ADVANCED ELECTRIC MOTOR
TECHNOLOGY
FLUX MAPPING
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Building upon work performed under NAS8-36955, D.O. 121, in which EMA requirements were generated and electric motor requirements generated; this work progresses to design and investigate permanent magnet motor realizationss for the EMA application.

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ABSTRACT

This report covers the design of electric motors which fulfill the needs of Thrust Vector Control (TVC) actuators used in large rocket propelled launch vehicles. To accomplish this end the methodology of design is laid out in some detail. In addition a point design of a motor to fulfill the requirements of a certain actuator specified by MSFC is accomplished and reported upon. In the course of this design great stress has been placed on ridding the actuator of internally generated heat. To conduct the heat out of the motor use is made of the unique properties of the in house MSFC designed driving electronics. This property is that as long as they are operated in a quasi-linear mode the electronics nullify the effects of armature inductance as far as the phase of the armature current versus the rotor position is concerned. Actually the additional inductance due to the extended end turns in this design is of benefit because in the shorted armature failure mode the armature current in the fault (caused by the rotor flux sweeping past the armature) is diminished at a given rotor speed when compared to a more conventional motor with lower inductance. The magnetic circuit is analyzed using electromagnetic finite element methods.

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PREFACE

This technical report was prepared by the Space Systems and Technology Laboratory (SSTL) of the University of Alabama in Huntsville Research Institute. This is the final report of work performed under contract NAS8-38609, Delivery Order 36.

The principal investigator was Dr. George B. Doane III, coordinator of the SSTL. Much of the technical work was contributed by Dr. Warren Campbell and Mr. Garvin Dean.

Ms. Rae Ann Weir of the Control Mechanisms Branch, Component Development Division, Propulsion Laboratory, MSFC/NASA was the technical coordinator for MSFC.

The views, opinions and/or findings contained in this report are those of the authors and should not be construed as an official; MSFC position, policy or finding unless so specified by other MSFC/NASA documentation.

Except as may be otherwise authorized this report and its findings require MSFC approval before release to third parties.

George B. Doane III, Ph.D., P.E.
Principal Investigator

Approval:
Research Institute

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STATEMENT OF RESEARCH PROBLEM AREA

The specific task undertaken concerned itself with the design of electric motors for use with electromechanical actuators (EMA) used for thrust vector control. The outcome of the task was to provide insight into the design of motors in general, to provide insight into and solutions to problems unique to this EMA application and to provide a point design for an in-house MSFC EMA design.

It was stipulated that brushless DC motors were the baseline technology. The motors were to be driven by MSFC designed electronics (a fortuitous choice as it turned out).

The physical envelope into which the motors were to fit was determined by an existing MSFC actuator design. As it turned out this forced several features of the design. See discussion of results.

ANALYTICAL BACKGROUND

All the phenomena of electromagnetic may be traced to Maxwell's equations. Until recently their direct use in low frequency analysis situations was limited because of the difficulty of solving them to obtain engineering results. This situation has changed somewhat with the advent of finite element approaches and the companion use of the computing power which has become available[1].

Maxwell's equations are listed below for convenience [2].

$$\nabla \times \underline{H} = \underline{i} + \frac{\partial \underline{D}}{\partial t}$$

$$\nabla \times \underline{E} = -\frac{\partial \underline{B}}{\partial t}$$

Where $\underline{H}$ is the magnetic intensity, $\underline{E}$ the electric vector, $\underline{B}$ magnetic flux density, $\underline{D}$ the electric flux density and $\underline{i}$ the conduction current. The term

$$\frac{\partial \underline{D}}{\partial t}$$

is the displacement current and at low frequencies such as are encountered in motor work may be assumed to be negligible (zero).

In as much as the magnetic field is globally solenoidal (sourceless) the divergence of $\underline{B}$ is zero and it is valuable as well as possible to find a magnetic potential vector, $\underline{A}$. This is done by noting that $\underline{B}$ is a vector and thus may be considered to be the curl of another vector $(\underline{A})$[2].

$$\underline{B} = \nabla X \underline{A}$$

This development is particularly relevant to this work because the finite element program ANSYS produces $\underline{A}$ values as part of its operation. $\underline{A}$ may in turn be used to evaluate the back emf in the motor at any given speed. This development is as follows. From Faraday's Law

$$EMF = -\frac{\partial \Phi}{\partial t}$$

where the flux is given by (for a given surface)

$$\Phi = \int \underline{B} \cdot d\underline{a}$$

and the voltage between two points is given by the line integral

$$V_{1,2} = \int_1^2 \underline{E} \cdot d\underline{s}$$

Substitution yields

$$\int_1^2 \underline{E} \cdot d\underline{s} = -\frac{\partial \Phi}{\partial t} = -\int \frac{\partial \underline{B}}{\partial t} \cdot d\underline{a} \cdot$$

Applying Stokes' Theorem from vector analysis converts the line integral on the left to a surface integral.

$$\int (\nabla \times \underline{E}) \cdot d\underline{a} = -\int \frac{\partial \underline{B}}{\partial t} \cdot d\underline{a}$$

From this it is seen that

$$\nabla \times \underline{E} = -\frac{\partial \underline{B}}{\partial t}$$

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Making use of the magnetic potential formulation $(\underline{B} = \nabla \times \underline{A})$ then

$$\underline{\nabla} \times \underline{E} = -\frac{\partial(\nabla \times \underline{A})}{\partial t}$$

So that

$$\underline{E} = -\frac{\partial \underline{A}}{\partial t}$$

In this work interest is in voltage induced along one side of a coil of wire placed in the motor stator slots. This defines the directions of interest. Letting $\underline{A}$ be directed along one side of the coil (down the slot) the electric vector $\underline{E}$ may be calculated provided the speed of the motor vector is specified (i.e. to make a numerical approximation to Δt) and $\Delta\underline{A}$ is found from A in the wire or coil side for different angles between the stator and the rotor magnets. Multiplying $|\underline{E}|$ by the length of the axially directed coil side yields the voltage of one coil side. Thus the voltage around the coil is given by

$$V = 2|E|\ell n$$

where n is the number of turns in the coil, ℓ is the length of a coil side in a slot and the 2 accounts for the coil having two sides in which voltage is being induced. This approach is different from the more familiar expression

$$e = b\ell v^{(3)}$$

where v is the relative velocity of the flux density B and the length ℓ. This is a simplified expression in that B and ℓ are assumed orthogonal, the more correct expression is

$$e = (\underline{B} \cdot \underline{v})\ell^{(3)}$$

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This latter formulation is sufficiently removed from the first enumerated approach using $\underline{A}$ to be used as a "sanity check" on the results of the approach using $\underline{A}$ (which should be more accurate if $\underline{B}$ is estimated from an ANSYS flux plot).

Likewise there is a dual approach to calculating the torque developed by an electric motor. The more accurate one used by ANSYS is to evaluate the torque by means of the Maxwell stress tensor. [4] [5] The form of it useful here is

$$\underline{T} = \int \left[(\underline{B} \cdot \underline{n}) \left(\frac{\underline{r} \times \underline{B}}{\mu_0} \right) \right] ds$$

This formulation is the one leading to the conceptual device of visualizing elastic strings (rubber bands) with one end attached to the stator and the other to the rotor so that as the stator associated mmf moves it tends to drag the rotor with it. Put a little more formally the magnetic field is attributed to posses stress analogous to stress in a structural member and in each case is associated a force on the surrounding environment. Similar to the voltage calculation there is a better known way in which to calculate force on a conductor and hence torque on a rotor. It is to use the formula [3]

$$T = rF = Bilr$$

where T, F, B and i (or l, in which i flows) are all orthogonal. In using this formula it is assumed that the current conductors which are really in the slots, are uniformly distributed around the stator side of the air gap. As Liwschtz-Garik has noted experiment confirms the legitimacy of this procedure[17].

Although the type of motor under consideration is sometimes called a brushless dc motor (because of the obvious lack of brushes and the fact that its power source can ultimately be traced to a dc bus) it is in reality more properly thought of as a synchronous motor. There are two major differences between this motor and the classical synchronous motor. One difference is that the electrical supply is controllable both as to current magnitude and phase (relative to the rotor-stator instantaneous geometry) and its temporal frequency (and hence the synchronous speed of rotation). The other is that the flux due to the rotor comes from permanent magnets rather than from electromagnets. Any course about electrical machines develops the equivalent circuit of the synchronous machine. References are numerous, see for instance numbers six and seven. This is done on a per phrase basis under the assumption of balanced three phase excitation and operation. Reference 6 develops one as shown below.

Equivalent circuit of a cylindrical-rotor synchronous machine.
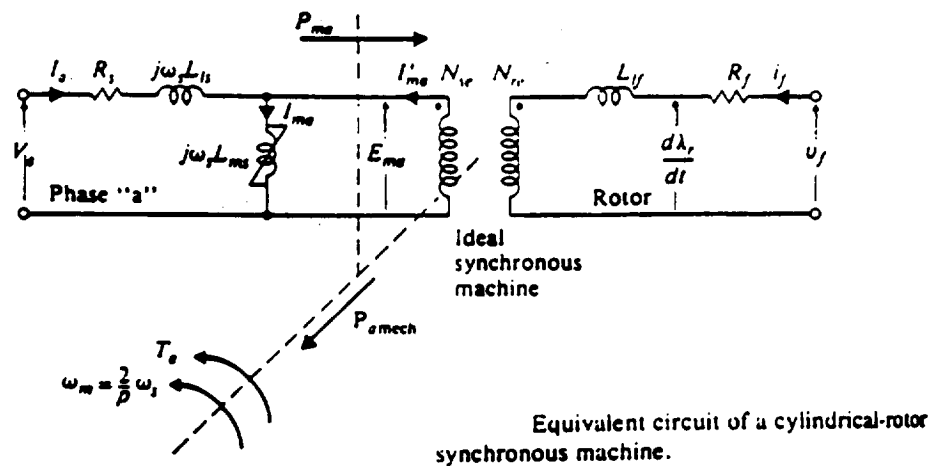
This equivalent circuit is of one phase, the a phase, and hence the various a subscripts. Lms is the usual magnetizing inductance (with the reactive VARS drawn from the a source) here shown nonlinear, Ws is the synchronous speed (rad/sec), Wm is the mechanical speed of the rotor, Ta the torque assigned to the a phase, Rs and Ls the stator resistance and inductance, Nse and Nre the stator and rotor effective number of turns and Ia and Va the a phase amps and volts. The rotor is characterized by the field resistance (R_f) and inductance (Lef) and coupled to the stator through the ideal transformer as shown.

Reference six, through a series of transformations particularizes this general equivalent circuit to that corresponding to a cylindrical permanent magnet rotor design. It is insightful to point out some interesting steps in evolving permanent magnet equivalent circuits. This development parallels that in reference six to where the interested reader is directed for a more detailed account.

Consider the permanent magnet - soft iron circuit shown below in which the mmf required to established flux in the soft iron is assumed to be negligible.
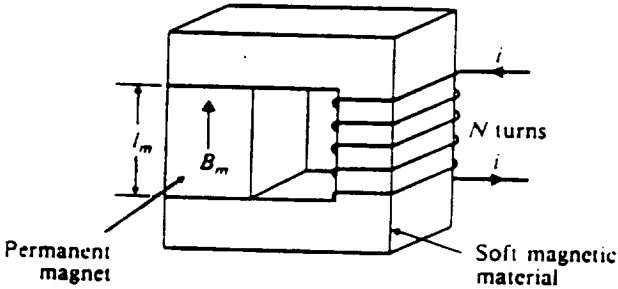
The permanent magnet has a cross section of area Am and length lm. The next figure shows the relationship between the magnetic flux $\emptyset$m and the mmf $\mathfrak{I}$n due to the current i in the N turns.
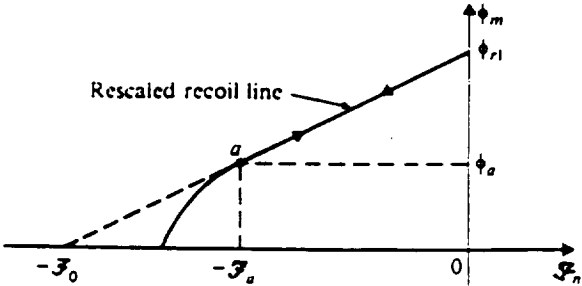
This graphical relationship between flux and mmf is obtained by rescaling a B-H curve normally furnished by the material supplier to the dimensions of the specified magnetic circuit. It should be noted that point a is where the demagnetization curve and the recoil line part company and that if the material is driven to the left of point a permanent weakening of the magnet will occur. It should also be noted that as the temperature of the magnet rises such a point will shift to the right. Thus as the magnet temperature rises it becomes progressively easier to weaken the magnet. It has been reported that such behavior may already have been observed in some designs. For this reason the designs done herein intentionally oversize the magnet (compared to using the maximum energy design points usually recommended).

It will be appreciated in the model that a perfect transformer is being modeled in that there is no leakage accounted for. In order to obtain a linear model operation must be restrained only to the linear recoil line. The flux present in the core is found on the straight line which may be expressed as

$$\emptyset m = \Im m /_{R_o} + \emptyset rl$$

$$\text{where } \frac{\emptyset r\ell}{\Im e} = \frac{1}{Re}$$

this may be manipulated to

$$Ro\emptyset m = \Im m + Ro\emptyset r\ell$$
$$\text{or}$$
$$Ro\emptyset m = \Im m + \Im o$$

From this follows the equivalent circuit
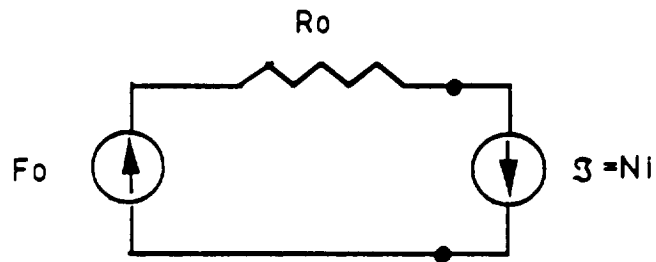
Applying a Thevinen equivalent to the circuit to the left of the terminals yields
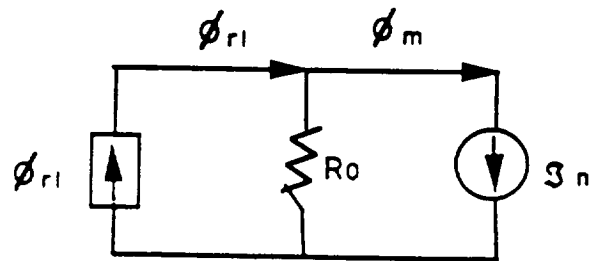
This in turn may be converted into an equivalent electric circuit as follows

$$i = \frac{\Im}{N}$$

$$e = N\frac{d\Phi}{dt}$$

$$\Im = R\Phi$$

Substituting

$$V = N\frac{d}{dt}\left[\frac{\Im}{R}\right] = \frac{N}{R}\frac{d\Im}{dt} = \frac{N^2}{R}\frac{di}{dt} \triangleq L\frac{di}{dt}$$

Thus an equivalent circuit of the form

X_0

E_0
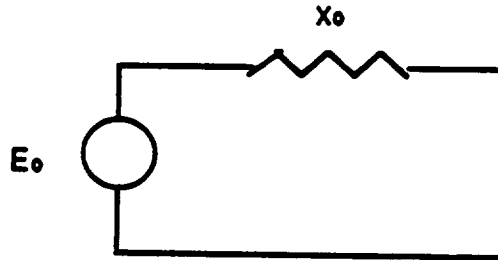
emerges. This may then be substituted for the rotor circuit of the original equivalent circuit to yield a per phase steady state equivalent circuit as

P_{m0}

I_s R_1 jX_{ls} jX_a

V_s jX_{m0} E_{m0} $E_a = E_a \lfloor \beta_{0r}$
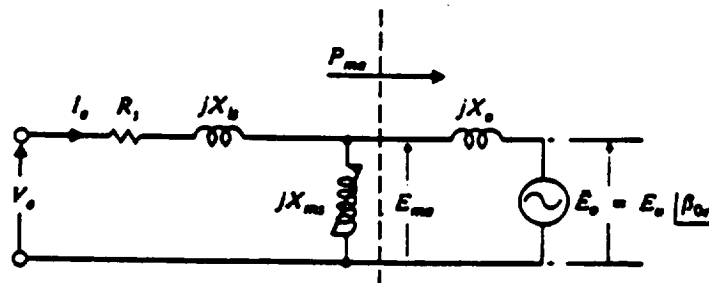
The relevance and importance of the foregoing is that there is firm ground to think of a multiphase motor on a per phase basis provided it is being operated in a balanced fashion. This fact is used in sizing the motor.

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MOTOR DESIGN CONSIDERATIONS

Initially it was thought that a 5 inch diameter motor would be allowable. Subsequently it was decided that 3 inch diameter motors would be needed to fit a four electric motor actuator that MSFC has designed in house. From those exercises it seems that the somewhat larger diameter motor would be preferable because it allows keeping the speed at rated power and the length to diameter ratio smaller than is the case with the smaller diameter motor.

The specification called for the actuator to develop 30 horsepower under nominal conditions but be able to develop 45 horsepower peak under off nominal conditions. Probably a desire to develop 30 horsepower at a stroking velocity of 5 inches/second and a stall force of 60,000 pounds gave rise to these specifications (30 horsepower at 5 in/sec requires 40,000 pounds of force). Thus designing each motor for 7.5 horsepower nominal with a surge possibility of 11 horsepower seems to be reasonable. The gear train connecting the motor to the load is two pass. One pass is a spur gear ratio in the range from 1 to 10. The other pass is roller screw gear with a range up to 1 inch per revolution possibility. Previous work [4] has shown the desirability of matching the reflected inertia of the load to that of the motor to the extent possible while still meeting the stall force requirement.

When assigning a power rating to an electric motor close attention needs to be paid to the methodology followed. Electric motors are basically power limited by heating. Heating of the insulation of the wire used in the coils and, in a permanent magnet design, by magnet heating are principal questions. Overheating the wire insulation will drastically shorten its life even if not driven to instantaneous failure. The permanent magnets, as already noted, will, even below their Curie temperature, be susceptible to permanent irrevocable weakening because of the shift with temperature of the point where the demagnetization curve and the recoil line diverge.

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Thus various ways of stating power ratings are encountered (sometimes for the same machine). Terms such as continuous rating, peak rating, time limited rating (all these with side conditions on the ambient environment, duty cycle, type of housing etc.) are found. They are codified for industrial use in the NEMA (national electrical manufacturers association) standards. The question here is how to rate the motors used in electromechanical actuators (EMA) used for large launch vehicle thrust vector control (TVC).

Inspection of the flight records of Shuttle flights discloses very little activity of the actuators. The identifiable active times are during the initial roll maneuver to obtain orbital azimuth and during the maximum dynamic pressure encounter (max Q) when the air loads on this asymmetrical vehicle peak. But none of these loading periods last very long. Indeed the whole powered booster flight is about two minutes (without on average much activity). Thus short of an unspecified anomaly something other than flight stress needs to be used. Experience has shown many times that test and checkout of equipment stresses it more than flight. Operation in a boatail of a stacked vehicle at KSC in August during a functional checkout might be a high temperature regime. Perhaps others exist also. The current hydraulic actuator specifications [8] call for "operating performance...during and after exposure to..." an ambient of -40 to +275°F (-40°C to + 135°C). The low temperature end of the scale would seem to impinge on electronic and mechanical things rather than electromagnetic concerns. The upper temperature range, when one considers that it begins to approach the upper limit of allowable magnet temperature is a problem. The magnets are innermost in the motor material and while heating of the rotor will be minimized by every means (e.g. using a laminated rotor) still heat generated there must cause a sensibly higher temperature than the ambient in order to make its way out through the air gap (radiation, perhaps convection) and the shaft (through the bearings). MSFC (Mr. Martin, EP-64) has

indicated upon questioning that the upper temperature might be modified as it is derived from a standard aerospace specification. To grasp the problem more quantitatively an estimate of the heat transfer possible from the body of the actuator was made as detailed in Appendix A. This development assumed that the motor heat is to be dissipated from the aft body or tailstock end of the actuator and that the actuator may be approximated by an equivalent right circular cylinder. For worst case conditions it was also assumed that the cylinder was horizontal. The natural convection heat transfer coefficient was obtained from reference nine. The results of the analysis are presented in Appendix A as the figure on page 37. They show that heat dissipation during a stalled or otherwise loaded condition (i.e. high current) will be a problem. It may be ameliorated by the use of fins, perhaps a brake with the motor unenergized during motionless periods (adds complexity) or in extremum use of cooling air from a fan or other source. Once again the necessity of providing a low thermal resistance path from the origin of the heat to the actuator body is made plain. Appendix B does show for a representative geometry that if the thermal conductivity of the end turn to copper heat sink can be made approximately comparable to that of one inch of the wire itself than long periods of stalled operation could be thermally tolerated.

In appendix C the core loss analysis is detailed. It shows that even under worst case conditions the temperature rise in the stator iron is small (delta temperature of 10-11°F above stator outer temperature). Thus this factor is not a serious temperature rise concern. Comparing the wire temperature analysis to this one shows clearly that if a way could be found to couple the wire thermally to the stator iron an appreciable amount of heat could be extracted from the wire (recall that in appendix B it was assumed that all the heat exited the copper wire via the end windings). This might be brought about if the wires could be potted into the slots with something like the Stycast material. This latter might present fabrication problems and would have to be investigated.

The lamination design was driven by two factors. One was the fixed outer diameter (OD) of three inches. The other was the choice of the number of poles. The choice of the number of poles for a synchronous motor intended for conventional service is straight forward. For a three phrase p-pole, synchronous machine the relationship between mechanical shaft speed and the angular frequency of the supply is

$$wm = \frac{2}{p} ws \qquad rad/sec.$$

Thus if the supply is 60HZ the only useful speeds i.e. those at which mechanical power can be produced[6] are the discrete values 3600 rpm, 1800 rpm, 1200 rpm etc. Therefore to choose the number of poles the load speed characteristic is considered and a straight forward choice made. No such situation obtains here. In effect the electronics powering the motor can (and do) produce a wide range of frequencies. Thus some other criterion was needed. The initial choice made was to optimize the various possibilities according to the maximum torque they produce when full pitched windings are used. As seen below this led to an initial choice of a 4 pole design. To do this a series of 3 inch OD laminations were designed according to the procedure outlined below. They were then modeled in ANSYS and torque versus torque angle data gathered. Laminations incorporating 8, 6, 4 and 2 poles were designed and so evaluated. As is seen in the table below the torque production peaked for the 4 pole machine. However when later the zero current or reluctance torques were evaluated the choice changed to that of the 6 pole motor.

Number of		3" Torque		5" Torque	
Poles	Slots	Max.	No Current	Max.	No Current
2	3x2x3 24	78	27.3	—	—
4	3x4x2 24	108	26.4136	—	—
6	3x6x2 36	96	0.79968	163.722	-1.89312
8	3x8x2 48	77	-4.68328	—	—

The units of torque are Newton-Meters per meter length of the rotor.

