coolant hoses on the SC Coil #8 to determine the effect of rigid and flexible pipe under short circuit.

Core Shields

The shielded core cylinders were tested as described in the dielectrics section of this report. After determining that we had dielectric problems with voids in the epoxy fiberglass cylinder over the strip shields, we examined the sheet core strip shields under a high power microscope. These types of shields would be used for dielectrically shielding the core steps and other sharp corners. The microscope examination revealed a few voids, see Chart 7.10 which could be a source of corona in an operating transformer. We will develop a better process which will eliminate these voids.

CGIT PROTOTYPE

COOLING PANEL HEADERS

EPOXY DISK BUSHINGS

SYSTEM SCHEMATIC

CORE SHIELDING

0

CHART 7.0

PRESSURE (PSIG)	Dimension at	
	A (in.)	B (in.)
0	1.000	.375
150	1.050	.445
200	1.065	.484
220	1.085	.505
240	1.137	.525
250	1.164	.625
260	1.245	.866
280	1.329	1.024

FULL SIZE PANEL HEADER (AS IS) STATIC PRESSURE TEST

CHART 7.1

56" PANEL HEADER TESTS

CHART 7.2

PRESSURE (PSIG)	DIMENSION AT				
	A	B	C	D	E
0	.950	.961	.980	.348	.353
400	.952	.964	.981	.351	.356
500	.954	.964	.981	.354	.365
800	.958	.964	.987	.358	.363
1000	.982	.968	.996	.358	.368
1200	.984	.974	1.000	.364	.370
1500	.989	.984	1.005	.376	.393
1700	Leak in weld along pipe seam				
	Rewelded				
1650	Leak in weld along pipe seam				

FULL SIZE PANEL HEADER (WITH 17 SUPPORT PINS)

PRESSURE (PSIG)	DIMENSION AT	
	A (In.)	B (In.)
0	.348	.987
10	.349	.988
20	.353	.989
30	.357	.990
28	.353	.990
40	.357	.992
28	.353	.990
50	.361	.993
30	.354	.990
60	.362	.994
20	.353	.990
70	.366	.998
30	.354	.990
80	.369	.997
30	.354	.990
100	.372	.999
30	.354	.990
120	.375	1.005
30	.357	.991
140	.382	1.007
30	.357	.990
160	.392	1.012
30	.359	.992
180	.409	1.019
30	.365	.996
200	.424	1.026
30	.381	1.012
220	.432	1.037
30	.400	1.012

FULL SIZE PANEL HEADER (WITH .037" - THINNED SECTION CUT AWAY) STATIC
PRESSURE TEST

CHART 7.4

PRESSURE (PSIG)	DIMENSION AT	
	A (In.)	B (In.)
0	.239	.736
20	.245	.739
30	.247	.737
40	.251	.738
27	.248	.737
52	.245	.737
70	.242	.739
82	.242	.740
90	.242	.738
100	.242	.738
110	.246	.740
120	.245	.740
27	.240	.737
135	.247	.740
150	.250	.741
27	.241	.737
170	.250	.742
190	.251	.743
210	Leak visible at bottom plate, sealed back up	
260	.259	.749
	Leaking slowly at 260, source not visible	
320	Visible leaks along fill piece along pipe seam and end cap	
0	.255	.749

SC COIL #7 OVEN BRAZED PANEL HEADER STATIC PRESSURE TEST

CHART 7.5

Epoxy Disk Bushing Test Setup

CHART 7.6

EPOXY DISK BUSHING OUTER ELECTRODE CONFIGURATION

SUMMARY OF HIGH VOLTAGE DIELECTRIC STRENGTH TESTS
ON 18" EPOXY DISK BUSHING

<u>VOLTAGE LEVEL</u>	<u>TEST</u>	<u>SHOT</u>	<u>RESULTS</u>
130%	+ 1365 KV FULL WAVE	5	NO BREAKDOWNS
	- 1365 KV FULL WAVE	5	"
130%	+ 1570 KV 3 μ S CHOPPED WAVE	5	"
	- 1570 KV "	5	"
130%	+ 1131 KV SWITCHING SURGE	10	"
	- 1131 KV "	10	"
130%	598 KV 60 HZ	1 Min.	"

NOMENCLATURE

- 1 FLOW METER
- 2 DENSITY MONITOR
- 3 PR-VAC GAGE
- 4 TEMP GAGE
- 5 PR RELIEF VLV
- 6 LIQ LEV GAGE
- 7 PR GAGE

CGIT SYSTEM SCHEMATIC

CORE SHIELD

5.7 - 13

CHART 7.10

5.8 ACCESSORIES

DISSOLVED GAS SEPARATOR TEST PROGRAM

A report was written which describes the test program recommended for evaluating the gas separator built as an ancillary component for the compact gas insulated transformer. The test loop which was fabricated to evaluate short circuit coils #6 and #7 will be used to evaluate the prototype gas separator.

The primary objective of the test program is to evaluate the performance of the separator during a manual purge operation. Testing will include evaluating the effect of key variables (heat input, feed rate and coolant temperature) on the performance of the separator over the expected operating range of these variables in the field. In addition, verification test will be performed to establish that the controls are working satisfactorily.

Estimated time of testing is five days. Personnel required include an engineer and a technician. Five days of analysis is expected in order to analyse and report the results.

Description Test Loop

The separator test loop is located in Bldg. 9E of the Materials Laboratory. The test loop consists of a primary loop where Freon^R R113 flow can be maintained at 30 gpm using valves #3 and #4. A bypass to the primary loop is used to feed the separator at 0.5 gpm. Chart 8.1 is a sketch of the envisioned test loop. A displacement pump is used which delivers flow at 90 gpm. A bypass to the pump is required to maintain the 30 gpm flow through the main loop. The recommended location for mounting the separator and the separator feed preheater is across the cooler. The maximum heat duty of the water cooled heat exchanger is 5 kW. The water cooler will be used to regulate the temperature of the coolant loop during quasi steady state operation. Chart 8.2 lists the test loop control valves and their respective functions. Chart 8.3 provides a time schedule for the project. Chart 8.4 summarizes the manpower requirement for the suggested test program.

Chart 8.5 lists the suggested separator test to be performed to evaluate the separator performance as a function of start up and quasi steady state operation. Two feed temperatures are suggested to evaluate the heat requirement during anticipated summer and worst case winter conditions. Chart 8.6 lists the operating procedure for saturating the Freon^R coolant with SF₆ gas. The recommended saturation concentration is equilibrium at 30 psia pressure and 25 C temperature. At this saturation temperature and pressure condition cavitation and possible damage to the coolant pump can be prevented at test pressures of 60 psia. Chart 8.7 lists the operating sequence suggested for purging the coolant system of dissolved gas (air or SF₆). Chart 8.8 provides a set of verification tests to be performed to evaluate that each of the control functions of the separator is operating properly.

5.8 Accessories

DISSOLVED GAS DETECTOR

A patent docket was prepared for an online dissolved gas detector. A sketch of the proposed gas detector is shown in Chart 5.12. The method for detecting dissolved gasses is by lowering the coolant pressure using a sharp edge orifice which thereby induces local cavitation of dissolved gas. The gas will again dissolve as the velocity profile reestablishes itself leaving the detector. An audio sensor can be used to monitor vibrations released during gas cavitation and gas bubble collapse. It is believed that the intensity of audio vibration is directly proportional to the dissolved gas concentration.

Equations were developed for sizing the orifice of the detector. Chart 5.12 lists typical design characteristics that would create a 9.28 psi drop across the orifice based on a 1.38 psi main coolant driving force and a 20 gpm coolant flow.

REV
NO.

TITLE

CONT ON SHEET

SH NO.

GAS SEPARATOR TEST SYSTEM

CONT ON SHEET

SH NO.

FIRST MADE FOR

REVISION:

PRINTS TO

MADE BY

Alverson June 29, '83

ISSUED

APPROVALS

5.8 - 3

DIV OR
DEPT.

CHART 8.1

LOCATION

CONT ON SHEET

SH NO.