All the laminations were designed basically the same way. With the OD specified a priori the consensus formulas from reference fifteen (section 9-73) were used. But first it was necessary to decide how many slots would be specified for each number of poles. Also rationale pro or con fractional slotting was considered. Fractional slotting is often used when a lamination design exists and it is desired to use these laminations for a new design for which they were not designed. Other reasons to use fractional pitch windings include noise, wave form and locking torques specially on machines of eight or more poles[15]. This is because it behaves as a winding with many slots per pole per phase which reduces the distribution factors of the harmonics. Clearly if the number of slots per pole per phase became less than two a fractional slot design would be called for because a single slot per pole per phase will in all likelihood lead to large harmonics[16]. Induction or synchronous motors have essentially the same stator laminations and are designed in most cases with integral slots. Here there are less than eight poles and more than one slot per pole per phase. Therefore integral slots were chosen as appropriate and consistant with the general motor design literature. This choice renders the machine electrically easy to balance, makes analysis simpler because only one pole of the machine need be modeled (with appropriate boundary conditions) whereas a non integral machine must have the full 360 mechanical degrees modeled. However if testing shows the desirability of non integral slots and fractional pitch windings they could be designed. Two samples of commercial motors examined do indeed have non integral slot designs. The consensus formulas (dimensions in inches) are (given OD)

$$\text{inside diameter of rotor, } D = \frac{OD - 0.647}{1.175 + (1.03 / P)}$$

where P is the number of poles.

The diameter of the bottom of the slots is

$$D_1 = 1.175D + 0.647$$

and the tooth width

$$tw = \frac{1.35D}{S_1}$$

where S_1 is the number of slots. For partially closed slots the pole tip to pole tip distance e^1 is given by

$$e^1 = 0.0143D + 0.0643$$

The value resulting from these formulas are likely dimensions for trial designs. However they have proven to be good guides. During the course of this design effort the outer radius of the motor (i.e. the OD) was increased as a trial. The torque analysis showed that even at high flux levels little torque gain resulted although of course the back iron flux density decreased. A value of one millimeter (about 4 mils) was chosen as the air gap between rotor and stator. This may be a little too small when the mechanical design is executed. A study was done which showed the air gap flux density to be a weak function of the air radial gap as long as that gap is small compared to the air gap between the alternating magnet edges. In the figure below the distance between the magnets was approximately 7 mm.
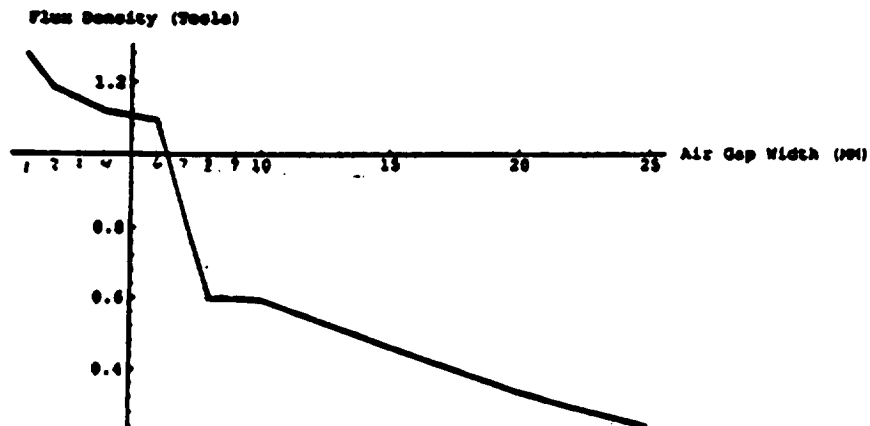
It is seen that another one or two millimeters would not be too bad although the gap should be kept as small as possible to achieve maximum air gap flux density.

As previously discussed it was decided to have an integral number of slots per pole per phase. Thus for the six pole machine use of the pole /slot formula

No. of slots = No. of phases X No. of poles X No. of slots per pole per phase

or here yields the number of slots as

$$36 = 3 \times 6 \times 2$$

Applying the consensus formulas yields

$$D = 1.7473$$
$$D_1 = 2.7000$$
$$tw = 0.0655$$
$$e^1 = 0.0893$$

It will be seen from the lamination figure that these values were adhered to by and large.

LAYOUT OF A
6 POLE 3" OD
MOTOR

SLOT

AIR GAP

MAGNET

NONMAGNETIC SHAFT

ROTOR IRON

BACK IRON

TOOTH
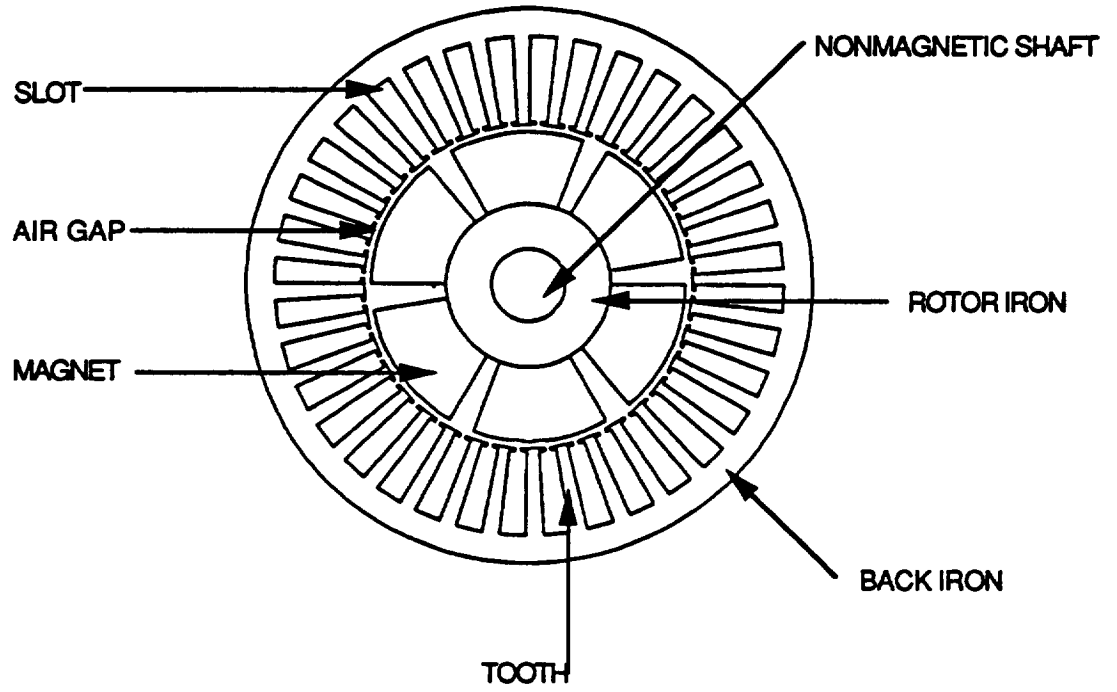
This same procedure was followed for 2, 4 and 8 pole designs. This was required to model them in ANSYS for the torque, flux and back EMF evaluations.

As previously mentioned when discussing torque optimization all the work so far has been done with full pitch windings. However it may be desirable to chord or short pitch the stator windings to minimize harmonics. With two slots per pole per phase it would be possible to short pitch the winding by 30 electrical degrees (one pole is 180 electrical degrees, thus 180 divided by 6 yields 30 electrical degrees per slot). A 150° pitch yields pitch, distribution and combined factors for various harmonics as [7]

Harmonic	Pitch (150°=5/6)	Distribution Factor	KpKd
Fundamental	0.966	0.966	0.933
Third	0.707	0.707	0.499
Fifth	0.259	0.259	0.067
Seventh	-0.259	0.259	0.067
Ninth	-0.707	0.707	0.499
Eleventh	-0.966	0.966	0.933

From the table it is seen that the desired fundamental is diminished only 6.7% where as the other harmonics are diminished quite a bit. Connecting the motor in wye or star will eliminate the third harmonic at the terminals and as a delta connection would allow circulating third harmonic currents, a wye connection is chosen. The details of the winding are given in appendix D. The flux plot, see p. 21, of the 4 pole design is interesting. As previously pointed out only one quadrant of a 4 pole motor needs to be modeled (360°/4=90°). The flux densities are shown in various colors ranging from dark blue to red. The peak air gap flux is quite high (above 2.9 Tesla) and perhaps just as

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4 Pole 3" Motor
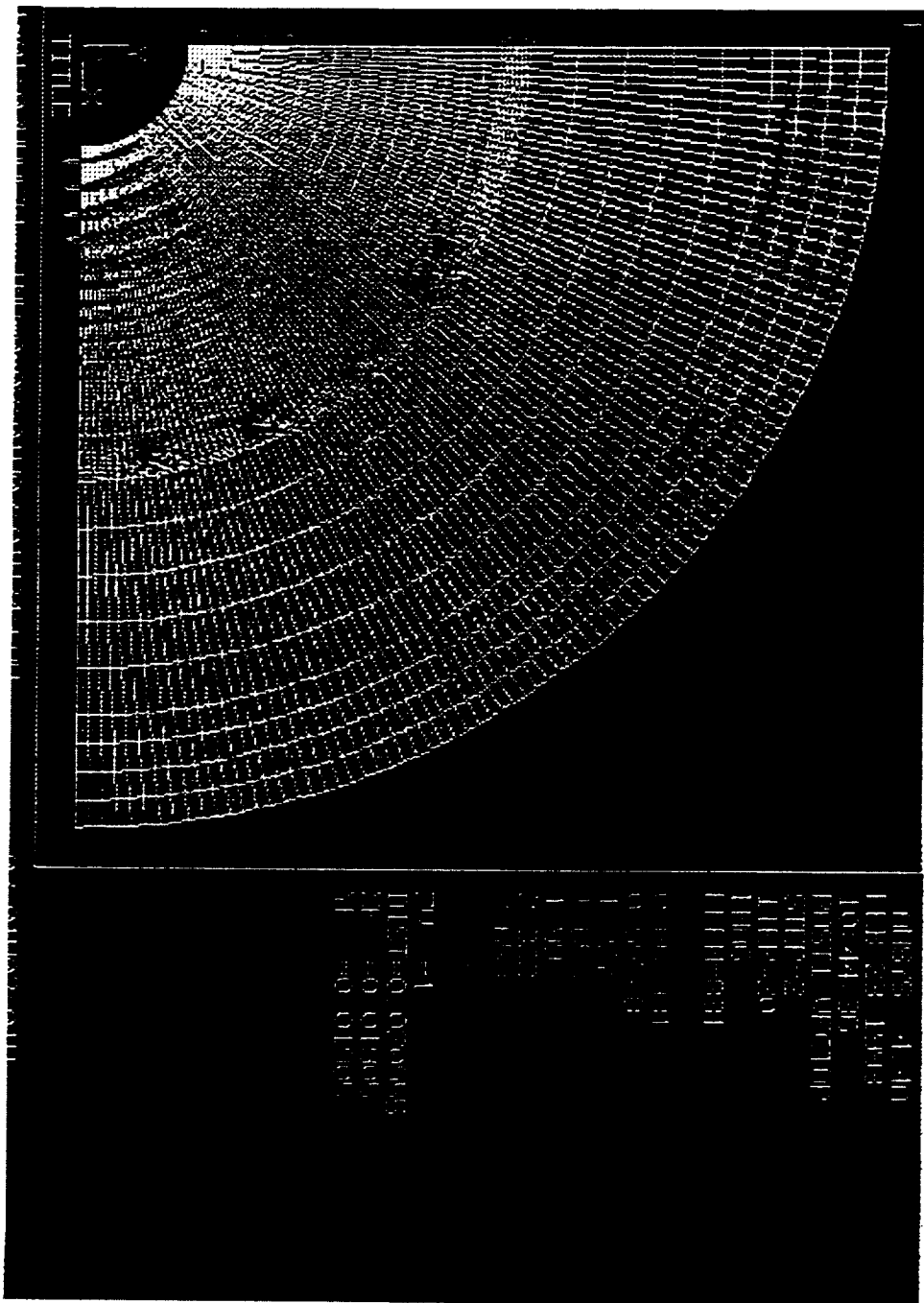
important is oriented rather close to the optimum angle of 45° as derivable from the Maxwell stress expression based torque equation [4]. Both of these factors explain the high peak torque production. At this point it is instructive to compare the flux plot of the 8 pole machine to that of the 4 pole machine. The plot is given on p. 23. Note that the overall levels of flux density are lower than for the 4 pole case. Also notice that there is only one area of 2.38 Tesla flux density per pole here whereas there were four areas of nearly 3 Teslas flux density per pole in the 4 pole case. Also notice that while much of the flux density orientation in the four pole case approximated the optimum 45 degree angle little of the flux (at a lower density level) in the eight pole case favored the 45 degree optimum. This spreading of the flux amongst a number of teeth may explain why the reluctance torque of the 8 pole motor is so low. The next figure, on p. 24, is a plot of torque (in Newton-Meter/Meter of motor length). From this it is seen that torque remains within approximately 2 N-M/M of the maximum for commutation angles of 20° of peak. Thus it is seen that to minimize torque ripple and retain a maximum torque capability at all shaft positions the use of a revolver based rotor - stator position sensor is desired rather than the 6 segment 3 Hall effect 60 electrical degree switching sometimes used.

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Stress Plot of an 8 Pole 3" Motor
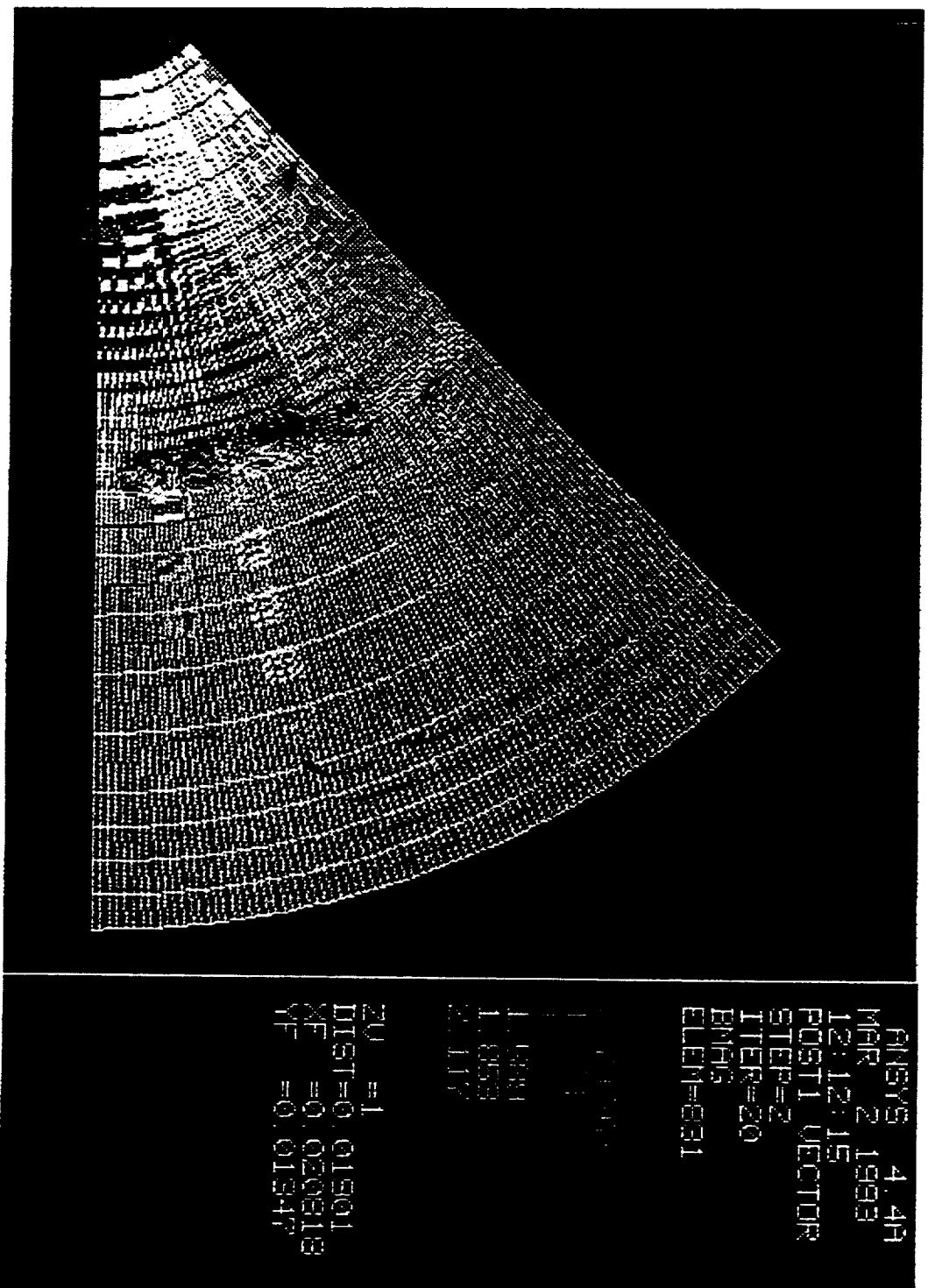
In[37]:=

```
T4 = {{15,25.952},{16,27.347},{17,25.992},{18,26.906},
{19,24.727},{20,24.685},{21,24.417},{22,25.725},
{23,25.065},{24,25.183},{25,24.337},{26,23.6},
{27,23.091},{28,22.5},{29,21.984},{30,20.555},
{31,20.973},{33,20.02},{35,19.303},{37,18.303},
{39,16.548},{40,15.31}}
ListPlot[T4,PlotJoined->True,GridLines->Automatic,
 AxesLabel-> {"Torque Angle Degrees",
"Torque N-M/M"},PlotRange->{0,28} ]
```
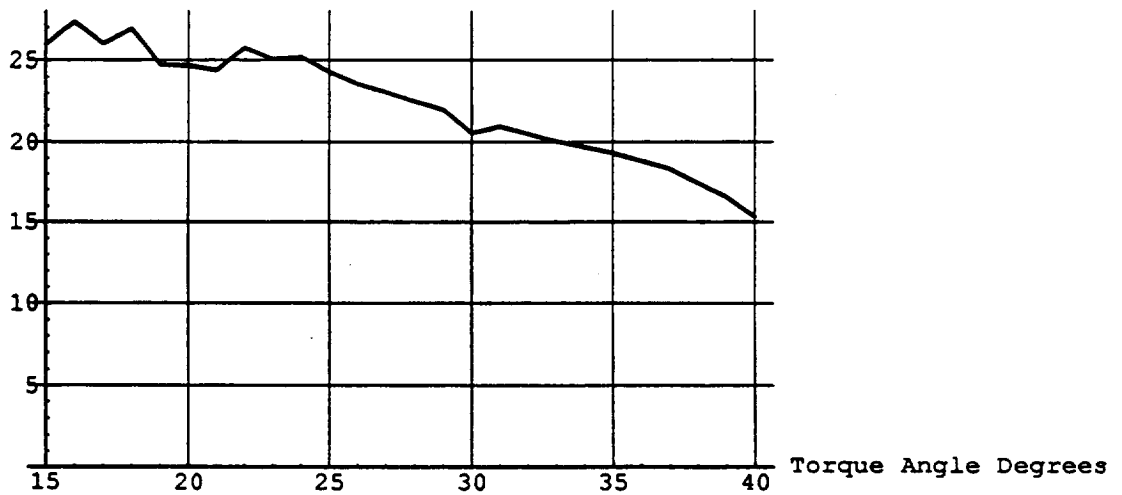
Knowing that a full slot of 8 MA/M^2 current density produces about 96 N-M/M of torque the motor sizing may be completed. For the ensuing calculations a fill factor of 50% will be assumed which means the peak torque actually available will be 96/2=48 N-M/M. The problem now is to establish the length of the active rotor and the speed at which rated power is to be developed. To keep the rotor length as short as possible the highest rotation speed thought practical i.e. 20,000 rpm was chosen. The rotor length calculation, assuming 48 N-M/M of torque is available to produce 7.5 horsepower is a follows.

$$48 \frac{N-M}{M} \times 0.7376 = 35.4 \frac{lb-ft}{m}$$

$$7.5 \text{horsepower} \times 550 \frac{lb-ft}{sec \cdot HP} = 4125 \frac{lb-ft}{sec}$$

$$20,000 \text{ rpm} = 2094 \text{ rad/sec}$$

$$2094 \frac{r}{sec} \times 35.4 \left(\frac{lb-ft}{m} \right) \times \ell(m) = 4125 \left(\frac{lb-ft}{sec} \right)$$

$$\ell = \frac{4125}{(35.4)(2094)} = 0.05565 \text{meter}$$

or

$$\ell = (0..05565)(39.37) = 2.191 \text{inches}$$

The rotor force stress is calculated as follows. The equivalent maximum tangential force is

$$(F \cdot r)(\text{Speed}) = \text{power}$$

$$F = \frac{\text{power}}{(\text{radius})(\text{speed})} = \frac{4125}{\left(\frac{1.75}{2(12)} \right)(2094)}$$

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$$F = 27.02 \text{ lbs}$$

The rotor surface area is

$$\text{Area} = (1.75\pi)\,(2.2) = 12.1\text{in}^2$$

so the force density is

$$\delta = \frac{F}{A} = \frac{27.02}{12.1} = 2.233\frac{\text{lb}}{\text{in}^2}$$

This is in line with usual good industrial practice[17]. See discussion in Appendix I.

As was noted earlier a late switch was made in the choice of 6 versus 4 poles. Evaluating the $\underline{A}$ values requires many ANSYS runs and hence was not repeated. The method remains the same for any number of poles. To determine the number of turns per coil per pole ANSYS was queried to produce the magnetic potential [4] at the various coil locations so that the procedure described early in this report could be applied. The value of A at each side of each coil location or slot was found for a variety of rotor - stator angles and then averaged. These data were entered into a spread sheet program to find the coil (one turn) induced voltage. The spread sheet results are displayed in Appendix E. These results were calculated assuming a 10,000 rpm rotor speed 4 poles and a 7 inch long rotor. Because the calculations are linear they may be rescaled to the 20,000 rpm rotor speed as (taking 9V per coil as the spread sheet maximum)

$$9 \times \frac{20,000}{10,000} \times \frac{7.78}{7} = 20\frac{\text{volts}}{\text{coil}}(\text{max.})$$

In this design where the basic dc bus is 270 volts (which may sag to 240 volts) the terminal voltage value is not critical as long as the back emf of the motor never rises so high as to threaten the linear operation of the current source amplifier feeding the motor. It is estimated that a voltage no higher than 200-210 volts will achieve this. Other than this consideration

there is much more freedom to select maximum back emf i.e. the number of turns in a coil than is the usual case. In this completely balanced electrical design there is freedom to series or parallel the coils in a given phase provided the current rating of any given coil is not exceeded (and since usually all coils are wound with the same wire gage this means having the same current in all the coils). If the terminal voltage is applied to the wye connected motor it is expected that the new phase voltage will be on the order of 200-210 divided by $\sqrt{3}$ (i.e. 115 to 120 volts). At 20 volts per coil only one or two turn coils in series connection (4x20=80 or 4x20x2=160) of all coils would produce an emf less than that desired. If the 4 coils were connected 2 by 2 in series and then in parallel 3 turn coils (3x[20+20]) would yield 120 volts. The third possibility is to parallel all the coils with 6 turns each to yield 120 volts (6X20). Keep in mind that each turn of the coil can be made from wire which in its turn is made from a number of wire strands in parallel. Once again consulting with the winder would help to make the choice by seeing which option will lead to the highest fill factor. It is essential that after a motor rotor and stator have been fabricated and assembled a search coil of a few turns be placed in the stator slots and the actual voltage be measured. With that knowledge the final winding specification can be developed.