CODE IDENT

CHART _

Fluid Flow
Control Valve

Description

1	Sump Valve
2	SF ₆ Cylinder/Coolant Loop Feed Valve
3	Primary Bypass Valve
4	Primary Loop Control Valve
5	Separator Feed Valve
6	Drain Valve

CHART 8.2

CHART 8.3
TIME TABLE

	<u>June</u>				<u>July</u>				<u>August</u>	
	<u>23</u>	<u>24</u>	<u>25</u>	<u>26</u>	<u>27</u>	<u>28</u>	<u>29</u>	<u>30</u>	<u>31</u>	<u>32</u>
<u>Equipment Accrual</u>										
Preheater, LL Gauge Sight Gauge, 3 Temp. Probes, Flow Meter	o									
Separator Tank		o								
LL Control Package & Heaters								o		
Test Loop to 9E			o							
<u>Assembly</u>										
Clean Tank, Install Probe & Gauges			o							
Plumbing & Leak Proof				o						
Install Heaters, Control Package & Debug								o		
<u>Tests</u>										
Test & Chemically Eval. Analysis & Report									o	o

CHART 8.3

CHART 8.4

CGIT Gas Separator Test Program
Assembly and Test Labor Requirements

<u>Task</u>	<u>Schedule</u>	<u>SE</u>	<u>E</u>	<u>ST</u>	<u>T</u>
1. Clean Tank, Install Probes & Gages	FW 25	0	0	16	0
2. Plumbing and Leak Proof	FW 26	0	0	32	0
3. Install Headers and Control Package	FW 30	8	0	40	0
4. System Tests	FW 31 & 32	8	0	40	0
5. Chemical Analysis	FW 31 & 32	0	16	0	0
6. Analysis and Report	FW 32 & 33	<u>32</u>	<u>0</u>	<u>0</u>	<u>4</u>
Total Labor		40	16	88	4

CHART 8.4

CHART 8.5

Separator Tests

- o Separator Heat Requirement
 - o Cold Feed (Simulate Cold Ambient Purge - Worst Case)
 - o Water cooled heat exchanger activated
 - o Vary separator feed rate
 - o Vary separator variac setting
 - o Hot Feed (Simulate Summer Ambient Purge)
 - o Cooler off
 - o Vary Separator feed rate
 - o Vary Separator variac setting
- o Dissolved Gas Purge Operation
 - o Saturate Coolant with SF₆ at RM temperature and 30 psia pressure using pump.
 - o Sample coolant to determine initial dissolve gas concentration. Gas chromatography will be used to analyse the sample.
 - o Adjust sump pressure using pressurized air to 60 psia.
 - o Adjust primary coolant flow to 30 gpm.
 - o Close feed valve to separator.
 - o Adjust separator variac setting to optimal value based on earlier test.
 - o Verify steady state heat up has been achieved (liquid level ocillation).
 - o Open variac feed valve and adjust flow to optimal feed setting established earlier.
 - o Monitor gas purge operation.
 - o Coolant dissolved gas concentration (chemical analysis and dissolved gas detector).
 - o Coolant, separator pot, preheater and condenser temperatures.
 - o Purge SF₆ when condenser region cool (10C lower than pot temperature). Purge slowly to prevent pot temperature from lowering more than 1 degreeC. Vent gas to outside via plastic tubing.
 - o Establish minimum coolant dissolved gas concentration and time required to attain.

CHART 8.6

SF₆ SATURATION OPERATION

- o Close valve #1 (Sump Outlet)
- o Activate coolant pump
- o Open SF₆ Feed valve #2
- o Adjust SF₆ gas cylinder pressure to 30 psia
- o Allow time to attain saturation equilibrium (room temperature, 30 psia pressure) as noted by cavitation within coolant pump. Turn off pump at this point.
- o Close SF₆ Feed valve #2
- o Adjust Sump pressure to 60 psia of Nitrogen within atmoseal bag
- o Open Sump valve #1
- o At this point Freon R113 coolant should be saturated close to 30 psia and 25 C concentration level

CHART 8.7

Separator Manual Operation

- o Adjust system pressure to 60 psia via sump (nitrogen cylinder)
- o Activate coolant pump and water coolant into HX
- o Adjust primary coolant flow to 30 gpm.
- o Close feed valve to separator.
- o Activate separator (variac setting 50% rated).
- o As a function of time
 - o Monitor separator pot temperature
 - o Monitor separator liquid level
 - o Monitor separator condenser temperatures
 - o Monitor separator power requirementatures
- o When quasi steady state operation is achieved (liquid level ocillating between upper liquid level sensors, open separator feed valve. Adjust separator feed to 0.5 gallon per minute (flow meter).
- o As a function of time monitor
 - o Time period of liquid level cycle
 - o Pot temperature
 - o Condenser temperatures
- o Purge air from upper separator region if required and monitor separ-vitals

CHART 8.8

Control Functions Needing to be Verified on Wellman Control System

Dwg. 40D424876 Sheet No. 2

1. Freon Liquid Overtemp Control
Tc probe to Honeywell Dialapak Controller #1 (Manual Reset on O.T.-
Auto reset on power failure - alarm light - 0-200°C)
Controls G.E. Def Purp contactor in series with (2) and (3)
2. Heater (Middle) Overtemp Control
Heater Tc to Honeywell Dialapak Controller #2 (Same as 1 except range
0-400 C) °
Controls G.E. Def Purp contractor in series with (1) and (3)
3. Emergency Low Level (3" High) Control
Bottom float switch of gems liquid level switch -
Controls Potter-Brumfield contractor which in turn controls G.E. Def Purp
contactor in Series with (1) and (2)
4. Normal Upper Level Control (11.5" High)
Top float switch of gems liquid level switch to "on" terminal of gems
flip-pak - controls Omega Solid state relay (which controls power to top
heater)
5. Normal Lower Level Control (7.5" High)
Middle float switch of gems liquid level switch to "off" terminal of gems
flip-pak - controls . Omega solid state relay (which controls power to
top heater).

CHART 8.8

5.8 - 11

CHART 8.9

ON LINE GAS DETECTOR DESIGN

Main Pipe Diameter = 1.5 in
Side Pipe Diameter = 0.50 in
Orifice Diameter = 0.25 in
Main Pipe Length = 12.0 in
Side Pipe Length = 16.0 in

<u>Parameter</u>	<u>Main</u>	<u>Side</u>
Flow Rate (gpm)	16.61	3.39
Pressure Drop (psi)	1.38	9.28
Reynolds Numbers	124407	76128

5.9 COMMERCIALIZATION (TASK 3000)

At the beginning of this period we generated an outline type of questionnaire to provide guidance for a five (contract spec) Customer Survey. We visited Con Edison (Noah Tai and Leo Sevis) to evaluate the approach and found that the interaction and information transfer was good, but very subjective with a personal understanding bias limitation. Based on this experience we were given guidance to contact our General Electric Corporate Marketing Consulting Services and obtain help to build a better questionnaire. Corporate Marketing (Dave McLean) organized a questionnaire to provide:

- . An introductory portion where questions of business size, and scope, and growth were identified.
- . Introduction question on value of characteristics and prior knowledge of CGIT were identified.
- . A period where the concept is discussed using slides and a summary of characteristics.
- . Questions on reactions to advantages and disadvantages of CGIT.
- . Questions on possible purchases and timing.

They were concerned about the General Electric Co. bias if the survey was conducted only by W.H. Rathbun and we were urged to include an outside consulting concern in the process. They recognized the need for a CGIT Program participant to present the technical presentations and discussions but were concerned about the bias question if the survey is only conducted by CGIT personnel.

We took the advice and obtained Power Transformer Marketing participation and were accompanied by an outside Marketing consultant the first two interviews. The integration with Marketing provided good customer contacts and meeting coordination. The consultant from Smith, Stanley & Co. felt that as a team we were quite unbiased in our approach and did not excessively lead the customers so that outside consultants were not needed.

Other guidance from Corporate Marketing Consulting Services was that to succeed in a statistically good result we should visit at least 20 customers picking 3 or 4 from the top 10, 4 to 6 from the next 90 and one or two from "friendly" small utilities. After several improving and clarifying revisions of the questionnaire we visited Southern Services Company, Alabama Power Co. and Houston Light and Power companies in late June 1983. The results are not definitive with only three interviews but I was surprised to see how quick they thought they would buy at least one of an equally priced alternative to obtain experience as a hedge against availability of present commercial offerings.

Minor improvements are needed to smooth the questionnaire which will be used on many customers this fall.