In the course of developing the exact winding to be used it should be kept in mind that the mechanical power delivered to the shaft is proportional to the back emf times the current. Thus as the various emf options are considered from the standpoint of winding ease or complexity there are direct implications to the current drawn. That is if the back emf is relatively low then the current drawn has to be relatively high so that their required product i.e. the power delivered) is maintained. Of course the converse is true for a high back emf case.

In a precursor study (reference four) a great deal of effort was spent in studying the interrelationships between the various system inertias. The more or less invariant inertia

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component is that of the load (here the reflected rocket motor mass) and the actuator load bearing parts. The variable factors to consider when designing the system include the values of the spur gear ratio and the roller screw ratio between translation and rotation (which among other things has a gear train like inertia reflection property) the pinion and mating gear inertia and the motor rotor inertia. As is shown in the previous final report if the two passes are selected to produce matching of the referred inertias (referred to any common point) then two optimum objectives are achieved. These are first the maximum bandwidth of the actuator (not the motor motion but the output motion) and second the maximum energy transfer to the load. Proper matching does not however generally achieve the other actuator requirement i.e. achieving specified actuator stall force. It was further shown that given a matched situation there is an optimum way in which to "detune" the system so as to achieve the required stall force and yet minimize the loss of system bandwidth and power transfer efficiency. Clearly any energy stored in the motor rotor is not energy getting to the actuator and load combination. Thus minimizing the motor inertia subject to power and thermal considerations is highly desirable. However this must be done in the context of an end to end optimized design to achieve its full potential. Attention is invited to Appendix I as well as the former work's final report for further thoughts on the inertia question.

Conclusions and Recommendations

An extensive array of analytical tools has been assembled to design and analyze electric motors. These have been applied to the point design of a brushless dc electric motor for use with large thrust vector control (TVC) electromechanical actuators (EMA). This array represents the current state of the art in motor design tools. This is exemplified by the use of finite element methods (specifically the ANSYS electromagnetic option 4.4A) to evaluate numerically the motor designs torque characteristics (e.g. torque versus torque angle), the optimum number of poles, the back emf, and to visualize the flux paths of the proposed designs. Use has also been made of a digitally implemented thermal network analyzer that was obtained from COSMIC (and which runs on the PC) to investigate heat transfer in the proposed motor. The designs of almost all electric motors are thermally driven. This design should promote heat removal from the motor to the greatest extent possible. To do this some traditional design principals were contravened with the knowledge that the MSFC electronics will control the current even if the motor inductance is higher than normal.

It will be noted in the table listing torque for various motors and circumstances that a 5 inch diameter motor is indicated. This is because initially such a motor was thought suitable for the actuator. However in addition to the usual tests a number of other tests were made with this model. Basically these tests held the slot current density constant as the motor's slots were elongated. The results of these preliminary tests showed that placing three separate windings in the slots *with the currents in phase* created no particular problem. If the motor were to be powered from a conventional low impedance or voltage source of electrical power it would however be very difficult if not impossible to insure adequately-in-phase currents. This is because as the slots are elongated to accommodate the additional windings the per winding inductance would be markedly different one from another and thus when they are all driven from the same low impedance source the various winding currents would

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not be in phase (as is required to produce maximum or additive torque). Furthermore no passive tuning would be able to compensate for this because of the changing frequency applied as motor speed is changed. Fortunately the MSFC amplifier removes this current phasing problem/concern because it incorporates sufficient feedback so that its output current is essentially independent of the load impedance. This latter happy circumstance opens the possibility of incorporating three electrically isolated windings in a single motor stator with one rotor (on a single shaft) with the resulting implications on possible redundancy schemes.

This motor design incorporates an innovative heat dissipation scheme. This scheme makes use of the MSFC amplifier indifference to winding inductance. This indifference allows an increase in the length of the end windings of the motor so as to couple the stator windings thermally with a copper heat sink placed at each end of the motor. The design then is such as to invite the thermal coupling of the motor to the actuator so as to make use of the surface area of the actuator for heat dissipation to the environment.

A design study has also been performed which looks into the use of a Titanium retaining sleeve proposed to be fitted around the rotor magnet structure. The purpose of this sleeve is to assure that the magnets remain tightly fixed to the rotor at high rotor speeds. An ANSYS study of this design disclosed that the Young's Modulus given in the literature for the magnets is extremely low. A check with the manufacturer showed an error of a thousand in the value. The ANSYS program was run with the correct value of Young's Modulus and showed that a feasible heating shrinking scenario is possible for mounting such a ring. An interesting result was that as the diameter of the motor increased the heat shrinking technique became less feasible.

This study has resulted in the electromagnetic design of a motor. There now needs to be a mechanical design made, materials ordered and the design resulting therefrom mechanized. This will serve to explore the ramifications of this outside diameter and thermally driven design. If discrepancies are found between the laboratory results and the analysis they will need to be rationalized.

When building the motor the mechanical parts (including the rotor magnets) should be assembled with but a few turn test coil of 6 slot pitch in the stator. The rotor should then be spun at various rpm's to validate the back emf analysis. After this has been done and any modifications to the winding design made the motor would then be wound in the final stator winding configuration. Of course then tests should be performed to determine the developed torque at various electric current levels.

At the conclusion of this build and test cycle there will be a motor design tailored to the TVC application with special emphasis on the heat transfer questions.

In the future if the opportunity should arise to configure a new design it is recommended that serious consideration be given to relaxing the small (here 3 inch) outer diameter constraint. This constraint in the present design has caused the loss of the opportunity to optimize the aspect ratio of the motor. A shorter but larger diameter motor would be worthy of further serious study and would allow the optimization procedure to include additional parameters (i.e. simultaneous inertia matching and stall torque considerations as shown in previous work) than does the present case.

Computer sketches of the motor design are enclosed immediately below.

TYPICAL 2-D MOTOR DRAWING

TYPICAL MOTOR 3-D VIEW

SPACERS

COPPER
HEAT SINKS

OUTPUT
SHAFT

TWO POLE
RESOLVERS
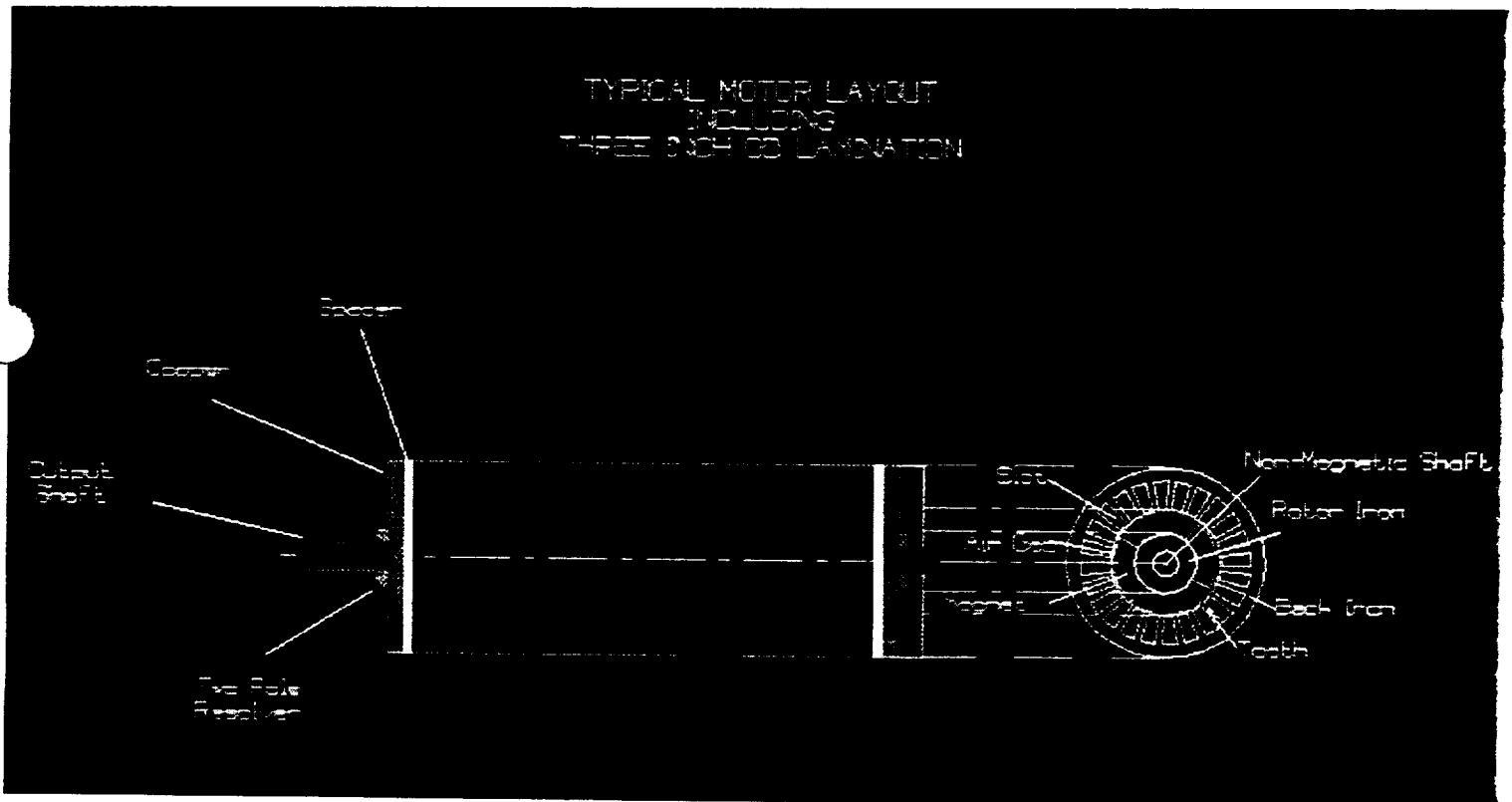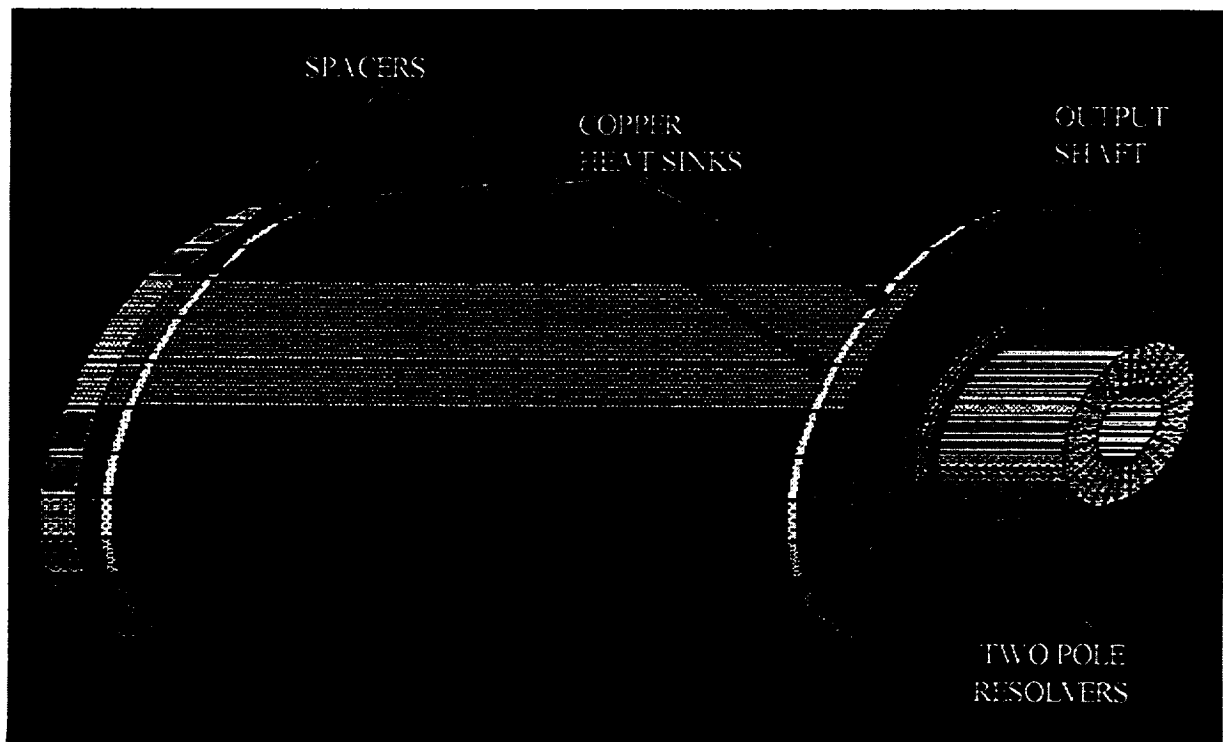
Appendix A:

Heat Loss From Actuator Body

As mentioned in the main body of the text the following calculations were made to gain knowledge of the heat transfer possibilities from the actuator body to the ambient air (at one atmosphere of pressure). Almost certainly test and check out of actuators will take place at one atmosphere. Flight, of course, will rapidly decrease the ambient pressure and heat energy will have to be stored in the thermal capacity of the motor and actuator for the relatively short (less than 10 minutes) flight time.

As previously mentioned the Rockwell Specification document [8] calls for an operating ambient of 275°F (135°C). Magnequench 30 (the permanent magnet material modeled in this study) can withstand 180°C (356°F) to perhaps a maximum of 200°C (392°F). Thus there is something on the order of 80°F to 100°F (26°C to 38°C) between the maximum ambient (275°F) and the magnet temperature. Because most of the heat will be generated in the stator this does not leave much temperature difference to promote the outflow of thermal energy. Clearly if definitive data as to the maximum actual ambient were available (and showed less than 275°F) the situation would be eased.

The actuator body to which the motors are mounted is described in reference 10. For the purpose of this work the tailstock of the actuator was assumed to be the active heat loss part because the bolted flange between it and the headstock end of the actuator is normally a relatively poor heat transmission path.

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The heat loss surface was taken to be a right circular cylinder of Aluminum 12 inches in diameter and 14 inches long (based on an estimate of the convecting surface of the housing; in principle fins could be added to aid convection).

Assuming the actuator is small compared to its enclosure and that the enclosure is at the same temperature as the ambient the simplified heat transfer equations may be written as (for radiation and convection).[9] [11]

$$qr = \delta \varepsilon_1 A_1 \left(T_1{}^4 - T_2{}^4 \right)$$

$$qc = hc(T_1 - T_2)$$

where

qi = rate of heat flow (BTU/HR)

hc = Convective heat transfer coefficient (BTU/HR-$^\circ$R)

T_1 = actuator temperature ($^\circ$R)

T_2 = ambient temperature ($^\circ$R)

δ = Stefan - Boltzman constant (0.174×10^{-8} BTU/FT^2-HR-$^\circ$R^4)

ε = emissivity of Aluminum

Combining radiation and convection yields.

$$qc + qr = \left\{ 0.27(T_1 - T_2)^{5/4} + 0.174 \times 10^{-8} \times 10^{-1} \left[T_1{}^4 - T_2{}^4 \right] \right\} A_1$$

$$A_1 = 2\Pi r \ell = (2\Pi) \left(\frac{1}{2} \right) \left(\frac{14}{12} \right) = 3.67 \text{FT}^2$$

$$T_2 = 275 + 459.69 = 734.69^\circ R \_ \text{ (maximum ambient temperature)}$$

The convective heat transfer term uses the relationship from page 177 of reference nine

$$\left[\frac{(T_1 - T_2)}{Do}\right]^{\frac{1}{4}}$$

where

        Do = diameter of cylinder (FT)

The emissivity of Aluminum was taken from Table A-23 of reference nine and is representative of a number of Aluminum finishes in the 75-212°F range.

Using the factor 0.293 to convert BTU/HR to watts and plotting the heat transfer for several combinations of T_1 and T_2 (see figure on page 37) it is seen that the housing would have to get fairly warm with respect to the ambient to dispose of appreciable heat. From the figure, if the housing temperature T_1 were at 100°F and the ambient was 75°F the heat loss would be approximately 40 watts and so forth. It is not unusual for one motor of this type to dissipate at least this much power at stall. Here there are four motors; so clearly peak power at stall could be a major problem if the motors are called upon to sustain a large stalled force against a load or are cycled during testing for prolonged periods at high force loading.

ln[47]:=

```
aa=0.27  ((t1+459.69)-(t2+459.69))^(5/4)
bb=0.174 10^-9  ((t1+459.69)^4-(t2+459.69)^-4)
Area=3.67
QcQrF=(aa+bb) Area
Plot3D[0.293 QcQrF,{t1,80,340},{t2,75,275},AxesLabel->{"T1"
,T2,"Watts"},FaceGrids->All]
```
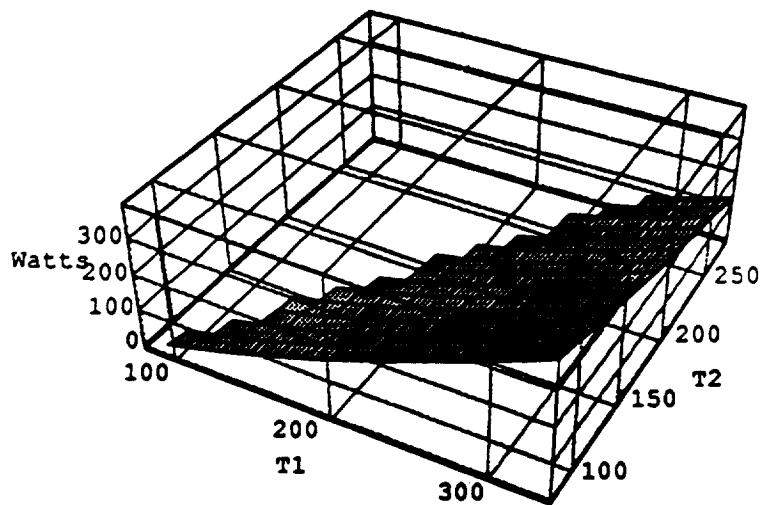
Appendix B:

Considerations On Individual Wire Heating

No matter how many or how few turns are called for or how many conductors will be used in parallel ("in hand") for the windings, wire of about AWG25 will be used. This is because of the requirement to fit the wire into the slots and to wind it on a long thin stator. The data in reference twelve indicates current density in the wire as follows.

Standard Machine (Presumably Air Cooled)

2 KA/in^2 to 6 KA/in^2

or $\qquad 3 \times 10^6 \text{ A/m}^2$ to $9.3 \times 10^6 \text{ A/m}^2$

Exotic Machines (Liquid Cooled)

12 KA/in^2

or $\qquad 18.6 \times 10^6 \text{ A/m}^2$

Pulse Loading

20 KA/in^2

or $\qquad 31 \times 10^6 \text{ A/in}^2$

The maximum current recommended in reference thirteen for 18 AWG (the smallest listed) copper wire according to the National Electric Code is 5 amperes. This yields a current density of

3.9 KA/in^2

or $\qquad 6.1 \times 10^6 \text{ A/m}^2$

which falls in the standard machine range. There are some exotic wire insulations such as ceramic coatings in existence but it is not clear if they are suitable for use in a motor this size. At 8×10^6 A/m^2 (5.1613 KA/in^2) single 25 AWG wire will carry up to

$$3.173 \times 10^{-4} \times 5161.29 = 1.64 \text{ Amps.}$$

It is common design practice to assume that all the heat energy generated in the stator copper windings should be transported to and dissipated from the end windings. This is generally considered conservative by up to 20% of the heat to be dissipated. The rationale is that the coupling of the wire to the stator iron is nebulous at best (and high resistance) and that conduction through the iron is harder than conduction through the copper. Our laboratory experiment disclosed fairly good iron copper coupling, surprisingly, but no thermal resistance values were obtained (See Appendix G). Dissipating the heat in the end turns commonly leads to having a fan mounted on the shaft of the motor to blow air over the end windings, down the air gap and across the other end winding. This design expedient is not available here. This is a servo motor application i.e. the motor does not spend much time turning and may spend time stalled but producing torque. The design pursued here substitutes large copper heat sinks at both ends of the motor for the usual fan. However, it is still necessary to remove the heat from these copper sinks and to get it into the sinks in the first place.

As a matter of fact approaches reminiscent of this one are found in other servo motors although they are not carried as far as is proposed in this design.

For the sake of preliminary design suppose the wire in the slot is 7 inches long, AWG 25 and that it is carrying 1.64 Amps. In addition suppose it is connected to the two end copper heat sinks by a thermal resistance at each end of the wire (see below).

Assume the Cu heat sinks' temperatures may be varied for analysis purposes. Divide the wire into 7 segments and represent them as lumped conductances of

$$\text{thermal conductance} = \frac{\text{thermal conductivity x cross sectional area}}{\text{length}}$$

$$= \frac{0.061 \dfrac{\text{BTU} / \text{SEC}}{\text{Ft}^\circ\text{F}} \times \dfrac{2.51 \times 10^{-4} \text{Ft}^2}{144}}{(1/12)\text{Ft}}$$

$$\text{Cond} = 1.2795 \times 10^{-6} \frac{\text{BTU/SEC}}{^\circ\text{F}} \quad \text{per inch}$$

A transient analysis also requires each node to have a thermal capacity. It is calculated as

$$\text{Capacity} = \text{Volume x Density x Specific heat}$$

Here the

$$\text{Volume} = \left(\frac{17}{12}\right)\left(\frac{2.517 \times 10^{-4}}{144}\right) = 1.456 \times 10^{-7} \text{Ft}^3$$

so

$$\text{Capacity} = \left(1.456\text{x}10^{-7}\right)\left(556.42\right)\left(0.092\right) = 7.4564\text{x}10^{-6}\frac{\text{BTU}}{^\circ\text{F}}$$

The power dissipated in each one inch section of a wire was calculated for the worst case as follows. The resistance of one inch of wire is, at 20°C, given from references 2 and 13 as

$$R_{20} = 2.7 \times 10^{-3} \text{ ohms}$$

This value was adjusted to 180°C by the relationship [13]

$$Rt = \left(\frac{100}{C}\right)R_{20}\left[1 + 0.00393(t - 20)\right]$$

where C = percent purity of the copper (used 97%)

   t = temperature in degrees Celsius

$$Rt = 4.5 \times 10^{-3} \text{ ohms}$$

Thus the power per inch is given by

$$P = RI^2 = \left(4.5\text{x}10^{-3}\right)\left(1.65\right)^2 = 0.0123\text{watts}$$

or

$$P = \frac{(0.0123)\left(5.689 \times 10^{-2}\right)}{60} = 1.162 \times 10^{-5}\frac{\text{BTU}}{\text{SEC}}$$

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The accompanying data, see pgs. 45-63, show a number of things. As they should the wire node temperatures final values vary linearly with the end node temperatures, the wire temperature is a strong function of the wire to heat sink conductance (it was varied from 10 times better to 10 times worse than that of a one inch piece of wire).