UTILITY INDUSTRY
SURVEY FOR COMPACT
GAS-INSULATED POWER
TRANSFORMER PROJECT

**Large Transformer
Division**
PITTSFIELD, MA 01201

GAS-INSULATED
TRANSFORMER PROJECT

GENERAL ELECTRIC

5.9-2

ELECTRIC UTILITY DISCUSSION GUIDE

Utility Name: _____

Respondent's Name: _____

Respondent's Title: _____

Address: _____

Date: _____

Thank you for the time to meet with us. As we explained on the phone, we are conducting a study of the market interest and potential for a new large power transformer in the over 50 mVA range. (INSERT UTILITY NAME) was selected as part of a sample of utilities to which the technical and operational aspects of the concept are being presented. Your response is important to the assessment of the market for the product. Neither you nor the utility will be identified with the responses you give; the results will be reported in aggregate across all utilities sampled.

1. First, I would like to talk about the large power transformers you now have installed . . . those with an FOA base rating of over 50 mVA.

How many transformers this size does your utility currently have in operation? _____

- 2a. Now, so we understand the volume of your likely purchases, how many large power transformers in this size range do you plan to order in total in the next 4 years, 1984-87? SPECIFY mVA (FOA BASE) CATEGORY

FOA BASE mVA RATING	1984 - 1987	1988 - 2000
50.1 to 200		
200.1 to 400		
400.1 and larger		

- 2b. Now, to the extent you can, give me an idea of the range of units of this size you think you will be ordering in the period 1988 - 2000.

3. Now think about the transformers your utility has installed and will be ordering in this size range. In what percent of the situations into which these transformers are or will be placed are each of the following important? (RECORD % AND VERBATIM COMMENTS. MAY USE # OF UNITS, IF MORE APPROPRIATE)

	<u>OF CURRENT/ ANTICIPATED APPLICATIONS</u>	<u>COMMENTS</u>
a. Non-flammability and/or explosion resistance	_____ %	_____
b. Light installed weight and/or reduced size	_____ %	_____
c. Low sound	_____ %	_____

4. Is there a trend with respect to any of these?

5. Are there situations into which oil filled transformers cannot usually now be placed, but into which a lighter, smaller, lower sound transformer with non-flammable coolant in this mVA range could be used if such a technology were now available? For example . . .

(MAY USE UNITS, IF MORE APPROPRIATE.)

	<u>OF CURRENT/ANTICIPATED APPLICATIONS</u>	<u>COMMENTS</u>
Substation in a building or other space saving location	_____ %	_____
Underground locations	_____ %	_____
Other situations not currently feasible	_____ %	_____

6. I'm going to read you some factors that may or may not be important to you when you are evaluating transformers of this size for purchase. Please tell me how important each one is to you by rating it on a scale of 10, with "10" representing "Extremely Important," and "0" "Not Important At All." Numbers between 0 and 10 should be assigned to represent degrees of importance between "Not Important At All" and "Extremely Important." (ASK FOR EACH FACTOR) (SHOW EXHIBIT #1)

Are there any other factors that are important to you when you are considering purchasing transformers of this size? (RECORD AND RATE)

10 = "Extremely Important" 0 = "Not at All Important"	Importance
Non-flammability, explosion resistance	
Reliability	
Initial purchase cost	
Losses	
Total owning cost	
Maintenance required	
Ease of servicing	
Manufacturer	
Short circuit capacity	
Low impedance	
Low sound level	
Transformer size	
Designed for rapid installation	
Lighter installed weight	
Gas bus compatibility	
Quality of design/construction	
Other:	
Other:	

7a. Are you aware of any new transformer technology being developed in this size range?

b. IF UNAWARE OF CGIT. Are you aware of the development of the Compact Gas Insulated Power Transformer?

c. (IF AWARE IN EITHER 7A or 7B) Please describe that technology.

d. What manufacturer is developing this technology?

TECHNOLOGY	7a. AWARE UNAIDED	7b. AWARE AIDED	7d. MANUFACTURER
Compact gas insulated power transformer	Yes ☐ No ☐	Yes ☐ No ☐	
Other	Yes ☐ No ☐		

8. Now, without regard to owning cost, to what degree would this utility be interested in a transformer product in the over 50 mVA range, which has the following characteristics . . .

- Non-oil cooled
- Non-flammable, explosion resistant
- 10-15 dB lower sound
- One-third smaller size
- Lighter installed weight

Extremely interested	()
Somewhat interested	()
Neither interested or disinterested	()

→ Skip to Q10

Somewhat disinterested	()
Extremely disinterested	()

→ Ask Q9

9. What are the reasons for your not being more interested? (PROBE)

10. Next, I would like to introduce to you a more detailed concept statement of the compact gas insulated power transformer.

PRESENT CONCEPT IN DETAIL

- 10a. What advantages do you perceive in this concept? What is the most significant advantage? What other elements do you find appealing? (PROBE FOR SPECIFICS)
- 10b. Do you perceive disadvantages in the concept? What is the most significant disadvantage? What other drawbacks are there? (PROBE FOR SPECIFICS)
- 10c. What other questions, if any, do you have about the technology?

11. Here is a list of components or characteristics which may contribute to the value of the (CGIT, traditional oil filled) transformer (CGIT: Exhibit 1, Oil Filled: Exhibit 2). First, are there components or characteristics not listed which you think may contribute value to this transformer type? ADD TO LIST.

Now here is a list of characteristics which may add value to the (other) transformer type. Are there other characteristics which you feel add value to this type of transformer? ADD TO LIST.

Now, assume the CGIT and oil filled transformer owning costs are in the same range . . . each about \$1 million for the same mVA rated unit.

Take the list of characteristics for the _____ (CGIT, oil filled) transformer. I would like you to divide them into three categories . . . one of components or characteristics which contribute a high degree of value to the overall product, one of those which contribute some value, and one of components or characteristics which you think contribute little or no value.

Now assign a percentage amount to each characteristic corresponding to the value that characteristic contributes to the whole, so that the total of all characteristics sums to 100%. (MAY USE \$)

11a. CGIT Characteristics

	<u>Component Value</u>
Basic operating transformer	_____ %
No oil	_____ %
<ul style="list-style-type: none"> ● Non flammable ● No oil handling ● No oil maintenance ● Low explosion potential ● No oil containment facilities ● No fire deluge equipment 	
Size: 1/3 smaller	_____ %
Weight: lighter	_____ %
Low sound: 10-15 dB lower	_____ %
Losses: 5% - 15% lower	_____ %
Compatibility with CGI equipment	_____ %
Ease of installation	_____ %
Monitoring equipment	_____ %
Gas separator-automated	_____ %
<ul style="list-style-type: none"> ● pressure ● density alarms 	
Other _____	_____ %
	=====
	100 %

11b. Oil Filled Characteristics

	<u>Component Value</u>
Basic operating transformer	_____ %
Reliability	_____ %
Consistency with available equipment	_____ %
• Oil handling equipment	
• Monitoring equipment	
• Interchangeability of equipment	
Conventional	_____ %
• "Known" technology	
• Established standards	
• Station layout	
Trained maintenance force	_____ %
Alternative sources of supply	_____ %
Container, not pressure vessel	_____ %
Other _____	_____ %
Other _____	_____ %
	=====
	100 %

12. What elements are included in your total owning cost in addition to the initial transformer cost . . .

Installation cost	()	Oil handling	()
Losses	()	Maintenance	()
Firewall	()	Insurance	()
Coolant containment	()	Monitoring equipment	()
Oil sump	()	Other _____	()

13. Now let's think again about the transformers you plan to purchase in the over 50 mVA category in the next five years.

If the CGIT I described were available in 1988, with one or more demonstration units having operated successfully in the field to that time, what percent of your utility's orders in the year 1988 - 2000 period would likely be of the oil filled vs. CGIT type, if total owning costs were as follows . . . (USE UNITS IF MORE APPROPRIATE)

OF TOTAL LIKELY ORDERS

	<u>OIL FILLED</u>	<u>CGIT</u>
a. CGIT <u>10% more</u> than owning cost of oil	____ %	____ %
b. CGIT <u>equal</u> to owning cost of oil	____ %	____ %
c. CGIT <u>10% less</u> than owning cost of oil	____ %	____ %

14. (FOR THOSE INDICATING LIKELY CGIT ORDERS) About how long would it be before you ordered CGIT units from the point in time at which the demonstration unit was installed? (PROMPT WITH 3 YEARS . . . 5 YEARS . . . 7 YEARS) _____