Qualitatively then it is clearly shown that keeping the heat sink temperatures down (this design incorporates a sink at each end of the motor; not just at one end) and minimizing the thermal resistance between the wire and the heat sink are vital.

An estimate of the wire to heat sink conductivity was made by assuming the following geometry.

1" long piece of Cu AWG 25 wire encapsulated
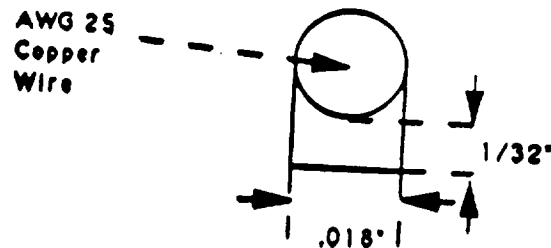
Assume a reasonable model is (of potting compound)

$$\text{Area} = \frac{0.018" \times 1"}{144 \text{in}^2 / \text{ft}^2} = 1.25 \times 10^{-4} \text{ft}^2$$

$$\text{Length} = \frac{1}{(32)(12)} = 2.6 \times 10^{-3} \text{ft}$$

Conductance per inch of wire length is found from:

(2850 KT Stykast)

$$\text{Conductivity} = 19.3 \frac{\text{BTU} - \text{in}}{\text{Ft}^2\text{HR}°\text{F}} \times \frac{1}{12} \frac{\text{Ft}}{\text{in}} = 1.61 \frac{\text{BTU}}{\text{FtHR}°\text{F}}$$

which compares to Cu as

$$210 \frac{\text{BTU}}{\text{HRFt}°\text{F}}$$

Thus the potting to Cu conductivity ratio inverse is

$$\frac{210}{1.61} = 130.6$$

$$\text{Conductance} = \text{Conductivity} \frac{\text{Area}}{\text{Length}}$$

$$\text{Cond.} => \frac{\text{BTU}}{°\text{FHRft}} \times \frac{ft^2}{ft} => \frac{\text{BTU}}{°\text{FHR}}$$

here for one inch of wire

$$\text{Conductance} = \frac{(1.61)(1.25 \times 10^{-4})}{(2.6)(10^{-3})} = 0.077 \frac{\text{BTU}}{°\text{FHR}}$$

or

$$0.077 \frac{\text{BTU}}{°\text{FHR}} \times \frac{1}{3600} \frac{\text{HR}}{\text{SEC}} = 2.15 \times 10^{-5} \frac{\text{BTU}}{°\text{FSec}}$$

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Compare to conductance of 1" of Cu wire (AWG25) from end to end which is

$$1.2795 \times 10^{-6} \frac{BTU}{Sec^{\circ}F}$$

Ratio

$$\frac{CondofCmpd}{Ccu} = \frac{2.15 \times 10^{-5}}{1.2795 \times 10^{-6}} = 16.8$$

If this can be achieved one would expect Re in the model to be somewhere between equal to Ccu and Ccu/10. The following data were run on the thermal analysis program for this case. From the results one sees that with the heat sinks held constant at 200°F, the wire started at 100°F, and the conductance from the wire to the heat sink set equal to that of 1 inch of AWG25 (end to end conductance) the final hot spot temperature of 272°F (133°C) was reached in approximately 5 minutes. 133°C is well within the insulation capacity of good grade magnet wire.
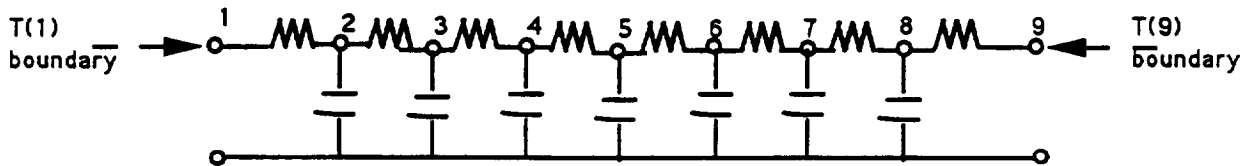
Thermal Network Used In Wire Analysis

44

```
752 DATA 2,7.46E-6,2,0
754 DATA 1.28E-6,1,1.28E-6,3
756 DATA 3,7.46E-6,2,0
758 DATA 1.28E-6,2,1.28E-6,4
760 DATA 4,7.46E-6,2,0
762 DATA 1.28E-6, 3, 1.28E-6, 5
764 DATA 5,7.46E-6,2,0
766 DATA 1.28E-6,4,1.28E-6,6
768 DATA 6,7.46E-6,2,0
770 DATA 1.28E-6,5,1.28E-6,7
772 DATA 7,7.46E-6,2,0
774 DATA 1.28E-6,6,1.28E-6,8
776 DATA 8,7.46E-6,2,0
778 DATA 1.28E-6,7,1.28E-6,9
780 Q(2) = 1.162E-05
782 Q(3) = 1.165E-05
784 Q(4) = 1.165E-05
786 Q(5) = 1.165E-05
788 Q(6) = 1.165E-05
790 Q(7) = 1.165E-05
792 Q(8) = 1.165E-05
794 T(1) = 200
796 T(9) = 200
```

```
STEADY STATE        SIGNIFICANT DIGITS= 4         RELAX ITER'NS= 14
      NODE      TEMP - F          TEMP - R           Q-INPUT Q-NET
       1       200.000           659.690         0.000    0.000000000000000
       2       231.772           691.462         0.000    0.000000051235634
       3       254.519           714.209         0.000    0.000000125966594
       4       268.183           727.873         0.000    0.000000111325612
       5       272.753           732.443         0.000    0.000000082773582
       6       268.223           727.913         0.000    0.000000051015277
       7       254.587           714.277         0.000    0.000000025734055
       8       231.846           691.536         0.000    0.000000009502783
       9       200.000           659.690         0.000    0.000000000000000

Elapsed computer time with printing= 3.333333333330302D-02 minutes
Date is 02-25-1993      Time is 09:40:18
```

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TIME=   0.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
        NODE    TEMP - F          TEMP - R          Q-INPUT Q-NET
         1      200.000          659.690          0.000      0.000000000000000
         2      100.000          559.690          0.000      0.000139619995025
         3      100.000          559.690          0.000      0.000011649999578
         4      100.000          559.690          0.000      0.000011649999578
         5      100.000          559.690          0.000      0.000011649999578
         6      100.000          559.690          0.000      0.000011649999578
         7      100.000          559.690          0.000      0.000011649999578
         8      100.000          559.690          0.000      0.000139650001074
         9      200.000          659.690          0.000      0.000000000000000

TIME=  40.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
        NODE    TEMP - F          TEMP - R          Q-INPUT Q-NET
         1      200.000          659.690          0.000      0.000000000000000
         2      205.622          665.312          0.000      0.000001922702722
         3      207.179          666.869          0.000      0.000016218846213
         4      204.963          664.653          0.000      0.000004641791293
         5      205.749          665.439          0.000      0.000022936137611
         6      204.969          664.659          0.000      0.000004641791293
         7      207.191          666.881          0.000      0.000016219080862
         8      205.639          665.329          0.000      0.000001922702722
         9      200.000          659.690          0.000      0.000000000000000

TIME=  80.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
        NODE    TEMP - F          TEMP - R          Q-INPUT Q-NET
         1      200.000          659.690          0.000      0.000000000000000
         2      223.042          682.732          0.000      0.000001318639647
         3      238.489          698.179          0.000      0.000004236555014
         4      247.018          706.708          0.000      0.000003183478157
         5      250.029          709.719          0.000      0.000005991394573
         6      247.024          706.714          0.000      0.000003183478611
         7      238.501          698.191          0.000      0.000004236556379
         8      223.059          682.749          0.000      0.000001318640102
         9      200.000          659.690          0.000      0.000000000000000

TIME= 120.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
        NODE    TEMP - F          TEMP - R          Q-INPUT Q-NET
         1      200.000          659.690          0.000      0.000000000000000
         2      228.875          688.565          0.000      0.000000540234169
         3      249.143          708.833          0.000      0.000001254034032
         4      261.101          720.791          0.000      0.000001304240641
         5      265.095          724.785          0.000      0.000001773471922
         6      261.106          720.796          0.000      0.000001304240641
         7      249.155          708.845          0.000      0.000001254034032
         8      228.892          688.582          0.000      0.000000540234169
         9      200.000          659.690          0.000      0.000000000000000

TIME= 160.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
        NODE    TEMP - F          TEMP - R          Q-INPUT Q-NET
         1      200.000          659.690          0.000      0.000000000000000
         2      230.837          690.527          0.000      0.000000195862242
         3      252.751          712.441          0.000      0.000000398260966
         4      265.838          725.528          0.000      0.000000472853259
         5      270.197          729.887          0.000      0.000000563226081
         6      265.844          725.534          0.000      0.000000472853259
         7      252.762          712.452          0.000      0.000000398260966
         8      230.855          690.545          0.000      0.000000195862242
         9      200.000          659.690          0.000      0.000000000000000
```

```
TIME= 200.0000     RCMIN=    2.91406     MIN NODE # 8      ITERATIONS= 0
        NODE      TEMP - F           TEMP - R          Q-INPUT Q-NET
         1        200.000          659.690          0.000    0.000000000000000
         2        231.498          691.188          0.000    0.000000068028399
         3        253.970          713.660          0.000    0.000000130866653
         4        267.434          727.124          0.000    0.000000164235075
         5        271.922          731.612          0.000    0.000000185073404
         6        267.440          727.130          0.000    0.000000164235075
         7        253.982          713.672          0.000    0.000000130866653
         8        231.516          691.206          0.000    0.000000068028399
         9        200.000          659.690          0.000    0.000000000000000

TIME= 240.0000     RCMIN=    2.91406     MIN NODE # 8      ITERATIONS= 0
        NODE      TEMP - F           TEMP - R          Q-INPUT Q-NET
         1        200.000          659.690          0.000    0.000000000000000
         2        231.721          691.411          0.000    0.000000023233687
         3        254.382          714.072          0.000    0.000000043664503
         4        267.973          727.663          0.000    0.000000056091082
         5        272.504          732.194          0.000    0.000000061750931
         6        267.979          727.669          0.000    0.000000056091082
         7        254.394          714.084          0.000    0.000000043664503
         8        231.739          691.429          0.000    0.000000023233687
         9        200.000          659.690          0.000    0.000000000000000

TIME= 280.0000     RCMIN=    2.91406     MIN NODE # 8      ITERATIONS= 0
        NODE      TEMP - F           TEMP - R          Q-INPUT Q-NET
         1        200.000          659.690          0.000    0.000000000000000
         2        231.797          691.487          0.000    0.000000007880508
         3        254.521          714.211          0.000    0.000000014665628
         4        268.155          727.845          0.000    0.000000019025229
         5        272.701          732.391          0.000    0.000000020740330
         6        268.160          727.850          0.000    0.000000019025229
         7        254.533          714.223          0.000    0.000000014665628
         8        231.814          691.504          0.000    0.000000007880508
         9        200.000          659.690          0.000    0.000000000000000

TIME= 320.0000     RCMIN=    2.91406     MIN NODE # 8      ITERATIONS= 0
        NODE      TEMP - F           TEMP - R          Q-INPUT Q-NET
         1        200.000          659.690          0.000    0.000000000000000
         2        231.822          691.512          0.000    0.000000002665296
         3        254.568          714.258          0.000    0.000000004939654
         4        268.216          727.906          0.000    0.000000006434593
         5        272.767          732.457          0.000    0.000000006985725
         6        268.222          727.912          0.000    0.000000006434593
         7        254.580          714.270          0.000    0.000000004939654
         8        231.840          691.530          0.000    0.000000002665296
         9        200.000          659.690          0.000    0.000000000000000

TIME= 360.0000     RCMIN=    2.91406     MIN NODE # 8      ITERATIONS= 0
        NODE      TEMP - F           TEMP - R          Q-INPUT Q-NET
         1        200.000          659.690          0.000    0.000000000000000
         2        231.831          691.521          0.000    0.000000000900358
         3        254.584          714.274          0.000    0.000000001665751
         4        268.237          727.927          0.000    0.000000002173655
         5        272.789          732.479          0.000    0.000000002355728
         6        268.242          727.932          0.000    0.000000002173655
         7        254.595          714.285          0.000    0.000000001665751
         8        231.848          691.538          0.000    0.000000000900358
         9        200.000          659.690          0.000    0.000000000000000
```

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TIME= 400.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
        NODE     TEMP - F        TEMP - R           Q-INPUT Q-NET
         1       200.000        659.690        0.000    0.000000000000000
         2       231.833        691.523        0.000    0.000000000303994
         3       254.589        714.279        0.000    0.000000000562008
         4       268.244        727.934        0.000    0.000000000733907
         5       272.797        732.487        0.000    0.000000000794799
         6       268.249        727.939        0.000    0.000000000733907
         7       254.601        714.291        0.000    0.000000000562008
         8       231.851        691.541        0.000    0.000000000303994
         9       200.000        659.690        0.000    0.000000000000000

TIME= 440.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
        NODE     TEMP - F        TEMP - R           Q-INPUT Q-NET
         1       200.000        659.690        0.000    0.000000000000000
         2       231.834        691.524        0.000    0.000000000102618
         3       254.591        714.281        0.000    0.000000000189656
         4       268.246        727.936        0.000    0.000000000247742
         5       272.799        732.489        0.000    0.000000000268214
         6       268.252        727.942        0.000    0.000000000247742
         7       254.603        714.293        0.000    0.000000000189656
         8       231.852        691.542        0.000    0.000000000102618
         9       200.000        659.690        0.000    0.000000000000000

TIME= 480.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
        NODE     TEMP - F        TEMP - R           Q-INPUT Q-NET
         1       200.000        659.690        0.000    0.000000000000000
         2       231.835        691.525        0.000    0.000000000034637
         3       254.591        714.281        0.000    0.000000000064007
         4       268.247        727.937        0.000    0.000000000083622
         5       272.800        732.490        0.000    0.000000000090520
         6       268.253        727.943        0.000    0.000000000083622
         7       254.603        714.293        0.000    0.000000000064007
         8       231.852        691.542        0.000    0.000000000034637
         9       200.000        659.690        0.000    0.000000000000000

TIME= 520.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
        NODE     TEMP - F        TEMP - R           Q-INPUT Q-NET
         1       200.000        659.690        0.000    0.000000000000000
         2       231.835        691.525        0.000    0.000000000011691
         3       254.592        714.282        0.000    0.000000000021603
         4       268.247        727.937        0.000    0.000000000028224
         5       272.801        732.491        0.000    0.000000000030551
         6       268.253        727.943        0.000    0.000000000028224
         7       254.603        714.293        0.000    0.000000000021603
         8       231.852        691.542        0.000    0.000000000011691
         9       200.000        659.690        0.000    0.000000000000000

TIME= 560.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
        NODE     TEMP - F        TEMP - R           Q-INPUT Q-NET
         1       200.000        659.690        0.000    0.000000000000000
         2       231.835        691.525        0.000    0.000000000003946
         3       254.592        714.282        0.000    0.000000000007291
         4       268.247        727.937        0.000    0.000000000009526
         5       272.801        732.491        0.000    0.000000000010311
         6       268.253        727.943        0.000    0.000000000009526
         7       254.603        714.293        0.000    0.000000000007291
         8       231.853        691.543        0.000    0.000000000003946
         9       200.000        659.690        0.000    0.000000000000000
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TIME=  600.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
       NODE    TEMP - F        TEMP - R          Q-INPUT Q-NET
        1      200.000         659.690           0.000    0.000000000000000
        2      231.835         691.525           0.000    0.000000000001332
        3      254.592         714.282           0.000    0.000000000002461
        4      268.247         727.937           0.000    0.000000000003215
        5      272.801         732.491           0.000    0.000000000003480
        6      268.253         727.943           0.000    0.000000000003215
        7      254.604         714.294           0.000    0.000000000002461
        8      231.853         691.543           0.000    0.000000000001332
        9      200.000         659.690           0.000    0.000000000000000

TIME=  640.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
       NODE    TEMP - F        TEMP - R          Q-INPUT Q-NET
        1      200.000         659.690           0.000    0.000000000000000
        2      231.835         691.525           0.000    0.000000000000449
        3      254.592         714.282           0.000    0.000000000000831
        4      268.247         727.937           0.000    0.000000000001085
        5      272.801         732.491           0.000    0.000000000001175
        6      268.253         727.943           0.000    0.000000000001085
        7      254.604         714.294           0.000    0.000000000000831
        8      231.853         691.543           0.000    0.000000000000449
        9      200.000         659.690           0.000    0.000000000000000

TIME=  680.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
       NODE    TEMP - F        TEMP - R          Q-INPUT Q-NET
        1      200.000         659.690           0.000    0.000000000000000
        2      231.835         691.525           0.000    0.000000000000152
        3      254.592         714.282           0.000    0.000000000000280
        4      268.247         727.937           0.000    0.000000000000366
        5      272.801         732.491           0.000    0.000000000000396
        6      268.253         727.943           0.000    0.000000000000366
        7      254.604         714.294           0.000    0.000000000000280
        8      231.853         691.543           0.000    0.000000000000152
        9      200.000         659.690           0.000    0.000000000000000

TIME=  720.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
       NODE    TEMP - F        TEMP - R          Q-INPUT Q-NET
        1      200.000         659.690           0.000    0.000000000000000
        2      231.835         691.525           0.000    0.000000000000051
        3      254.592         714.282           0.000    0.000000000000095
        4      268.247         727.937           0.000    0.000000000000124
        5      272.801         732.491           0.000    0.000000000000134
        6      268.253         727.943           0.000    0.000000000000124
        7      254.604         714.294           0.000    0.000000000000095
        8      231.853         691.543           0.000    0.000000000000051
        9      200.000         659.690           0.000    0.000000000000000

TIME=  760.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
       NODE    TEMP - F        TEMP - R          Q-INPUT Q-NET
        1      200.000         659.690           0.000    0.000000000000000
        2      231.835         691.525           0.000    0.000000000000017
        3      254.592         714.282           0.000    0.000000000000032
        4      268.247         727.937           0.000    0.000000000000042
        5      272.801         732.491           0.000    0.000000000000045
        6      268.253         727.943           0.000    0.000000000000042
        7      254.604         714.294           0.000    0.000000000000032
        8      231.853         691.543           0.000    0.000000000000017
        9      200.000         659.690           0.000    0.000000000000000
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TIME= 800.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
       NODE      TEMP - F        TEMP - R           Q-INPUT Q-NET
         1       200.000         659.690        0.000      0.000000000000000
         2       231.835         691.525        0.000      0.000000000000006
         3       254.592         714.282        0.000      0.000000000000011
         4       268.247         727.937        0.000      0.000000000000014
         5       272.801         732.491        0.000      0.000000000000015
         6       268.253         727.943        0.000      0.000000000000014
         7       254.604         714.294        0.000      0.000000000000011
         8       231.853         691.543        0.000      0.000000000000006
         9       200.000         659.690        0.000      0.000000000000000

TIME= 840.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
       NODE      TEMP - F        TEMP - R           Q-INPUT Q-NET
         1       200.000         659.690        0.000      0.000000000000000
         2       231.835         691.525        0.000      0.000000000000002
         3       254.592         714.282        0.000      0.000000000000004
         4       268.247         727.937        0.000      0.000000000000005
         5       272.801         732.491        0.000      0.000000000000005
         6       268.253         727.943        0.000      0.000000000000005
         7       254.604         714.294        0.000      0.000000000000004
         8       231.853         691.543        0.000      0.000000000000002
         9       200.000         659.690        0.000      0.000000000000000

TIME= 880.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
       NODE      TEMP - F        TEMP - R           Q-INPUT Q-NET
         1       200.000         659.690        0.000      0.000000000000000
         2       231.835         691.525        0.000      0.000000000000001
         3       254.592         714.282        0.000      0.000000000000001
         4       268.247         727.937        0.000      0.000000000000002
         5       272.801         732.491        0.000      0.000000000000002
         6       268.253         727.943        0.000      0.000000000000002
         7       254.604         714.294        0.000      0.000000000000001
         8       231.853         691.543        0.000      0.000000000000001
         9       200.000         659.690        0.000      0.000000000000000

TIME= 920.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
       NODE      TEMP - F        TEMP - R           Q-INPUT Q-NET
         1       200.000         659.690        0.000      0.000000000000000
         2       231.835         691.525        0.000      0.000000000000000
         3       254.592         714.282        0.000      0.000000000000000
         4       268.247         727.937        0.000      0.000000000000001
         5       272.801         732.491        0.000      0.000000000000001
         6       268.253         727.943        0.000      0.000000000000001
         7       254.604         714.294        0.000      0.000000000000000
         8       231.853         691.543        0.000      0.000000000000000
         9       200.000         659.690        0.000      0.000000000000000

TIME= 960.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
       NODE      TEMP - F        TEMP - R           Q-INPUT Q-NET
         1       200.000         659.690        0.000      0.000000000000000
         2       231.835         691.525        0.000      0.000000000000000
         3       254.592         714.282        0.000      0.000000000000000
         4       268.247         727.937        0.000      0.000000000000000
         5       272.801         732.491        0.000      0.000000000000000
         6       268.253         727.943        0.000      0.000000000000000
         7       254.604         714.294        0.000      0.000000000000000
         8       231.853         691.543        0.000      0.000000000000000
         9       200.000         659.690        0.000      0.000000000000000
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TIME=1000.0000      RCMIN=   2.91406      MIN NODE # 8      ITERATIONS= 0
        NODE      TEMP - F          TEMP - R          Q-INPUT Q-NET
         1        200.000          659.690           0.000      0.000000000000000
         2        231.835          691.525           0.000      0.000000000000000
         3        254.592          714.282           0.000      0.000000000000000
         4        268.247          727.937           0.000      0.000000000000000
         5        272.801          732.491           0.000      0.000000000000000
         6        268.253          727.943           0.000      0.000000000000000
         7        254.604          714.294           0.000      0.000000000000000
         8        231.853          691.543           0.000      0.000000000000000
         9        200.000          659.690           0.000      0.000000000000000

TIME=1040.0000      RCMIN=   2.91406      MIN NODE # 8      ITERATIONS= 0
        NODE      TEMP - F          TEMP - R          Q-INPUT Q-NET
         1        200.000          659.690           0.000      0.000000000000000
         2        231.835          691.525           0.000      0.000000000000000
         3        254.592          714.282           0.000      0.000000000000000
         4        268.247          727.937           0.000      0.000000000000000
         5        272.801          732.491           0.000      0.000000000000000
         6        268.253          727.943           0.000      0.000000000000000
         7        254.604          714.294           0.000      0.000000000000000
         8        231.853          691.543           0.000      0.000000000000000
         9        200.000          659.690           0.000      0.000000000000000

TIME=1080.0000      RCMIN=   2.91406      MIN NODE # 8      ITERATIONS= 0
        NODE      TEMP - F          TEMP - R          Q-INPUT Q-NET
         1        200.000          659.690           0.000      0.000000000000000
         2        231.835          691.525           0.000      0.000000000000000
         3        254.592          714.282           0.000      0.000000000000000
         4        268.247          727.937           0.000      0.000000000000000
         5        272.801          732.491           0.000      0.000000000000000
         6        268.253          727.943           0.000      0.000000000000000
         7        254.604          714.294           0.000      0.000000000000000
         8        231.853          691.543           0.000      0.000000000000000
         9        200.000          659.690           0.000      0.000000000000000

TIME=1120.0000      RCMIN=   2.91406      MIN NODE # 8      ITERATIONS= 0
        NODE      TEMP - F          TEMP - R          Q-INPUT Q-NET
         1        200.000          659.690           0.000      0.000000000000000
         2        231.835          691.525           0.000      0.000000000000000
         3        254.592          714.282           0.000      0.000000000000000
         4        268.247          727.937           0.000      0.000000000000000
         5        272.801          732.491           0.000      0.000000000000000
         6        268.253          727.943           0.000      0.000000000000000
         7        254.604          714.294           0.000      0.000000000000000
         8        231.853          691.543           0.000      0.000000000000000
         9        200.000          659.690           0.000      0.000000000000000

TIME=1160.0000      RCMIN=   2.91406      MIN NODE # 8      ITERATIONS= 0
        NODE      TEMP - F          TEMP - R          Q-INPUT Q-NET
         1        200.000          659.690           0.000      0.000000000000000
         2        231.835          691.525           0.000      0.000000000000000
         3        254.592          714.282           0.000      0.000000000000000
         4        268.247          727.937           0.000      0.000000000000000
         5        272.801          732.491           0.000      0.000000000000000
         6        268.253          727.943           0.000      0.000000000000000
         7        254.604          714.294           0.000      0.000000000000000
         8        231.853          691.543           0.000      0.000000000000000
         9        200.000          659.690           0.000      0.000000000000000
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TIME=1200.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
     NODE      TEMP - F        TEMP - R          Q-INPUT Q-NET
      1        200.000        659.690        0.000        0.000000000000000
      2        231.835        691.525        0.000        0.000000000000000
      3        254.592        714.282        0.000        0.000000000000000
      4        268.247        727.937        0.000        0.000000000000000
      5        272.801        732.491        0.000        0.000000000000000
      6        268.253        727.943        0.000        0.000000000000000
      7        254.604        714.294        0.000        0.000000000000000
      8        231.853        691.543        0.000       -0.000000000000000
      9        200.000        659.690        0.000        0.000000000000000

TIME=1240.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
     NODE      TEMP - F        TEMP - R          Q-INPUT Q-NET
      1        200.000        659.690        0.000        0.000000000000000
      2        231.835        691.525        0.000        0.000000000000000
      3        254.592        714.282        0.000        0.000000000000000
      4        268.247        727.937        0.000       -0.000000000000000
      5        272.801        732.491        0.000        0.000000000000000
      6        268.253        727.943        0.000       -0.000000000000000
      7        254.604        714.294        0.000        0.000000000000000
      8        231.853        691.543        0.000       -0.000000000000000
      9        200.000        659.690        0.000        0.000000000000000

TIME=1280.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
     NODE      TEMP - F        TEMP - R          Q-INPUT Q-NET
      1        200.000        659.690        0.000        0.000000000000000
      2        231.835        691.525        0.000       -0.000000000000000
      3        254.592        714.282        0.000        0.000000000000000
      4        268.247        727.937        0.000        0.000000000000000
      5        272.801        732.491        0.000        0.000000000000000
      6        268.253        727.943        0.000        0.000000000000000
      7        254.604        714.294        0.000        0.000000000000000
      8        231.853        691.543        0.000        0.000000000000000
      9        200.000        659.690        0.000        0.000000000000000

TIME=1320.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
     NODE      TEMP - F        TEMP - R          Q-INPUT Q-NET
      1        200.000        659.690        0.000        0.000000000000000
      2        231.835        691.525        0.000       -0.000000000000000
      3        254.592        714.282        0.000        0.000000000000000
      4        268.247        727.937        0.000        0.000000000000000
      5        272.801        732.491        0.000        0.000000000000000
      6        268.253        727.943        0.000        0.000000000000000
      7        254.604        714.294        0.000        0.000000000000000
      8        231.853        691.543        0.000        0.000000000000000
      9        200.000        659.690        0.000        0.000000000000000

TIME=1360.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
     NODE      TEMP - F        TEMP - R          Q-INPUT Q-NET
      1        200.000        659.690        0.000        0.000000000000000
      2        231.835        691.525        0.000       -0.000000000000000
      3        254.592        714.282        0.000        0.000000000000000
      4        268.247        727.937        0.000        0.000000000000000
      5        272.801        732.491        0.000        0.000000000000000
      6        268.253        727.943        0.000        0.000000000000000
      7        254.604        714.294        0.000        0.000000000000000
      8        231.853        691.543        0.000        0.000000000000000
      9        200.000        659.690        0.000        0.000000000000000
```

```
TIME=1400.0000      RCMIN=   2.91406      MIN NODE # 8      ITERATIONS= 0
        NODE     TEMP - F          TEMP - R              Q-INPUT Q-NET
         1       200.000          659.690        0.000        0.000000000000000
         2       231.835          691.525        0.000       -0.000000000000000
         3       254.592          714.282        0.000        0.000000000000000
         4       268.247          727.937        0.000        0.000000000000000
         5       272.801          732.491        0.000        0.000000000000000
         6       268.253          727.943        0.000        0.000000000000000
         7       254.604          714.294        0.000        0.000000000000000
         8       231.853          691.543        0.000        0.000000000000000
         9       200.000          659.690        0.000        0.000000000000000

TIME=1440.0000      RCMIN=   2.91406      MIN NODE # 8      ITERATIONS= 0
        NODE     TEMP - F          TEMP - R              Q-INPUT Q-NET
         1       200.000          659.690        0.000        0.000000000000000
         2       231.835          691.525        0.000       -0.000000000000000
         3       254.592          714.282        0.000        0.000000000000000
         4       268.247          727.937        0.000        0.000000000000000
         5       272.801          732.491        0.000        0.000000000000000
         6       268.253          727.943        0.000        0.000000000000000
         7       254.604          714.294        0.000        0.000000000000000
         8       231.853          691.543        0.000        0.000000000000000
         9       200.000          659.690        0.000        0.000000000000000

TIME=1480.0000      RCMIN=   2.91406      MIN NODE # 8      ITERATIONS= 0
        NODE     TEMP - F          TEMP - R              Q-INPUT Q-NET
         1       200.000          659.690        0.000        0.000000000000000
         2       231.835          691.525        0.000       -0.000000000000000
         3       254.592          714.282        0.000        0.000000000000000
         4       268.247          727.937        0.000        0.000000000000000
         5       272.801          732.491        0.000        0.000000000000000
         6       268.253          727.943        0.000        0.000000000000000
         7       254.604          714.294        0.000        0.000000000000000
         8       231.853          691.543        0.000        0.000000000000000
         9       200.000          659.690        0.000        0.000000000000000

TIME=1520.0000      RCMIN=   2.91406      MIN NODE # 8      ITERATIONS= 0
        NODE     TEMP - F          TEMP - R              Q-INPUT Q-NET
         1       200.000          659.690        0.000        0.000000000000000
         2       231.835          691.525        0.000       -0.000000000000000
         3       254.592          714.282        0.000        0.000000000000000
         4       268.247          727.937        0.000        0.000000000000000
         5       272.801          732.491        0.000        0.000000000000000
         6       268.253          727.943        0.000        0.000000000000000
         7       254.604          714.294        0.000        0.000000000000000
         8       231.853          691.543        0.000        0.000000000000000
         9       200.000          659.690        0.000        0.000000000000000

TIME=1560.0000      RCMIN=   2.91406      MIN NODE # 8      ITERATIONS= 0
        NODE     TEMP - F          TEMP - R              Q-INPUT Q-NET
         1       200.000          659.690        0.000        0.000000000000000
         2       231.835          691.525        0.000       -0.000000000000000
         3       254.592          714.282        0.000        0.000000000000000
         4       268.247          727.937        0.000        0.000000000000000
         5       272.801          732.491        0.000        0.000000000000000
         6       268.253          727.943        0.000        0.000000000000000
         7       254.604          714.294        0.000        0.000000000000000
         8       231.853          691.543        0.000        0.000000000000000
         9       200.000          659.690        0.000        0.000000000000000
```

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```
TIME=1600.0000     RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
       NODE      TEMP - F        TEMP - R            Q-INPUT  Q-NET
        1        200.000        659.690        0.000     0.000000000000000
        2        231.835        691.525        0.000    -0.000000000000000
        3        254.592        714.282        0.000     0.000000000000000
        4        268.247        727.937        0.000     0.000000000000000
        5        272.801        732.491        0.000     0.000000000000000
        6        268.253        727.943        0.000     0.000000000000000
        7        254.604        714.294        0.000     0.000000000000000
        8        231.853        691.543        0.000     0.000000000000000
        9        200.000        659.690        0.000     0.000000000000000

TIME=1640.0000     RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
       NODE      TEMP - F        TEMP - R            Q-INPUT  Q-NET
        1        200.000        659.690        0.000     0.000000000000000
        2        231.835        691.525        0.000    -0.000000000000000
        3        254.592        714.282        0.000     0.000000000000000
        4        268.247        727.937        0.000     0.000000000000000
        5        272.801        732.491        0.000     0.000000000000000
        6        268.253        727.943        0.000     0.000000000000000
        7        254.604        714.294        0.000     0.000000000000000
        8        231.853        691.543        0.000     0.000000000000000
        9        200.000        659.690        0.000     0.000000000000000

TIME=1680.0000     RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
       NODE      TEMP - F        TEMP - R            Q-INPUT  Q-NET
        1        200.000        659.690        0.000     0.000000000000000
        2        231.835        691.525        0.000    -0.000000000000000
        3        254.592        714.282        0.000     0.000000000000000
        4        268.247        727.937        0.000     0.000000000000000
        5        272.801        732.491        0.000     0.000000000000000
        6        268.253        727.943        0.000     0.000000000000000
        7        254.604        714.294        0.000     0.000000000000000
        8        231.853        691.543        0.000     0.000000000000000
        9        200.000        659.690        0.000     0.000000000000000

TIME=1720.0000     RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
       NODE      TEMP - F        TEMP - R            Q-INPUT  Q-NET
        1        200.000        659.690        0.000     0.000000000000000
        2        231.835        691.525        0.000    -0.000000000000000
        3        254.592        714.282        0.000     0.000000000000000
        4        268.247        727.937        0.000     0.000000000000000
        5        272.801        732.491        0.000     0.000000000000000
        6        268.253        727.943        0.000     0.000000000000000
        7        254.604        714.294        0.000     0.000000000000000
        8        231.853        691.543        0.000     0.000000000000000
        9        200.000        659.690        0.000     0.000000000000000

TIME=1760.0000     RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
       NODE      TEMP - F        TEMP - R            Q-INPUT  Q-NET
        1        200.000        659.690        0.000     0.000000000000000
        2        231.835        691.525        0.000    -0.000000000000000
        3        254.592        714.282        0.000     0.000000000000000
        4        268.247        727.937        0.000     0.000000000000000
        5        272.801        732.491        0.000     0.000000000000000
        6        268.253        727.943        0.000     0.000000000000000
        7        254.604        714.294        0.000     0.000000000000000
        8        231.853        691.543        0.000     0.000000000000000
        9        200.000        659.690        0.000     0.000000000000000
```

```
TIME=1800.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
        NODE    TEMP - F        TEMP - R        Q-INPUT Q-NET
          1     200.000         659.690         0.000     0.000000000000000
          2     231.835         691.525         0.000    -0.000000000000000
          3     254.592         714.282         0.000     0.000000000000000
          4     268.247         727.937         0.000     0.000000000000000
          5     272.801         732.491         0.000     0.000000000000000
          6     268.253         727.943         0.000     0.000000000000000
          7     254.604         714.294         0.000     0.000000000000000
          8     231.853         691.543         0.000     0.000000000000000
          9     200.000         659.690         0.000     0.000000000000000

TIME=1840.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
        NODE    TEMP - F        TEMP - R        Q-INPUT Q-NET
          1     200.000         659.690         0.000     0.000000000000000
          2     231.835         691.525         0.000    -0.000000000000000
          3     254.592         714.282         0.000     0.000000000000000
          4     268.247         727.937         0.000     0.000000000000000
          5     272.801         732.491         0.000     0.000000000000000
          6     268.253         727.943         0.000     0.000000000000000
          7     254.604         714.294         0.000     0.000000000000000
          8     231.853         691.543         0.000     0.000000000000000
          9     200.000         659.690         0.000     0.000000000000000

TIME=1880.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
        NODE    TEMP - F        TEMP - R        Q-INPUT Q-NET
          1     200.000         659.690         0.000     0.000000000000000
          2     231.835         691.525         0.000    -0.000000000000000
          3     254.592         714.282         0.000     0.000000000000000
          4     268.247         727.937         0.000     0.000000000000000
          5     272.801         732.491         0.000     0.000000000000000
          6     268.253         727.943         0.000     0.000000000000000
          7     254.604         714.294         0.000     0.000000000000000
          8     231.853         691.543         0.000     0.000000000000000
          9     200.000         659.690         0.000     0.000000000000000

TIME=1920.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
        NODE    TEMP - F        TEMP - R        Q-INPUT Q-NET
          1     200.000         659.690         0.000     0.000000000000000
          2     231.835         691.525         0.000    -0.000000000000000
          3     254.592         714.282         0.000     0.000000000000000
          4     268.247         727.937         0.000     0.000000000000000
          5     272.801         732.491         0.000     0.000000000000000
          6     268.253         727.943         0.000     0.000000000000000
          7     254.604         714.294         0.000     0.000000000000000
          8     231.853         691.543         0.000     0.000000000000000
          9     200.000         659.690         0.000     0.000000000000000

TIME=1960.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
        NODE    TEMP - F        TEMP - R        Q-INPUT Q-NET
          1     200.000         659.690         0.000     0.000000000000000
          2     231.835         691.525         0.000    -0.000000000000000
          3     254.592         714.282         0.000     0.000000000000000
          4     268.247         727.937         0.000     0.000000000000000
          5     272.801         732.491         0.000     0.000000000000000
          6     268.253         727.943         0.000     0.000000000000000
          7     254.604         714.294         0.000     0.000000000000000
          8     231.853         691.543         0.000     0.000000000000000
          9     200.000         659.690         0.000     0.000000000000000
```

```
TIME=2000.0000      RCMIN=   2.91406      MIN NODE # 8     ITERATIONS= 0
       NODE      TEMP - F          TEMP - R            Q-INPUT Q-NET
        1        200.000         659.690         0.000    0.000000000000000
        2        231.835         691.525         0.000   -0.000000000000000
        3        254.592         714.282         0.000    0.000000000000000
        4        268.247         727.937         0.000    0.000000000000000
        5        272.801         732.491         0.000    0.000000000000000
        6        268.253         727.943         0.000    0.000000000000000
        7        254.604         714.294         0.000    0.000000000000000
        8        231.853         691.543         0.000    0.000000000000000
        9        200.000         659.690         0.000    0.000000000000000

TIME=2040.0000      RCMIN=   2.91406      MIN NODE # 8     ITERATIONS= 0
       NODE      TEMP - F          TEMP - R            Q-INPUT Q-NET
        1        200.000         659.690         0.000    0.000000000000000
        2        231.835         691.525         0.000   -0.000000000000000
        3        254.592         714.282         0.000    0.000000000000000
        4        268.247         727.937         0.000    0.000000000000000
        5        272.801         732.491         0.000    0.000000000000000
        6        268.253         727.943         0.000    0.000000000000000
        7        254.604         714.294         0.000    0.000000000000000
        8        231.853         691.543         0.000    0.000000000000000
        9        200.000         659.690         0.000    0.000000000000000

TIME=2080.0000      RCMIN=   2.91406      MIN NODE # 8     ITERATIONS= 0
       NODE      TEMP - F          TEMP - R            Q-INPUT Q-NET
        1        200.000         659.690         0.000    0.000000000000000
        2        231.835         691.525         0.000   -0.000000000000000
        3        254.592         714.282         0.000    0.000000000000000
        4        268.247         727.937         0.000    0.000000000000000
        5        272.801         732.491         0.000    0.000000000000000
        6        268.253         727.943         0.000    0.000000000000000
        7        254.604         714.294         0.000    0.000000000000000
        8        231.853         691.543         0.000    0.000000000000000
        9        200.000         659.690         0.000    0.000000000000000

TIME=2120.0000      RCMIN=   2.91406      MIN NODE # 8     ITERATIONS= 0
       NODE      TEMP - F          TEMP - R            Q-INPUT Q-NET
        1        200.000         659.690         0.000    0.000000000000000
        2        231.835         691.525         0.000   -0.000000000000000
        3        254.592         714.282         0.000    0.000000000000000
        4        268.247         727.937         0.000    0.000000000000000
        5        272.801         732.491         0.000    0.000000000000000
        6        268.253         727.943         0.000    0.000000000000000
        7        254.604         714.294         0.000    0.000000000000000
        8        231.853         691.543         0.000    0.000000000000000
        9        200.000         659.690         0.000    0.000000000000000