15. How would the impact of first cost of the CGIT relative to traditional type transformers have on your likely purchase of the CGIT? That is, what if the CGIT were higher? The same as? Lower?
16. What would the impact of primary owning cost, including first cost and losses, relative to traditional oil filled units have on your likely purchase of the CGIT units? Again, what if the CGIT were higher? The same as? Lower?
- 17a. Please describe the procedure (what formula) you would use to evaluate losses. (PROBE FOR \$ VALUE)
- 17b. Are these conditions under no load or load?
- 17c. How do you evaluate auxiliary losses?
- 17d. What mVA basis do you use in evaluating losses . . . OA, FOA, or other?
18. Routine maintenance on early units is perceived to be higher than on conventional type transformers. To what degree, if any, would this inhibit purchase? (PROBE)

19. If buying a new concept like the Compact Gas-Insulated Transformer, would you require additional testing or levels of test like:

- a. Increase BIL 1/2 step?
- b. Increase BIL 1 step?
- c. Heat runs on each unit?
- d. Overload heat runs?
- e. Different RIV or Partial Discharge Limits?
- f. Special leak testing?
- g. Others?

20. Is there anything about the CGIT that you think would deter its acceptance? (PROBE)

21. Are there any new product features or accessories you would like to see introduced on transformers of this size range? (PROBE FOR SPECIFIC FEATURES)

21a. Finally, for classification purposes, how many mega-watt hours do you sell in total annually?

b. How has this changed over the last 5 years? (PROBE FOR INCREASE OR DECREASE AND % CHANGE)

c. How do you expect it to change in the next 5 years? (PROBE FOR INCREASE OR DECREASE AND % CHANGE)

	ANNUAL MEGAWATT HOUR SALES
Current	_____
Change in last 5 years	_____ %
Expected change in next 5 years	_____ %

Utility Type:

Investor owned	1
Municipal	2
REC	3
Government	4

COMPACT GAS -INSULATED POWER TRANSFORMERS

Introduction

For many years General Electric Company, at its Corporate Research and Development Branch has studied the feasibility of ideas for Future Transformer Concepts. With the advent of the oil embargo in 1972 extra emphasis was placed on this effort, by the additional interest of the Federal Government to bring these studies to more rapid fruition. Many concepts were analyzed for cost, technical feasibility, and probability of success, with the following specific concept being identified for prototypal work.

Concept

The concept for transformers we are offering uses sheet windings, polymer film insulation, Freon cooling and SF₆ gas insulation. The design components are interrelated because the use of SF₆ gas allows the use of polymers not acceptable in oil. The use of film insulation suggests sheet windings. The use of SF₆ gas, a good dielectric, though a poor heat transfer agent, suggests another cooling system. Freon is a good heat transfer agent and also a good dielectric, but expensive. Thus, the concept is not the integration of several independent ideas, but forms a consistent whole because of the interrelationships.

Features:

No Oil	No oil handling equipment. Gas handling equipment is less bulky. No oil containment system required in the event of a leak.
Non-Flammable	Neither SF ₆ nor Freon sustain combustion. Therefore the installation site requires no fire deluge system.
Explosion Resistant	Arcing in gas generates little pressure. Also the pressure vessel will contain any pressure build up and vent it in a specific safe manner.
Short Circuit	Strength of sheet windings is inherently high, improving reliability.
Lower Impedance Designs Cost Less.	Characteristics of sheet windings permit less expensive low impedance designs than conventional transformers. Thus the economically optimum impedance is at a lower value than a comparable oil design.
Overload Capability	The CGIT will be designed to meet any specified overload. Quicker transient response requires design adjustment for high short time overloads.

Low Sound

The fact that there is a compressible material between the core and coils, and the tank is expected to reduce the sound level similar to a double wall tank design.

Complete mechanical isolation of the core mounting from the tank is required to minimize flexing and an energy adsorber must be installed in the tank to reduce internal sound energy build-up. 10 to 15 db lower sound appears achievable, but it will cost extra for the special mechanical design features. Inherent with these features is the "double wall", shipped in place, for good savings in cost and installation time.

Environmentally More Compatible

Spills or leaks do not affect the environment. Reduced sound available with minor mechanical design effort.

Compact Size

Size measured by volume is reduced by approximately 1/3.