TIME=2160.0000      RCMIN=   2.91406      MIN NODE # 8     ITERATIONS= 0
       NODE      TEMP - F          TEMP - R            Q-INPUT Q-NET
        1        200.000         659.690         0.000    0.000000000000000
        2        231.835         691.525         0.000   -0.000000000000000
        3        254.592         714.282         0.000    0.000000000000000
        4        268.247         727.937         0.000    0.000000000000000
        5        272.801         732.491         0.000    0.000000000000000
        6        268.253         727.943         0.000    0.000000000000000
        7        254.604         714.294         0.000    0.000000000000000
        8        231.853         691.543         0.000    0.000000000000000
        9        200.000         659.690         0.000    0.000000000000000
```

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```
TIME=2000.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
       NODE      TEMP - F        TEMP - R          Q-INPUT Q-NET
         1       200.000        659.690      0.000      0.000000000000000
         2       231.835        691.525      0.000     -0.000000000000000
         3       254.592        714.282      0.000      0.000000000000000
         4       268.247        727.937      0.000      0.000000000000000
         5       272.801        732.491      0.000      0.000000000000000
         6       268.253        727.943      0.000      0.000000000000000
         7       254.604        714.294      0.000      0.000000000000000
         8       231.853        691.543      0.000      0.000000000000000
         9       200.000        659.690      0.000      0.000000000000000

TIME=2040.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
       NODE      TEMP - F        TEMP - R          Q-INPUT Q-NET
         1       200.000        659.690      0.000      0.000000000000000
         2       231.835        691.525      0.000     -0.000000000000000
         3       254.592        714.282      0.000      0.000000000000000
         4       268.247        727.937      0.000      0.000000000000000
         5       272.801        732.491      0.000      0.000000000000000
         6       268.253        727.943      0.000      0.000000000000000
         7       254.604        714.294      0.000      0.000000000000000
         8       231.853        691.543      0.000      0.000000000000000
         9       200.000        659.690      0.000      0.000000000000000

TIME=2080.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
       NODE      TEMP - F        TEMP - R          Q-INPUT Q-NET
         1       200.000        659.690      0.000      0.000000000000000
         2       231.835        691.525      0.000     -0.000000000000000
         3       254.592        714.282      0.000      0.000000000000000
         4       268.247        727.937      0.000      0.000000000000000
         5       272.801        732.491      0.000      0.000000000000000
         6       268.253        727.943      0.000      0.000000000000000
         7       254.604        714.294      0.000      0.000000000000000
         8       231.853        691.543      0.000      0.000000000000000
         9       200.000        659.690      0.000      0.000000000000000

TIME=2120.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
       NODE      TEMP - F        TEMP - R          Q-INPUT Q-NET
         1       200.000        659.690      0.000      0.000000000000000
         2       231.835        691.525      0.000     -0.000000000000000
         3       254.592        714.282      0.000      0.000000000000000
         4       268.247        727.937      0.000      0.000000000000000
         5       272.801        732.491      0.000      0.000000000000000
         6       268.253        727.943      0.000      0.000000000000000
         7       254.604        714.294      0.000      0.000000000000000
         8       231.853        691.543      0.000      0.000000000000000
         9       200.000        659.690      0.000      0.000000000000000

TIME=2160.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
       NODE      TEMP - F        TEMP - R          Q-INPUT Q-NET
         1       200.000        659.690      0.000      0.000000000000000
         2       231.835        691.525      0.000     -0.000000000000000
         3       254.592        714.282      0.000      0.000000000000000
         4       268.247        727.937      0.000      0.000000000000000
         5       272.801        732.491      0.000      0.000000000000000
         6       268.253        727.943      0.000      0.000000000000000
         7       254.604        714.294      0.000      0.000000000000000
         8       231.853        691.543      0.000      0.000000000000000
         9       200.000        659.690      0.000      0.000000000000000
```

```
TIME=2200.0000      RCMIN=   2.91406      MIN NODE # 8      ITERATIONS= 0
        NODE      TEMP - F         TEMP - R              Q-INPUT Q-NET
        1        200.000          659.690          0.000        0.000000000000000
        2        231.835          691.525          0.000       -0.000000000000000
        3        254.592          714.282          0.000        0.000000000000000
        4        268.247          727.937          0.000        0.000000000000000
        5        272.801          732.491          0.000        0.000000000000000
        6        268.253          727.943          0.000        0.000000000000000
        7        254.604          714.294          0.000        0.000000000000000
        8        231.853          691.543          0.000        0.000000000000000
        9        200.000          659.690          0.000        0.000000000000000

TIME=2240.0000      RCMIN=   2.91406      MIN NODE # 8      ITERATIONS= 0
        NODE      TEMP - F         TEMP - R              Q-INPUT Q-NET
        1        200.000          659.690          0.000        0.000000000000000
        2        231.835          691.525          0.000       -0.000000000000000
        3        254.592          714.282          0.000        0.000000000000000
        4        268.247          727.937          0.000        0.000000000000000
        5        272.801          732.491          0.000        0.000000000000000
        6        268.253          727.943          0.000        0.000000000000000
        7        254.604          714.294          0.000        0.000000000000000
        8        231.853          691.543          0.000        0.000000000000000
        9        200.000          659.690          0.000        0.000000000000000

TIME=2280.0000      RCMIN=   2.91406      MIN NODE # 8      ITERATIONS= 0
        NODE      TEMP - F         TEMP - R              Q-INPUT Q-NET
        1        200.000          659.690          0.000        0.000000000000000
        2        231.835          691.525          0.000       -0.000000000000000
        3        254.592          714.282          0.000        0.000000000000000
        4        268.247          727.937          0.000        0.000000000000000
        5        272.801          732.491          0.000        0.000000000000000
        6        268.253          727.943          0.000        0.000000000000000
        7        254.604          714.294          0.000        0.000000000000000
        8        231.853          691.543          0.000        0.000000000000000
        9        200.000          659.690          0.000        0.000000000000000

TIME=2320.0000      RCMIN=   2.91406      MIN NODE # 8      ITERATIONS= 0
        NODE      TEMP - F         TEMP - R              Q-INPUT Q-NET
        1        200.000          659.690          0.000        0.000000000000000
        2        231.835          691.525          0.000       -0.000000000000000
        3        254.592          714.282          0.000        0.000000000000000
        4        268.247          727.937          0.000        0.000000000000000
        5        272.801          732.491          0.000        0.000000000000000
        6        268.253          727.943          0.000        0.000000000000000
        7        254.604          714.294          0.000        0.000000000000000
        8        231.853          691.543          0.000        0.000000000000000
        9        200.000          659.690          0.000        0.000000000000000

TIME=2360.0000      RCMIN=   2.91406      MIN NODE # 8      ITERATIONS= 0
        NODE      TEMP - F         TEMP - R              Q-INPUT Q-NET
        1        200.000          659.690          0.000        0.000000000000000
        2        231.835          691.525          0.000       -0.000000000000000
        3        254.592          714.282          0.000        0.000000000000000
        4        268.247          727.937          0.000        0.000000000000000
        5        272.801          732.491          0.000        0.000000000000000
        6        268.253          727.943          0.000        0.000000000000000
        7        254.604          714.294          0.000        0.000000000000000
        8        231.853          691.543          0.000        0.000000000000000
        9        200.000          659.690          0.000        0.000000000000000
```

```
TIME=2400.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
       NODE      TEMP - F         TEMP - R              Q-INPUT Q-NET
         1       200.000         659.690         0.000      0.000000000000000
         2       231.835         691.525         0.000     -0.000000000000000
         3       254.592         714.282         0.000      0.000000000000000
         4       268.247         727.937         0.000      0.000000000000000
         5       272.801         732.491         0.000      0.000000000000000
         6       268.253         727.943         0.000      0.000000000000000
         7       254.604         714.294         0.000      0.000000000000000
         8       231.853         691.543         0.000      0.000000000000000
         9       200.000         659.690         0.000      0.000000000000000

TIME=2440.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
       NODE      TEMP - F         TEMP - R              Q-INPUT Q-NET
         1       200.000         659.690         0.000      0.000000000000000
         2       231.835         691.525         0.000     -0.000000000000000
         3       254.592         714.282         0.000      0.000000000000000
         4       268.247         727.937         0.000      0.000000000000000
         5       272.801         732.491         0.000      0.000000000000000
         6       268.253         727.943         0.000      0.000000000000000
         7       254.604         714.294         0.000      0.000000000000000
         8       231.853         691.543         0.000      0.000000000000000
         9       200.000         659.690         0.000      0.000000000000000

TIME=2480.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
       NODE      TEMP - F         TEMP - R              Q-INPUT Q-NET
         1       200.000         659.690         0.000      0.000000000000000
         2       231.835         691.525         0.000     -0.000000000000000
         3       254.592         714.282         0.000      0.000000000000000
         4       268.247         727.937         0.000      0.000000000000000
         5       272.801         732.491         0.000      0.000000000000000
         6       268.253         727.943         0.000      0.000000000000000
         7       254.604         714.294         0.000      0.000000000000000
         8       231.853         691.543         0.000      0.000000000000000
         9       200.000         659.690         0.000      0.000000000000000

TIME=2520.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
       NODE      TEMP - F         TEMP - R              Q-INPUT Q-NET
         1       200.000         659.690         0.000      0.000000000000000
         2       231.835         691.525         0.000     -0.000000000000000
         3       254.592         714.282         0.000      0.000000000000000
         4       268.247         727.937         0.000      0.000000000000000
         5       272.801         732.491         0.000      0.000000000000000
         6       268.253         727.943         0.000      0.000000000000000
         7       254.604         714.294         0.000      0.000000000000000
         8       231.853         691.543         0.000      0.000000000000000
         9       200.000         659.690         0.000      0.000000000000000

TIME=2560.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
       NODE      TEMP - F         TEMP - R              Q-INPUT Q-NET
         1       200.000         659.690         0.000      0.000000000000000
         2       231.835         691.525         0.000     -0.000000000000000
         3       254.592         714.282         0.000      0.000000000000000
         4       268.247         727.937         0.000      0.000000000000000
         5       272.801         732.491         0.000      0.000000000000000
         6       268.253         727.943         0.000      0.000000000000000
         7       254.604         714.294         0.000      0.000000000000000
         8       231.853         691.543         0.000      0.000000000000000
         9       200.000         659.690         0.000      0.000000000000000
```

```
TIME=2600.0000    RCMIN=   2.91406    MIN NODE # 8    ITERATIONS= 0
        NODE    TEMP - F        TEMP - R        Q-INPUT Q-NET
         1      200.000        659.690        0.000     0.000000000000000
         2      231.835        691.525        0.000    -0.000000000000000
         3      254.592        714.282        0.000     0.000000000000000
         4      268.247        727.937        0.000     0.000000000000000
         5      272.801        732.491        0.000     0.000000000000000
         6      268.253        727.943        0.000     0.000000000000000
         7      254.604        714.294        0.000     0.000000000000000
         8      231.853        691.543        0.000     0.000000000000000
         9      200.000        659.690        0.000     0.000000000000000

TIME=2640.0000    RCMIN=   2.91406    MIN NODE # 8    ITERATIONS= 0
        NODE    TEMP - F        TEMP - R        Q-INPUT Q-NET
         1      200.000        659.690        0.000     0.000000000000000
         2      231.835        691.525        0.000    -0.000000000000000
         3      254.592        714.282        0.000     0.000000000000000
         4      268.247        727.937        0.000     0.000000000000000
         5      272.801        732.491        0.000     0.000000000000000
         6      268.253        727.943        0.000     0.000000000000000
         7      254.604        714.294        0.000     0.000000000000000
         8      231.853        691.543        0.000     0.000000000000000
         9      200.000        659.690        0.000     0.000000000000000

TIME=2680.0000    RCMIN=   2.91406    MIN NODE # 8    ITERATIONS= 0
        NODE    TEMP - F        TEMP - R        Q-INPUT Q-NET
         1      200.000        659.690        0.000     0.000000000000000
         2      231.835        691.525        0.000    -0.000000000000000
         3      254.592        714.282        0.000     0.000000000000000
         4      268.247        727.937        0.000     0.000000000000000
         5      272.801        732.491        0.000     0.000000000000000
         6      268.253        727.943        0.000     0.000000000000000
         7      254.604        714.294        0.000     0.000000000000000
         8      231.853        691.543        0.000     0.000000000000000
         9      200.000        659.690        0.000     0.000000000000000

TIME=2720.0000    RCMIN=   2.91406    MIN NODE # 8    ITERATIONS= 0
        NODE    TEMP - F        TEMP - R        Q-INPUT Q-NET
         1      200.000        659.690        0.000     0.000000000000000
         2      231.835        691.525        0.000    -0.000000000000000
         3      254.592        714.282        0.000     0.000000000000000
         4      268.247        727.937        0.000     0.000000000000000
         5      272.801        732.491        0.000     0.000000000000000
         6      268.253        727.943        0.000     0.000000000000000
         7      254.604        714.294        0.000     0.000000000000000
         8      231.853        691.543        0.000     0.000000000000000
         9      200.000        659.690        0.000     0.000000000000000

TIME=2760.0000    RCMIN=   2.91406    MIN NODE # 8    ITERATIONS= 0
        NODE    TEMP - F        TEMP - R        Q-INPUT Q-NET
         1      200.000        659.690        0.000     0.000000000000000
         2      231.835        691.525        0.000    -0.000000000000000
         3      254.592        714.282        0.000     0.000000000000000
         4      268.247        727.937        0.000     0.000000000000000
         5      272.801        732.491        0.000     0.000000000000000
         6      268.253        727.943        0.000     0.000000000000000
         7      254.604        714.294        0.000     0.000000000000000
         8      231.853        691.543        0.000     0.000000000000000
         9      200.000        659.690        0.000     0.000000000000000
```

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```
TIME=2800.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
       NODE    TEMP - F       TEMP - R        Q-INPUT Q-NET
        1      200.000        659.690      0.000    0.000000000000000
        2      231.835        691.525      0.000   -0.000000000000000
        3      254.592        714.282      0.000    0.000000000000000
        4      268.247        727.937      0.000    0.000000000000000
        5      272.801        732.491      0.000    0.000000000000000
        6      268.253        727.943      0.000    0.000000000000000
        7      254.604        714.294      0.000    0.000000000000000
        8      231.853        691.543      0.000    0.000000000000000
        9      200.000        659.690      0.000    0.000000000000000

TIME=2840.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
       NODE    TEMP - F       TEMP - R        Q-INPUT Q-NET
        1      200.000        659.690      0.000    0.000000000000000
        2      231.835        691.525      0.000   -0.000000000000000
        3      254.592        714.282      0.000    0.000000000000000
        4      268.247        727.937      0.000    0.000000000000000
        5      272.801        732.491      0.000    0.000000000000000
        6      268.253        727.943      0.000    0.000000000000000
        7      254.604        714.294      0.000    0.000000000000000
        8      231.853        691.543      0.000    0.000000000000000
        9      200.000        659.690      0.000    0.000000000000000

TIME=2880.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
       NODE    TEMP - F       TEMP - R        Q-INPUT Q-NET
        1      200.000        659.690      0.000    0.000000000000000
        2      231.835        691.525      0.000   -0.000000000000000
        3      254.592        714.282      0.000    0.000000000000000
        4      268.247        727.937      0.000    0.000000000000000
        5      272.801        732.491      0.000    0.000000000000000
        6      268.253        727.943      0.000    0.000000000000000
        7      254.604        714.294      0.000    0.000000000000000
        8      231.853        691.543      0.000    0.000000000000000
        9      200.000        659.690      0.000    0.000000000000000

TIME=2920.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
       NODE    TEMP - F       TEMP - R        Q-INPUT Q-NET
        1      200.000        659.690      0.000    0.000000000000000
        2      231.835        691.525      0.000   -0.000000000000000
        3      254.592        714.282      0.000    0.000000000000000
        4      268.247        727.937      0.000    0.000000000000000
        5      272.801        732.491      0.000    0.000000000000000
        6      268.253        727.943      0.000    0.000000000000000
        7      254.604        714.294      0.000    0.000000000000000
        8      231.853        691.543      0.000    0.000000000000000
        9      200.000        659.690      0.000    0.000000000000000

TIME=2960.0000    RCMIN=  2.91406    MIN NODE # 8    ITERATIONS= 0
       NODE    TEMP - F       TEMP - R        Q-INPUT Q-NET
        1      200.000        659.690      0.000    0.000000000000000
        2      231.835        691.525      0.000   -0.000000000000000
        3      254.592        714.282      0.000    0.000000000000000
        4      268.247        727.937      0.000    0.000000000000000
        5      272.801        732.491      0.000    0.000000000000000
        6      268.253        727.943      0.000    0.000000000000000
        7      254.604        714.294      0.000    0.000000000000000
        8      231.853        691.543      0.000    0.000000000000000
        9      200.000        659.690      0.000    0.000000000000000
```

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```
TIME=3000.0000    RCMIN=   2.91406    MIN NODE # 8    ITERATIONS= 0
        NODE      TEMP - F         TEMP - R         Q-INPUT Q-NET
         1       200.000          659.690          0.000      0.000000000000000
         2       231.835          691.525          0.000     -0.000000000000000
         3       254.592          714.282          0.000      0.000000000000000
         4       268.247          727.937          0.000      0.000000000000000
         5       272.801          732.491          0.000      0.000000000000000
         6       268.253          727.943          0.000      0.000000000000000
         7       254.604          714.294          0.000      0.000000000000000
         8       231.853          691.543          0.000      0.000000000000000
         9       200.000          659.690          0.000      0.000000000000000

Elapsed computer time with printing= 1.383333333333326 minutes
Date is 02-25-1993      Time is 09:46:24
752 DATA 2,7.46E-6,2,0
754 DATA 1.28E-6,1,1.28E-6,3
756 DATA 3,7.46E-6,2,0
758 DATA 1.28E-6,2,1.28E-6,4
760 DATA 4,7.46E-6,2,0
762 DATA 1.28E-6, 3, 1.28E-6, 5
764 DATA 5,7.46E-6,2,0
766 DATA 1.28E-6,4,1.28E-6,6
768 DATA 6,7.46E-6,2,0
770 DATA 1.28E-6,5,1.28E-6,7
772 DATA 7,7.46E-6,2,0
774 DATA 1.28E-6,6,1.28E-6,8
776 DATA 8,7.46E-6,2,0
778 DATA 1.28E-6,7,1.28E-6,9
780 Q(2) = 1.162E-05
    Q(3) = 1.165E-05
    Q(4) = 1.165E-05
786 Q(5) = 1.165E-05
```

Appendix C:

Core or Iron Loss Considerations:

Because this motor will be used in the servo application for TVC it will not in use experience much rotation and hence, in use, will not experience much core loss. However, during development, test and checkout it will be subjected to cyclic test, frequency response experiments and the like which will cause core loss.

This analysis was carried out as follows. It was assumed that the motor was rotating at 20,000 rpm and that this caused a sine wave of flux at a temporal frequency of 1333HZ. For the four pole motor, this should be a worst case by far. The separation of hysteresis and eddy current losses is difficult and not often attempted. Instead manufactures' data are used. These data are derived in turn from test. Data from reference fourteen was cross checked with other data in reference six. From these references it was estimated that the core loss of this material at 1330HZ would be 45.35 watts per pound of material. The final four pole configuration was then divided into 24 identical segments. Each segment consisted of one tooth and the adjoining back iron half way to each of the adjacent teeth. A planar analysis was performed under the assumption that all heat flow of consequence will be radial because of the deliberately high axial thermal resistance in the stator stack (put there also to inhibit eddy current losses, which vary approximately as the thickness of the lamination squared). The use of the one twenty fourth segment is justified on the basis of symmetry i.e. all the segments are heating evenly and hence all heat flow must be radial. The segment was divided into six pieces and a lumped thermal network constructed as shown below.

Lamination Core Los(

Geometric Model

2.272 2.615 2.97 4.444 4.18
x10^-6 x10^-6 x10^-6 x10^-6 x10^-6
Q(1) Q(2) Q(3) Q(5) Q(4)

3.865 3.153
x10^-6 4 x10^-6

1.46 1.67 1.65 1.17
x10^-6 x10^-6 x10^-6 x10^-5

1 2 3 5

3.36x10-6

6.341 7.81 8.31 1.236 7
x10^-6 x10^-6 x10^-6 x10^-6 200 F

.3.865x10-^6 6 3.153x10^-6

1.17 Q(6)
x10^-5 4.18
x10^-6
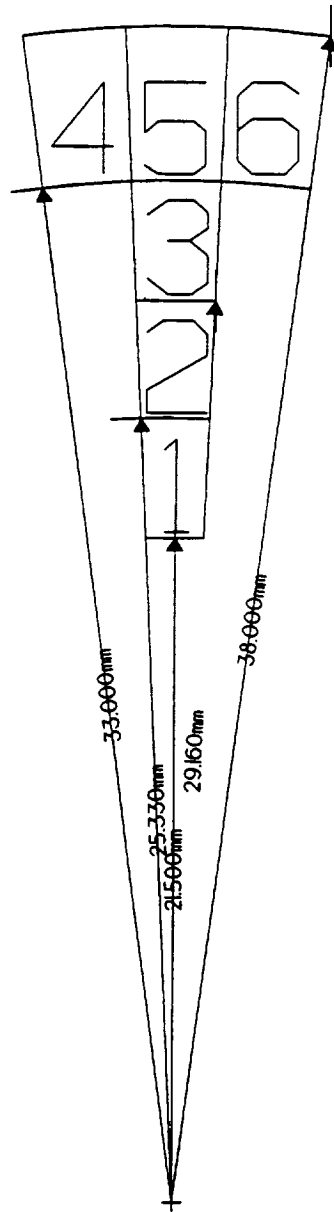
Core Loss Thermal Network
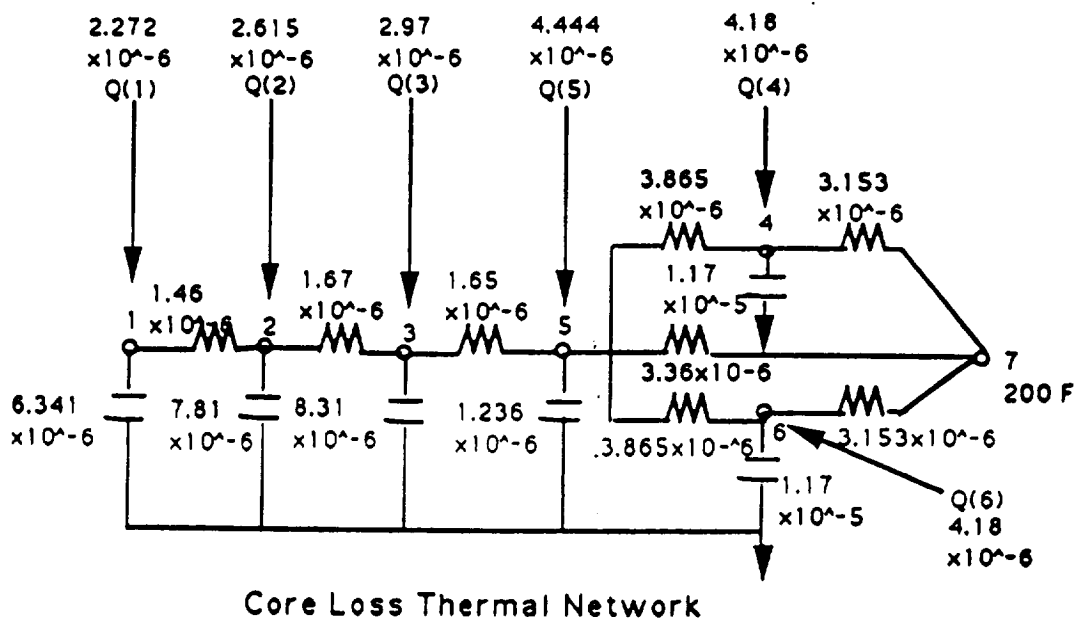
In the network above the initial dimensions are in millimeters but these were converted to feet in the calculations and the dimensions of the thermal conductance are

$$\frac{BTU}{sec\,°F}$$

the dimensions of the thermal capacity are

$$\frac{BTU}{°F}$$

and the entering power in

$$\frac{BTU}{sec}$$

All temperatures are Fahrenheit. From the diagrams it is seen that the outermost part of the stator was assumed to be at 200°F for the analysis. The rest of this appendix contains the network analyzer results and the input file used to characterize the network (see last sheet, lines 752 to 788). Both steady state and transient numerical analyses were performed.

```
STEADY STATE        SIGNIFICANT DIGITS= 4          RELAX ITER'NS= 12
        NODE      TEMP - F          TEMP - R          Q-INPUT Q-NET
          1        211.745          671.435        0.000     -0.000000030378878
          2        210.182          669.872        0.000     -0.000000033029913
          3        207.241          666.931        0.000     -0.000000038733759
          4        201.958          661.648        0.000      0.000000007822710
          5        202.473          662.163        0.000     -0.000000014680492
          6        201.958          661.648        0.000      0.000000007822710
          7        200.000          659.690        0.000      0.000000000000000
```

Elapsed computer time with printing= 3.333333333333144D-02 minutes
Date is 02-26-1993   Time is 03:58:50

```
TIME=    0.0000    RCMIN=   0.97017    MIN NODE # 5       ITERATIONS= 0
         NODE      TEMP - F         TEMP - R            Q-INPUT Q-NET
          1        100.000          559.690      0.000      0.000002272000074
          2        100.000          559.690      0.000      0.000002615000085
          3        100.000          559.690      0.000      0.000002969999969
          4        100.000          559.690      0.000      0.000319479993777
          5        100.000          559.690      0.000      0.000340439990396
          6        100.000          559.690      0.000      0.000319479993777
          7        200.000          659.690      0.000      0.000000000000000

TIME=   40.0000    RCMIN=   0.97017    MIN NODE # 5       ITERATIONS= 0
         NODE      TEMP - F         TEMP - R            Q-INPUT Q-NET
          1        181.143          640.833      0.000      0.000007742999514
          2        184.844          644.534      0.000      0.000007898842341
          3        191.201          650.891      0.000      0.000005324476206
          4        199.929          659.619      0.000      0.000000949694368
          5        199.034          658.724      0.000      0.000001700159146
          6        199.929          659.619      0.000      0.000000949694368
          7        200.000          659.690      0.000      0.000000000000000

TIME=   80.0000    RCMIN=   0.97017    MIN NODE # 5       ITERATIONS= 0
         NODE      TEMP - F         TEMP - R            Q-INPUT Q-NET
          1        205.635          665.325      0.000      0.000001540642529
          2        205.125          664.815      0.000      0.000001571254188
          3        204.046          663.736      0.000      0.000001058745056
          4        201.554          661.244      0.000      0.000000188528631
          5        201.789          661.479      0.000      0.000000337766863
          6        201.554          661.244      0.000      0.000000188528631
          7        200.000          659.690      0.000      0.000000000000000
```

```
TIME= 120.0000    RCMIN=  0.97017    MIN NODE # 5    ITERATIONS= 0
        NODE    TEMP - F        TEMP - R            Q-INPUT Q-NET
          1       210.508         670.198      0.000      0.000000306474334
          2       209.160         668.850      0.000      0.000000312563827
          3       206.601         666.291      0.000      0.000000210612242
          4       201.878         661.568      0.000      0.000000037503302
          5       202.337         662.027      0.000      0.000000067190712
          6       201.878         661.568      0.000      0.000000037503302
          7       200.000         659.690      0.000      0.000000000000000

TIME= 160.0000    RCMIN=  0.97017    MIN NODE # 5    ITERATIONS= 0
        NODE    TEMP - F        TEMP - R            Q-INPUT Q-NET
          1       211.477         671.167      0.000      0.000000060965810
          2       209.962         669.652      0.000      0.000000062177165
          3       207.109         666.799      0.000      0.000000041896318
          4       201.942         661.632      0.000      0.000000007460393
          5       202.446         662.136      0.000      0.000000013366001
          6       201.942         661.632      0.000      0.000000007460393
          7       200.000         659.690      0.000      0.000000000000000

TIME= 200.0000    RCMIN=  0.97017    MIN NODE # 5    ITERATIONS= 0
        NODE    TEMP - F        TEMP - R            Q-INPUT Q-NET
          1       211.670         671.360      0.000      0.000000012127704
          2       210.122         669.812      0.000      0.000000012368675
          3       207.210         666.900      0.000      0.000000008334280
          4       201.955         661.645      0.000      0.000000001484069
          5       202.468         662.158      0.000      0.000000002658849
          6       201.955         661.645      0.000      0.000000001484069
          7       200.000         659.690      0.000      0.000000000000000

TIME= 240.0000    RCMIN=  0.97017    MIN NODE # 5    ITERATIONS= 0
        NODE    TEMP - F        TEMP - R            Q-INPUT Q-NET
          1       211.708         671.398      0.000      0.000000002412520
          2       210.154         669.844      0.000      0.000000002460455
          3       207.230         666.920      0.000      0.000000001657908
          4       201.957         661.647      0.000      0.000000000295220
          5       202.472         662.162      0.000      0.000000000528915
          6       201.957         661.647      0.000      0.000000000295220
          7       200.000         659.690      0.000      0.000000000000000
```

```
TIME= 280.0000    RCMIN=   0.97017     MIN NODE # 5      ITERATIONS= 0
         NODE      TEMP - F        TEMP - R              Q-INPUT Q-NET
          1        211.716        671.406        0.000     0.000000000479914
          2        210.160        669.850        0.000     0.000000000489449
          3        207.234        666.924        0.000     0.000000000329801
          4        201.958        661.648        0.000     0.000000000058727
          5        202.473        662.163        0.000     0.000000000105215
          6        201.958        661.648        0.000     0.000000000058727
          7        200.000        659.690        0.000     0.000000000000000

TIME= 320.0000    RCMIN=   0.97017     MIN NODE # 5      ITERATIONS= 0
         NODE      TEMP - F        TEMP - R              Q-INPUT Q-NET
          1        211.717        671.407        0.000     0.000000000095467
          2        210.161        669.851        0.000     0.000000000097364
          3        207.235        666.925        0.000     0.000000000065606
          4        201.958        661.648        0.000     0.000000000011682
          5        202.473        662.163        0.000     0.000000000020930
          6        201.958        661.648        0.000     0.000000000011682
          7        200.000        659.690        0.000     0.000000000000000

TIME= 360.0000    RCMIN=   0.97017     MIN NODE # 5      ITERATIONS= 0
         NODE      TEMP - F        TEMP - R              Q-INPUT Q-NET
          1        211.718        671.408        0.000     0.000000000018991
          2        210.162        669.852        0.000     0.000000000019368
          3        207.235        666.925        0.000     0.000000000013051
          4        201.958        661.648        0.000     0.000000000002324
          5        202.473        662.163        0.000     0.000000000004164
          6        201.958        661.648        0.000     0.000000000002324
          7        200.000        659.690        0.000     0.000000000000000

TIME= 400.0000    RCMIN=   0.97017     MIN NODE # 5      ITERATIONS= 0
         NODE      TEMP - F        TEMP - R              Q-INPUT Q-NET
          1        211.718        671.408        0.000     0.000000000003778
          2        210.162        669.852        0.000     0.000000000003853
          3        207.235        666.925        0.000     0.000000000002596
          4        201.958        661.648        0.000     0.000000000000462
          5        202.473        662.163        0.000     0.000000000000828
          6        201.958        661.648        0.000     0.000000000000462
          7        200.000        659.690        0.000     0.000000000000000
```

Elapsed computer time with printing= .8833333333333258 minutes
Date is 02-26-1993   Time is 04:03:12

```
752    DATA 1,6.341E-6,1,0
754    DATA 1.46E-6,2
756    DATA 2,7.81E-6,2,0
758    DATA 1.46E-6,1,1.67E-6,3
760    DATA 3, 8.31E-6,2,0
762    DATA 1.67E-6,2,1.65E-6,5
764    DATA 5,1.236E-5,4,0
766    DATA 1.65E-6,3,3.865E-6,4,3.36E-6,7,3.865E-6,6
768    DATA 4,1.17E-5,2,0
770    DATA 3.865E-6, 5,3.153E-6,7
772    DATA 6, 1.17E-5,2,0
774    DATA 3.865E-6,5,3.153E-6,7
776    T(7) = 200
778    Q(1) = 2.272E-06
780    Q(2) = 2.615E-06
782    Q(3) = 2.97E-06
784    Q(5) = 4.44E-06
786    Q(4) = 4.18E-06
788    Q(6) = 4.18E-06
```

Appendix D:

Winding Considerations

There are a number of ways to depict winding information. The one preferred by this author is used below. It is assumed that a double layer i.e. two coils per slot winding is used. Because the lap and wave windings are electrically identical the choice between them is best left to the particular winding shop.

First lay out a series of slots according to the number decided upon. In the bottom of the slot diagram fill the slots according to the slot star with the rotation CCW or in the positive angle direction.

SLOT STAR
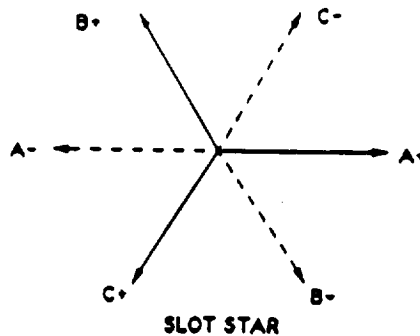
If a full pitch winding were being used both the top and the bottom of the slot would be carrying the same phase current. If as is the case shown here on the next page the coils are to be short pitched by one slot they will span 5 slots rather than the 6 slots required for the full pitch case. This may easily be depicted by sliding the top row of conductors one slot to the left from its position in the full pitch case. The resulting diagram is shown on the next page.

					Pole 1						Pole 2						Pole 3						Pole 4 →	
Upper	B-	B-	A+	A+	C-	C-	B+	B+	A-	A-	C+	C+	B-	B-	A+	A+	C-	C-	B+	B+	A-	A-	C+	C+
Lower	C+	B-	B-	A+	A+	C-	C-	B+	B+	A-	A-	C+	C+	B-	B-	A+	A+	C-	C-	B+	B+	A-	A-	C+
Slot No.	22	23	24	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21

Winding Diagram of 3 Phase

Four Pole Short Pitched Motor

Stator Winding

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The mmf resulting from such a winding may be depicted by assigning current magnitudes to the various phases (these magnitudes correspond to balanced 3 phase values e.g. A+=1, B+=-1/2, C+=-1/2, A-=-1, B-=1/2, C-=1/2). Then treat each slot as if the total current in that slot is the weight of an impulse and plot these impulses in the same position as each slot. Next integrate spatially all the impulses and plot the results after having made the average of the mmf zero. A computer program was written to do this. It is written in C and produces Mathcad plot files. Thus a C compiler and Mathcad are needed to run it. A listing is included below and a sample output is included.

```c
/*          This program calculates the MMF for an integer motor winding
            and creates files for the Mathcad program wind.mcd.

            Variable Definition:

                    idisp = displacement of upper windings from lower
                            winding.  idisp = 0 implies a full pitch
                            winding.  idisp = 1 implies a winding short
                            pitched by one slot.
                    mmf = the magnetomotive force.
                    iap = current in the the A+ phase
                    icm = current in the C- phase
                    ibp = current in the B+ phase
                    iam = current in the A- phase
                    icp = current in the C+ phase
                    ibm = current in the B- phase
                    phi = the phase angle of the A+ phase in degrees
                    ampl = the amplitude of the currents
                    current[i] = the magnitude of the ith current
                    nslots = number of slots
                    nspp = number of slots per pole
                    nspppp = number of slots per pole per phase
                    npoles = number of poles
                    deg = conversion from degrees to radians
                    ncases = number of cases; program allows calculation of
                            up to 5 mmf's.
                    icase = case counter
                                                                            */
#include <stdio.h>
#  :lude <math.h>
#....clude <conio.h>

#define        PI 3.14159265
#define        deg PI/180.
void    main(void)
{
        int     nslots, nspp, nspppp, islot, ib, it, ipole, iphase;
        int     npoles, i, icase, ncases, idisp, ip;
        float   current[7], phi, ampl, mmf[201], iap, icm, ibp;
        float   iam, icp, ibm, ibot[201], itop[201];
        FILE    *inp, *out1, *out2, *out3, *out4, *out5;

        inp = fopen("c:\\fort\\winding.in","r");
        out1 = fopen("c:\\fort\\mmf1.out","w");
        out2 = fopen("c:\\fort\\mmf2.out","w");
        out3 = fopen("c:\\fort\\mmf3.out","w");
        out4 = fopen("c:\\fort\\mmf4.out","w");
        out5 = fopen("c:\\fort\\mmf5.out","w");


        fscanf(inp," %d %d %d\n",&ncases, &nslots, &npoles);

        for(icase = 1; icase <= ncases; icase++)
        {
            fscanf(inp,"%f   %f   %d\n",
                        &phi, &ampl, &idisp);
            nspp = nslots/npoles;     /* # of slots per pole  */
            nspppp = nspp/3;          /* # of slots per pole per phase */

            iap = ampl*cos(phi*deg);
```
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```
icm = ampl*cos((phi + 60.)*deg);
ibp = ampl*cos((phi + 120.)*deg);
iam = -iap;
icp = -icm;
ibm = -ibp;

current[1] = iap;
current[2] = icm;
current[3] = ibp;
current[4] = iam;
current[5] = icp;
current[6] = ibm;

for (ipole = 1; ipole <= npoles; ipole += 2)
{
    for(iphase = 1; iphase <= 3; iphase++)
    {
        for(islot = 1; islot <= nspppp; islot++)
        {
          • ib = (ipole - 1)*nspppp*3 + (iphase - 1)*nspppp + islot;
            ibot[ib] = current[iphase];
        }
    }
}

for (ipole = 2; ipole <= npoles; ipole +=2)
{
    for(iphase = 4; iphase <= 6; iphase++)
    {
        for(islot = 1; islot <= nspppp; islot++)
        {
          ib = (ipole - 1)*nspppp*3 + (iphase - 4)*nspppp + islot;
            ibot[ib] = current[iphase];
        }
    }
}

for (ipole = 1; ipole <= npoles; ipole +=2)
{
    for(iphase = 4; iphase <= 6; iphase++)
    {
        for(islot = 1; islot <= nspppp; islot++)
        {
            ib = (ipole - 1)*nspppp*3 + (iphase - 4)*nspppp + islot;
            ib = ib + nspp - idisp;
            if (ib > nslots)
                ib = ib - nslots;
            itop[ib] = current[iphase];
        }
    }
}

for (ipole = 2; ipole <= npoles; ipole += 2)
{
    for (iphase = 1; iphase <= 3; iphase++)
    {
        for (islot = 1; islot <= nspppp; islot++)
        {
            ib = (ipole - 1)*nspppp*3 + (iphase - 1)*nspppp + islot;
            ib = ib + nspp - idisp;
```

```
                    if (ib > nslots)
                        ib = ib - nslots;
                    itop[ib] = current[iphase];
                }
            }
        }

        mmf[0] = 0.;
        for (islot = 1; islot <= nslots; islot++)
        {
            mmf[islot] = mmf[islot - 1] + ibot[islot] + itop[islot];
        }

        switch (icase)
        {
            case 1:
                for(i = 0; i <= nslots; i++)
                    fprintf(out1," %f\n", mmf[i]);
                break;
            case 2:
                for(i = 0; i <= nslots; i++)
                    fprintf(out2," %f\n", mmf[i]);
                break;
            case 3:
                for(i = 0; i <= nslots; i++)
                    fprintf(out3," %f\n", mmf[i]);
                break;
            case 4:
                for(i = 0; i <= nslots; i++)
                    fprintf(out4," %f\n", mmf[i]);
                break;
            case 5:
                for(i = 0; i <= nslots; i++)
                    fprintf(out5," %f\n", mmf[i]);
                break;
        }
    }
    fcloseall();
}
```

```
 5   24   4
        0.  1.  0
        30.  1.  0
        60.  1.  0
        90.  1.  0
        120.  1.  0 0.000000
2.000000
4.000000
5.000000
6.000000
5 000000
  )00000
2.000000
0.000000
-1.000000
-2.000000
```

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```
-1.000000
0.000000
2.000000
4.000000
      )00000
6.000000
5.000000
4.000000
2.000000
0.000000
-1.000000
-2.000000
-1.000000
0.000000
```

MMF := READPRN(MMF1 OUT)   N_Slots := length(MMF) − 1

i := 0 .. N_Slots
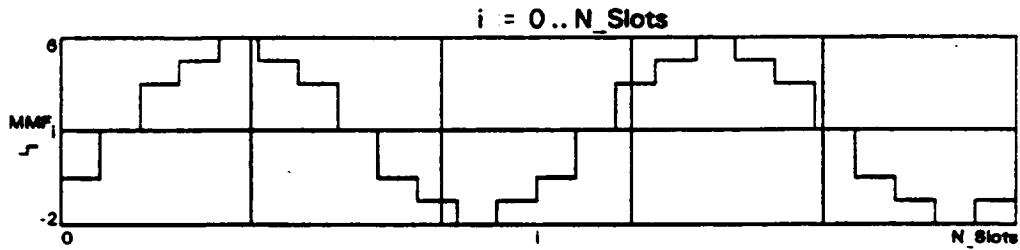
MMF := READPRN(MMF2 OUT)
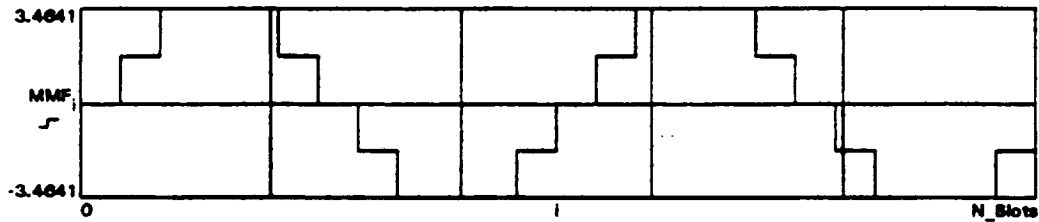
MMF := READPRN(MMF3 OUT)
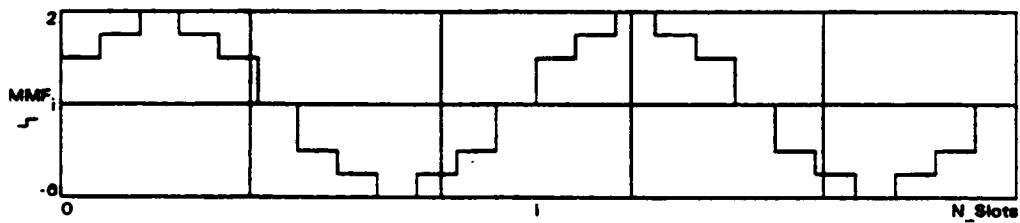
MMF := READPRN(MMF4 OUT)
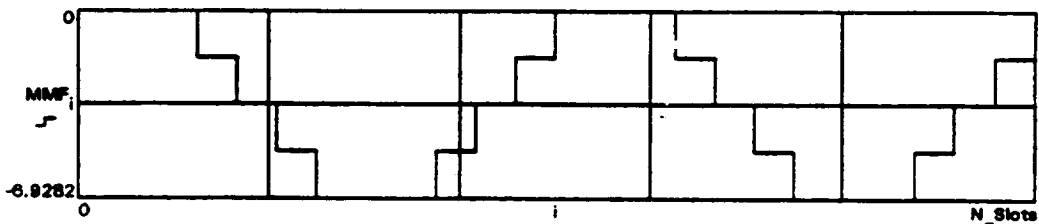
MMF := READPRN(MMF5 OUT)
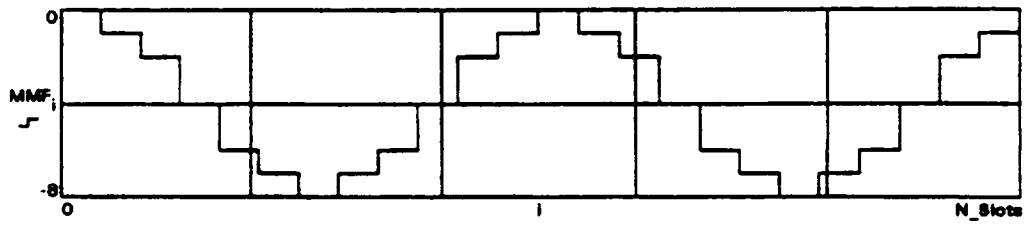
APPENDIX E

Magnetic Potential Calculations

This appendix contains the spread sheet which takes the averaged data from each side of the slots and for a 7 inch long rotor turning at 10,000 rpm produces the voltage that would be induced in a one turn full pitch coil of the 4 pole configuration. The maximum value of this voltage is used to determine the number of turns in the windings as explained in the main body of the text.

A average (We/m Degree)	Delta A (We/m Degree)	Electric Force (We/m s)	Back EMF (Volts)
7.56E-03	-1.50E-05	-0.90423486	-0.321545916
3.49E-03	-5.05E-05	-3.0383145	-1.080424636
-1.34E-03	4.05E-08	0.00243486	0.000865836
-5.82E-03	-7.85E-06	-0.47176164	-0.167758439
-1.02E-02	-2.11E-04	-12.68213364	-4.509766722
-8.68E-03	-5.29E-04	-31.79548404	-11.30647412
7.57E-03	2.61E-06	0.15673284	0.055734198
3.54E-03	4.96E-05	2.9808999	1.060008004
-1.34E-03	1.17E-07	0.0070641	0.002511994
-5.82E-03	-8.03E-06	-0.48300408	-0.171756251
-1.00E-02	-2.37E-04	-14.24657628	-5.066082525
-8.15E-03	-5.36E-04	-32.21596332	-11.45599656
7.57E-03	3.95E-06	0.23759424	0.084488512
3.49E-03	-1.81E-07	-0.01088172	-0.00386954
-1.34E-03	2.27E-07	0.01361718	0.004842269
-5.81E-03	-8.00E-06	-0.4808097	-0.170975929
-9.76E-03	-2.62E-04	-15.75477666	-5.602398858
-7.61E-03	-5.41E-04	-32.55281568	-11.57578126
7.56E-03	6.05E-06	0.36384624	0.129383723
3.49E-03	2.12E-07	0.01274544	0.004532278
-1.34E-03	3.65E-07	0.02191374	0.007792526
-5.80E-03	-7.93E-06	-0.47672154	-0.16952218
-9.50E-03	-2.87E-04	-17.28317736	-6.145897869
-7.07E-03	-5.46E-04	-32.81067036	-11.66747438
7.56E-03	9.09E-06	0.54643068	0.19431075
3.49E-03	7.62E-07	0.04581144	0.016290548
-1.34E-03	4.78E-07	0.02873736	0.010219005
-5.79E-03	-8.65E-06	-0.519878682	-0.184868859
-9.21E-03	-3.14E-04	-18.88140744	-6.714228486
-6.53E-03	-5.49E-04	-33.00630084	-11.73704058

7.55E-03	1.31E-04	7.852086828	2.792202076
3.49E-03	1.38E-04	8.31829338	2.957985126
-1.34E-03	1.38E-04	8.27197092	2.941512859
-5.78E-03	1.17E-04	7.018429842	2.495753652
-8.90E-03	-2.12E-04	-12.7224441	-4.524101122
-5.98E-03	-4.09E-04	-24.5597715	-8.733454745
7.42E-03	1.33E-04	7.974803772	2.835840221
3.35E-03	1.38E-04	8.29147986	2.948450238
-1.48E-03	1.37E-04	8.214452626	2.921085538
-5.90E-03	1.07E-04	6.421399164	2.283449543
-8.69E-03	-2.39E-04	-14.35948164	-5.106231671
-5.57E-03	-4.08E-04	-24.51519252	-8.71760246
7.29E-03	1.34E-04	8.04655098	2.861353528
3.21E-03	1.37E-04	8.26175052	2.937878485
-1.62E-03	1.36E-04	8.14764276	2.897301765
-6.01E-03	1.06E-04	6.354521676	2.259667908
-8.45E-03	-2.67E-04	-16.027796194	-5.699543266
-5.16E-03	-4.08E-04	-24.5028078	-8.713198454
7.15E-03	1.35E-04	8.090022816	2.876885134
3.08E-03	1.37E-04	8.2200573	2.923052376
-1.75E-03	1.34E-04	8.05875534	2.865693399
-6.11E-03	8.83E-05	5.30925732	1.887971903
-8.18E-03	-2.94E-04	-17.67380706	-6.284805791
-4.75E-03	-4.08E-04	-24.54374952	-8.727757329
7.02E-03	1.35E-04	8.108685	2.883448386
2.94E-03	1.36E-04	8.16781302	2.90447431
-1.89E-03	1.32E-04	7.94924676	2.826752148
-6.20E-03	7.02E-05	4.221927	1.501317241
-7.89E-03	-3.20E-04	-19.256796672	-6.847716914
-4.34E-03	-4.10E-04	-24.63353874	-8.759686376
6.88E-03	1.35E-04	8.12134026	2.887948596

2.80E-03	1.35E-04	8.114697	2.885586253
-2.02E-03	1.30E-04	7.83330534	2.785523379
-6.27E-03	4.81E-05	2.89035918	1.027811724
-7.57E-03	-3.44E-04	-20.69423586	-7.358870272
-3.93E-03	-4.12E-04	-24.76159434	-8.805222947
6.75E-03	1.12E-04	6.70734792	2.38513292
2.67E-03	1.34E-04	8.07375528	2.871027378
-2.15E-03	1.29E-04	7.74970848	2.755796335
-6.32E-03	2.30E-05	1.38507462	0.492532535
-7.22E-03	-3.64E-04	-21.90090438	-7.787961598
-3.52E-03	-4.14E-04	-24.89923908	-8.854169417
6.64E-03	1.61E-04	9.67715568	3.44119656
2.53E-03	1.34E-04	8.05514814	2.864410679
-2.28E-03	1.27E-04	7.63902756	2.7164382
-6.34E-03	-3.74E-06	-0.22460832	-0.079870719
-6.86E-03	-3.80E-04	-22.8221532	-8.115557678
-3.11E-03	-4.16E-04	-25.02834678	-8.900080115
6.48E-03	1.39E-04	8.36497656	2.974585665
2.40E-03	1.34E-04	8.06440662	2.867702994
-2.41E-03	1.27E-04	7.62826608	2.712611418
-6.34E-03	-3.15E-05	-1.892934832	-0.673128867
-6.48E-03	-3.91E-04	-23.50740096	-8.359231781
-2.69E-03	-4.18E-04	-25.1501499	-8.943393304
6.34E-03	1.42E-04	8.54061714	3.037043455
2.27E-03	1.35E-04	8.09446662	2.87839233
-2.53E-03	1.27E-04	7.632624478	2.714161372
-6.31E-03	-5.91E-05	-3.55528638	-1.264259837
-6.09E-03	-3.99E-04	-23.95785006	-8.519411481
-2.27E-03	-4.20E-04	-25.25725368	-8.981479409
0.006193924	0.000270539	16.26480468	5.783764544
0.002130953	0.000279142	16.78198698	5.96767457

-0.002660178	0.000271864	16.34446368	5.812091285
-0.00624756	4.8416E-05	2.91076992	1.035069784
-0.005690403	-0.000271289	-16.30989468	-5.799798548
-0.001853978	-0.000279929	-16.82933148	-5.984510274
0.005923385	0.000549735	33.0500682	11.75260425
0.001851811	0.000560453	33.69443436	11.98174086
-0.002932042	0.000544818	32.75442281	11.64747463
-0.006295976	1.97739E-05	1.18670868	0.421993607
-0.005419114	-0.00055018	-33.07685166	-11.76212845
-0.001574049	-0.000561526	-33.75891306	-12.00466948
0.00537365	0.000553562	33.28014744	11.83442043
0.001291358	0.000559357	33.62853983	11.95830876
-0.003476859	0.000535774	32.21073288	11.45413661
-0.006315715	-7.96955E-05	-4.79129346	-1.703783954
-0.004868933	-0.000553492	-33.27593904	-11.83292392
-0.001012523	-0.000560805	-33.71560562	-11.98926936
0.004820088	0.000552277	33.20289324	11.80694884
0.000732001	0.000554953	33.36378939	11.86416351
-0.004012633	0.000513318	30.8606481	10.97404646
-0.00623602	-0.000189054	-11.36592648	-4.041723456
-0.004315441	-0.000552176	-33.19682112	-11.80478959
-0.000451718	-0.000557933	-33.54291392	-11.92786019
0.004267811	0.000551228	33.13982736	11.78452261
0.000177048	0.000549825	33.05546698	11.75452406
-0.004525951	0.000471742	28.36112904	10.08521749
-0.006046966	-0.000301038	-18.0983745	-6.435781972
-0.003763265	-0.000551296	-33.14391552	-11.78597636
0.000106215	-0.000555889	-33.42004067	-11.88416646
0.003716583	0.000275756	16.57845072	5.895297076
-0.000372777	0.000272913	16.40751453	5.834512167
-0.004997693	0.000211009	12.68583102	4.511081511

-0.0057745928	-0.0000189408	-11.38720896	-4.049291506
-0.003211969	-0.0000275923	-16.5884607	-5.898856625
0.000662104	-0.0000277691	-16.69478593	-5.936665875
0.003440827			
-0.00064569			
-0.005208701			
-0.00555652			
-0.002936047			
0.000939795			

APPENDIX F

Explanation of ANSYS44A Code for File MTRM15A (Six Pole Motor)

The following program listing represents one sixth of the motor that was designed. This is a valid representation not only because the motor is symmetrical, but also because the analysis at all times spans one full pole. The electromagnetic flux that follows the air gap path between the stator and the magnet produces a torque, which effectively can be calculated by performing a line integral over that path. By definition, magnetic flux follows a closed path, so on either side of the motor, the magnetic flux should be equal and of opposite sign, therefore negating any contributions of flux on the sides of a pole to torque. The torque then, that a motor experiences may be calculated by summing up the line integral over a path in the air gap for a single pole to get a torque per pole value, and for a total torque value, multiplying the unit torque by the number of poles.