Rapid Installation

Unit arrives at site sealed with disk bushings at tank wall and approximately one atmosphere gas pressure internal. Unit may be "topped off" with SF₆, and the Freon system filled and pressurized in a short time for quick energization, thus reducing field labor costs. This also suggests that this design would be a superb spare.

Accessory Power

Requirements are the same level required for comparable FOA designs of Conventional Transformers.

Maintenance

Prototype units may require more maintenance, like periodic operation of the gas separator. Future designs will be automated.

Lighter Installed Weight

This feature would reduce the required foundation or structure to support the transformer. It would also be appropriate on off-shore generating stations.

Gas Bus Compatible

Direct connection of bus duct to tank does not require a large transition bushing.

CGI Station

Would be most compatible with CGI station equipment as oil would be totally eliminated. No oil containment pits or barriers would be needed.

COMMERCIALIZATION FEASABILITY STUDIES
(TASK 3000)

MARKET EVALUATION
(TASK 3100)

- o Mathematical Prediction of Reliability (FMEA)
- o Economic Evaluation of CGI Transformer Characteristics
- o Evaluation of Utility Acceptance
- o Forecast of Industry Volume

CHART 9.1

5.9-19

CONCERNS:

PURPOSE

NUMBER OF CUSTOMERS

KINDS OF CUSTOMERS

PARTICIPANTS IN SURVEY

BIAS OF SURVEYORS

CHART 9.2

5.9-20

SURVEY DESIGN

- o An introductory portion where questions of business size, kind, and growth were identified.
- o Introduction section where questions on value of characteristics and prior knowledge of CGIT were identified.
- o A period where the concept is discussed using slides and a summary of characteristics.
- o Questions on reactions to advantages and disadvantages of CGITransformers.
- o Questions on possible purchases and timing.

CHART 9.3

CUSTOMERS VISITED:

Alabama Power Co. (1)
Southern Services Co. (2)
Houston Light & Power Co. (3)

- (1) A large Utility
- (2) Holding - Services Co.
- (3) Smaller Utility with Urban Requirements

CHART 9.4

1st Reactions

1. Suprised at the positive response to buy one for experience as a hedge against the availability of present commercial offering.
2. Charts 11a & 11b need a better basis for responding. For instance "Use a \$1,000,000.00 Auto Transformer as the cost basis and do them in Dollars.

PLANS

To visit 15 to 20 Customers, some in each category.

URBAN

RURAL

SERVICES

LARGE 3/top 10

MEDIUM Top 100

SMALL 2/below 100

CHART 9.5

5.9-23

*Back-up
Blunk*

5.10 SYSTEM STUDIES

The single major difference in the characteristics of the compact gas insulated transformer from the conventional transformer is the internal capacitance distribution. These capacitances can have effects on a) the internal resonances experienced by the transformer during and after nearby faults, b) resonances occurring between the transformer and other system components during energization, fault clearing, and system overvoltage conditions, c) the harmonic components and magnitudes seen by transformer differential relaying during the same system condition described in b) above, and d) the duty of surge arresters protecting the transformer during system contingency condition.

The most appropriate tools for use in the analysis of the above characteristics are the Transient Network Analyzer and the digital Electro Magnetic Transient program. A study using both these tools allow a complete analysis of sensitivity of both the transformer and system characteristics to the possible effects described above.

CGIT

MAJOR VARIATION AFFECTING SYSTEM

INTERNAL CAPACITANCES

- . INTERNAL RESONANCES
- . SYSTEM RESONANCES
- . DIFFERENTIAL RELAYING
- . ARRESTER PROTECTION

CHART 10.1.

CGIT

SYSTEM CONDITIONS FOR STUDY

A. SYSTEM RESONANCES

- WEAK AC SYSTEM TRANSIENTS
 - ENERGIZING
 - RE-ENERGIZING (FAULT CLEARING)
 - DURING L/G FAULTS
 - SENSITIVITY TO SYSTEM COMPONENTS
 - COMPARISON TO SHELL/CORE TRANSFORMERS
 - CLOSE PROXIMITY TO SHELL/CORE TRANSFORMER

B. DIFFERENTIAL RELAYING

- ENERGIZING
- PARALLEL OPERATION
- HARMONICS

C. ARRESTER PROTECTION

- ENERGY ABSORPTION VARIATION

CHART 10.2