ANSYS44A was instrumental in the simulation of this motor because of its ability to handle the nonlinear material properties inherent in magnetic materials. The code breaks up the design in several phases. The first of these phases is to define the material types by assigning numbers to materials and properties to the material numbers to be used in the analysis. Material one is defined to be air, and material two is the rotor iron (Carpenter HI-MU 49). When considering the rotor iron and also the magnets (materials 3 and 4, which represent magnetization outward and inward respectively, MAGNEQUENCH MQ3-30H), the nonlinear properties of the materials must be included. This is accomplished by providing a BH curve for ANSYS44A to use, for each material posessing magnetic properties. In addition to these properties, for the magnets coercivity must be entered. For all of the material whether linear or nonlinear, the density of each material must be entered. A different material number was assigned to each phase of the windings: A+ A-, B+ B-, and C+ C-.

The next phase in this model was to create the nodes for the motor (see accompanying figure). This is accomplished by setting nodal limits. The radii from the center of the shaft to a material or shape change determine the limits. R0 is the radius of the rotor shaft. R1 is the radius to the bottom of the magnets. R2 is the radius to the bottom of the air gap. R3 is the radius to the bottom of the shoes. R4 is the radius to the top of the shoes. R5 is the radius to the top of the slots. Finally, R6 is the radius to the outer motor. Nodes between the radii limits are generated from R0 to R1, R1 to R2, etc., such that there are a total of 31 nodes from R0 to R6. It is important to have several elements in the air gap in the radial direction so that torque can be calculated accurately. For this model, five nodes in the air gap providing 4 elements was deemed sufficient.

Once the basic node pattern has been established along the radial direction, this pattern is copied along the theta direction for 60 degrees. Sixty degrees is calculated by dividing the number of elements per magnet, plus the air gap elements between magnets by the number of poles. The width of each element is one degree and the motor spans 360 degrees. Therefore, because this is a six pole motor simulation, 60 degrees is the sector of the motor over which the calculation is being done. The number of teeth per sector is found by dividing the number of elements per sector by the number of degrees per tooth (60/15), four slots per sector. The element type used for this model is the quadrilateral. Selecting a material number, for example, material two, is necessary to put the proper materials in their respective places, otherwise the default material number is one, which is air. Elements are formed by joining four nodes in this order:
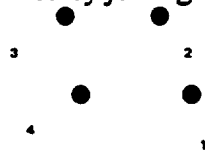
This pattern is repeated along the radial node path from element 1,2,33,32,1 to element 30,31,62,61,30, by the command egen. Next, this swath of elements is copied along the theta direction for 60 degrees to generate all of the elements for the simulation. All

elements were generated initially as rotor iron simply because the majority of the motor is composed of HI-MU 49. The other parts of the motor such as: magnets, shoes, slots, and air gaps are formed by literally punching out a section of the HI-MU 49 and replacing it with those materials over the range of elements for which they span.

The elements for the air gap were modified next by selecting the material number one, the nodal path that bounds the air gap in both the r and theta direction, and finally selecting all the elements within those bounds and modifying them to be composed of air. This procedure is also repeated for the magnets, shoes, and slots. The materials were assigned colors, to see if each material was in its correct place.

For a finite element program solving the magnetostatic equations, the natural boundary condition (BC) is the zero Neumann boundary condition. This means that if a BC is not specified, the one applied is the zero normal derivative of the magnetic vector potential. This boundary condition is clearly not desired at the outer edge of the back iron because it implies that the flux is perpendicular to the outer edge of the stator. The appropriate BC is to fix the magnetic vector potential. Usually, the potential is set to zero.

The appropriate BC at the inner shaft is not so easy to understand, but the condition that is commonly used is also the zero vector potential. Actually, the solution is not sensitive to the inner BC.

The final phase was the actual analysis of the model. ANSYS44A uses the Maxwell Stress Tensor to determine the maximum torque in these electromagnetic models. The result of which shows that the maximum torque occurs in the air gap when the flux is at a maximum and is directed at 45 degrees. ANSYS44A calculates and stores the magnetic flux by first having been given a convergence criterion and a maximum number of load steps in which to reach this criterion by means of iteration. Once the iteration at which the solution converges has been isolated, that load step is written as the final load step and is saved to FILE12 for further analysis in the ANSYS44A post

processor (POST1). Once the solution is completed in the post processor, it can be used to calculate the torque by performing a line integral between the magnetic flux and the length vector over a specified nodal path in the air gap.

These operations, once the initial model has been created can either be run interactively or in batch mode. In the interactive mode, a single simulation, it takes anywhere from 25 to 45 minutes. This is understandable because the magnetic flux must be evaluated at every node, and there are 1891 nodes and 1800 elements. In the batch mode, all of the steps are preprogrammed and all that is necessary to analyze the model is to submit the batch job. The IBM 3084 system takes about the same amount of time to run the batch job as the interactive, however, the batch job does not require constant human monitoring. Another advantage to the batch mode is that as many as four jobs at a time can be submitted. This is important because to show a fully developed torque curve, the model must be simulated at a range of rotor angles. Usually this requires at least 25 angular displacements.

```
/CORE,5800000
/COM,ANSYS REVISION 4.4A  UP419  97   13.9922  11/14/1991
1.    /TITLE, EMA MOTOR ANALYSIS
2.    /PREP7
3.    KAN,-1
4.    KAY, 9, 1
5.    ET,1,13,,,,1
6.    KNL,1
7.    NLSIZE,300
8.    /COM,
9.    /COM, MATERIAL 1 IS AIR
10.   /COM,
11.   NL,1,57,1
12.   /COM,
13.   /COM, MATERIAL 2 IS THE ROTOR IRON - CARPENTER HI-MU 49
14.   /COM,
15.   NLTAB,2,5
16.   MP,DENS,2,8249
17.   NLX,,1,10.,15.,20.,25.,30.,35.
18.   NLX,,,40,45,50,55,60,65
19.   NLX,,,70,75,80,85,90,95
20.   NLX,,,100,795.8
21.   NLY,,,,947,1.052,1.083,1.102,1.117,1.130
22.   NLY,,,,1.140,1.147,1.155,1.164,1.172,1.181
23.   NLY,,,,1.189,1.195,1.201,1.206,1.212,1.218
24.   NLY,,,,1.222,1.5
25.   /SHOW,4208
26.   /COM,
27.   /COM, DEFINE MAGNET CURVE AS MATERIALS 3 & 4
28.   /COM, MAGNETIZATION OUTWARD FOR 3, INWARD FOR 4
29.   /COM, MATERIAL - MAGNEQUENCH  MQ3-F 30H
30.   /COM,
31.   CSYS,1
32.   NLTAB,3,5
33.   MP,DENS,3,7550
34.   NLX,,1,31800,827600
35.   NLY,,1,,06,1.13
36.   HC = -827600
37.   NL,3,109,HC
38.   NL,3,163,0
39.   NLTAB,4,5
40.   MP,DENS,4,7550
41.   NLX,,1,31800,827600
42.   NLY,,1,,0.06,1.13
43.   HC = 827600
44.   NL,4,109,HC
45.   NL,4,163,0.
46.   /COM,
47.   /COM, MATERIALS 5 THROUGH 10 ARE A+, A-, B+, B-,
48.   /COM, C+, AND C- SOURCES RESPECTIVELY
49.   /COM,
50.   NL ,5,55,1
51.   NL ,6,55,1
52.   NL ,7,55,1
53.   NL ,8,55,1
54.   NL ,9,55,1
55.   NL ,10,55,1
56.   /COM,
57.   /COM, THET = THETA ORIENTATION OF ROTORS MEASURED TO LEADING
58.   /COM,      EDGE OF OUTWARDLY MAGNETIZED MAGNET
59.   /COM, NTEE = NUMBER OF TEETH
60.   /COM, NMAG = NUMBER OF MAGNETS
61.   /COM, NTHE = NUMBER OF ELEMENTS IN THE THETA DIRECTION
62.   /COM,
63.   /COM, R0 = RADIUS IN METERS FROM CENTER TO OUTSIDE OF THE SHAFT
64.   /COM, R1 = RADIUS TO BASE OF MAGNET
65.   /COM, R2 = RADIUS TO THE TOP OF THE MAGNET
66.   /COM, R3 = RADIUS TO TOOTH SHOE AT AIR GAP
```

```
67.   /COM, R4 = RADIUS TO END OF TOOTH AT THE SHOE
68.   /COM, R5 = RADIUS TO BACK IRON
69.   /COM, R6 = OUTER RADIUS OF THE MOTOR
70.   /COM,
71.   THET = -15.
72.   NTEE = 36
73.   NMAG = 6
74.   NTHE = 360
75.   R0 = 0.005
76.   R1 = 0.01118
77.   R2 = 0.02118
78.   R3 = 0.02218
79.   R4 = 0.02252
80.   R5 = 0.03429
81.   R6 = 0.03810
82.   NR01 = 5
83.   NR12 = 9
84.   NR23 = 5
85.   NR34 = 2
86.   NR45 = 5
87.   NR56 = 4
88.   NTR1 = (NR01 + 1)
89.   NTR2 = NTR1 + NR12
90.   NTR3 = NTR2 + NR23
91.   NTR4 = NTR3 + NR34
92.   NTR5 = NTR4 + NR45
93.   NTR6 = NTR5 + NR56
94.   THMG = 50
95.   /COM,
96.   /COM, THMA = NUMBER OF ELEMENTS PER MAGNET + AIR GAP BETWEEN
97.   /COM, NTPC = NUMBER OF TEETH PER SECTOR OVER WHICH THE CALCULATION
98.   /COM,      IS DONE
99.   /COM,
100.  THMA = NTHE/NMAG
101.  THPT = NTHE/NTEE
102.  NTPS = THMA/THPT
103.  N,1,R0
104.  N,NTR1,R1
105.  FILL,1,NTR1
106.  N,NTR2,R2
107.  FILL,NTR1,NTR2
108.  N,NTR3,R3
109.  FILL,NTR2,NTR3
110.  N,NTR4,R4
111.  FILL,NTR3,NTR4
112.  N,NTR5,R5
113.  FILL,NTR4,NTR5
114.  N,NTR6,R6
115.  FILL,NTR5,NTR6
116.  DTHE = (360/NTHE)
117.  /COM, THMX = MAXIMUM THETA OVER WHICH WE ARE DOING THE CALCULATION
118.  THMX = NTHE/NMAG
119.  NELT = (THMX/DTHE)
120.  NGEN,(NELT+1),NTR6,1,NTR6,1.,0.,DTHE
121.  /COM,
122.  /COM, GENERATE ALL ELEMENTS AS ROTOR IRON
123.  /COM,
124.  NALL $EALL
125.  MAT,2
126.  N1 = 1
127.  N2 = 2
128.  N3 = (NTR6 + 2)
129.  N4 = (NTR6 + 1)
130.  E,N1,N2,N3,N4
131.  ETR6 = (NTR6 - 1)
132.  EGEN,ETR6,1,1,1
133.  EGEN,NELT,NTR6,1,ETR6,1
134.  /COM,
135.  /COM, MODIFY ELEMENTS FOR AIR GAP
136.  /COM,
137.  EPS = .00001
```

```
138. MAT,1
139. NSEL,X,(R2-EPS),R3
140. ENODE,1
141. EMODIF,ALL
142. EALL $NALL
143. /COM,
144. /COM, NOW DO THE MAGNETS - AIR
145. /COM,
146. MAT,3
147. NSEL,X,(R1-EPS),R2
148. ENODE,1
149. EMODIF,ALL
150. MAT,1
151. T1 = THMG + THET - EPS
152. T2 = THMA + THET + EPS
153. NRSEL,Y,T1,T2
154. ENODE,1 $EMODIF, ALL
155. NALL $EALL
156. THEA = THMA - THMG
157. T1 = THET - THEA - EPS
158. T2 = THET + EPS
159. NSEL,X,(R1 - EPS),R2
160. NRSEL,Y,T1,T2
161. ENODE,1   $EMODIF,ALL
162. NALL $EALL
163. NSEL,X,(R1 - EPS),R2
164. T1 = THET - THMA - THEA - EPS
165. T2 = THET - THMA + EPS
166. NRSEL,Y,T1,T2
167. ENODE,1   $EMODIF,ALL
168. NALL $EALL
169. MAT,4
170. T1 = THET - THMA - EPS
171. T2 = THET - THEA + EPS
172. NSEL,X,(R1 - EPS),R2 $NRSEL,Y,T1,T2
173. ENODE,1 $EMODIF,ALL
174. NALL $EALL
175. T1 = THMA + THET - EPS
176. T2 = THMA + THMG + THET + EPS
177. NSEL,X,(R1 - EPS),R2 $NRSEL,Y,T1,T2
178. ENODE,1 $EMODIF,ALL
179. NALL $EALL
180. /COM,
181. /COM, SHOES - AIR
182. /COM,
183. MAT,1
184. /COM, THSH = 8.202
185. /COM, THSA = 11.122
186. THSH = 8 $THSA = 10
187. THAR = THSA - THSH
188. T1 = THSH/2   $T1 = T1 - EPS
189. T2 = T1 + THAR $T2 = T2 + EPS $T2 = T2 + EPS
190. NSEL,X,(R3-EPS),R4 $NRSEL,Y,T1,T2   $ENODE,1
191. EMODIF,ALL
192. EALL $NALL
193. T1 = T2 + THSH $T1 = T1 - EPS $T1 = T1 - EPS
194. T2 = T1 + THAR $T2 = T2 + EPS $T2 = T2 + EPS
195. NSEL,X,(R3-EPS),R4 $NRSEL,Y,T1,T2 $ENODE,1 $EMODIF,ALL
196. NALL $EALL
197. T1 = T2 + THSH $T2 = T1 + THAR $T1 = T1 - EPS $T1 = T1 - EPS
198. T2 = T1 + THAR $T2 = T2 + EPS $T2 = T2 + EPS
199. NSEL,X,(R3-EPS),R4 $NRSEL,Y,T1,T2 $ENODE,1 $EMODIF,ALL
200. EALL $NALL
201. T1 = T2 + THSH $T1 = T1 - EPS $T1 = T1 - EPS
202. T2 = T1 + THAR $T2 = T2 + EPS $T2 = T2 + EPS
203. NSEL,X,(R3-EPS),R4 $NRSEL,Y,T1,T2 $ENODE,1 $EMODIF,ALL
204. NALL $EALL
205. T1 = T2 + THSH $T1 = T1 - EPS $T1 = T1 - EPS
206. T2 = T1 + THAR $T2 = T2 + EPS $T2 = T2 + EPS
207. NSEL,X,(R3-EPS),R4 $NRSEL,Y,T1,T2 $ENODE,1 $EMODIF,ALL
208. NALL $EALL
```

209. T1 = T2 + THSH $T1 = T1 - EPS $T1 = T1 - EPS
210. T2 = T1 + THAR $T2 = T2 + EPS $T2 = T2 + EPS
211. NSEL,X,(R3-EPS),R4 $NRSEL,Y,T1,T2 $ENODE,1 $EMODIF,ALL
212. NALL $EALL
213. /PNUM,MAT,1 $/NUMBER,1
214. /COM,
215. /COM, FIND R THAT DIVIDES THE AREA FOR THE UPPER AND
216. /COM, LOWER WINDING INTO EQUAL AREAS
217. /COM,
218. T1 = (R5*R5) $T2 = (R4*R4) $T3 = ((T1+T2)/2)
219. R = SQRT(T3) $DR45 = (R5 - R4)/NR45 $D452 = DR45/2
220. /COM, *****
221. /COM, THT = THETA WIDTH OF A TOOTH (NOT INCLUDING SHOE)
222. /COM, THC = THETA WIDTH OF CONDUCTOR
223. /COM, THT = 4.331 $THC = 6.791
224. THT = 4 $THC = 6
225. /COM,
226. /COM, INSERT THE A+ MATERIAL IN THE BOTTOM OF SLOTS 1 & 2
227. /COM, THE C- MATERIAL IN THE BOTTOM OF SLOTS 3 & 4
228. /COM, AND THE B+ MATERIAL IN THE BOTTOM OF SLOTS 5 & 6
229. /COM,SLOT #1
230. MAT,5
231. T1 = THT/2 $T2 = T1 + THC + EPS $T1 = T1 - EPS
232. NSEL,X,(R - EPS),(R5 + EPS) $NRSEL,Y,T1,T2
233. ENODE,1 $EMODIF,ALL
234. NALL $EALL
235. /COM,SLOT #2
236. T1 = T2 + THT - 2*EPS $T2 = T1 + THC + 2*EPS
237. NSEL,X,(R - EPS),(R5+EPS) $NRSEL,Y,T1,T2
238. $ENODE,1 $EMODIF,ALL
239. NALL $EALL
240. /COM, SLOT #3
241. MAT,10
242. T1 = T2 + THT - 2*EPS $T2 = T1 + THC + 2*EPS
243. NSEL,X,(R - EPS),(R5+EPS) $NRSEL,Y,T1,T2
244. ENODE,1 $EMODIF,ALL
245. NALL $EALL
246. /COM,SLOT #4
247. T1 = T2 + THT - 2*EPS $T2 = T1 + THC + 2*EPS
248. NSEL,X,(R - EPS),(R5+EPS) $NRSEL,Y,T1,T2
249. ENODE,1 $EMODIF,ALL
250. NALL $EALL
251. /COM, SLOT #5
252. MAT,7
253. T1 = T2 + THT - 2*EPS $T2 = T1 + THC + 2*EPS
254. NSEL,X,(R - EPS),(R5+EPS) $NRSEL,Y,T1,T2
255. ENODE,1 $EMODIF,ALL
256. NALL $EALL
257. /COM,SLOT #6
258. T1 = T2 + THT - 2*EPS $T2 = T1 + THC + 2*EPS
259. NSEL,X,(R - EPS),(R5+EPS) $NRSEL,Y,T1,T2
260. ENODE,1 $EMODIF,ALL
261. NALL $EALL
262. /COM,
263. /COM, NOW INSERT THE A+ MATERIAL IN THE TOP OF SLOTS 1 & 2
264. /COM, THE C- MATERIAL IN THE TOP OF SLOTS 3 & 4
265. /COM, AND THE B+ MATERIAL IN THE TOP OF SLOTS 5 & 6
266. /COM, NEW MODIFICATIONS ON 1/26/93 INDICATE FULL PITCH WINDINGS
267. /COM,SLOT #2
268. MAT,5
269. T1 = THT*1.5+THC-EPS $T2 = T1 + THC + 2*EPS
270. NSEL,X,(R4 - EPS),(R+D452) $NRSEL,Y,T1,T2
271. ENODE,1 $EMODIF,ALL
272. NALL $EALL
273. /COM,SLOT #3
274. MAT,10
275. T1 = T2 + THT - 2*EPS $T2 = T1 + THC + 2*EPS
276. NSEL,X,(R4-EPS),(R+D452) $NRSEL,Y,T1,T2
277. ENODE,1 $EMODIF,ALL
278. NALL $EALL
279. /COM,SLOT #4

```
280. MAT,10
281. T1 = T2 + THT - 2*EPS  ST2 = T1 + THC + 2*EPS
282. NSEL,X,(R4-EPS),(R+D452) SNRSEL,Y,T1,T2
283. ENODE,1 SEMODIF,ALL
284. NALL SEALL
285. /COM,SLOT #5
286. MAT,7
287. T1 = T2 + THT - 2*EPS  ST2 = T1 + THC + 2*EPS
288. NSEL,X,(R4-EPS),(R+D452) SNRSEL,Y,T1,T2
289. ENODE,2 SEMODIF,ALL
290. NALL SEALL
291. /COM,SLOT #6
292. MAT,7
293. T1 = T2 + THT - 2*EPS  ST2 = T1 + THC + 2*EPS
294. NSEL,X,(R4-EPS),(R+D452) SNRSEL,Y,T1,T2
295. SENODE,1 SEMODIF,ALL
296. /COM,SLOT #1
297. NALL SEALL
298. MAT,5
299. T1 = THT/2 - EPS  ST2 = T1 + THC + 2*EPS
300. NSEL,X,(R4-EPS),(R+D452) SNRSEL,Y,T1,T2
301. SENODE,1 SEMODIF,ALL
302. NALL SEALL
303. /PNUM,MAT,1 S/COLOR,1,CYAN S/COLOR,2,BLUE   S/COLOR,3,RED
304. /COLOR,4,MAGENTA S/COLOR,5,MRED  S/COLOR,6,BMAGENT
305. /COLOR,7,CBLUE S/COLOR,8,GCYAN  S/COLOR,9,GREEN  S/COLOR,10,GREEN
306. /NUMBER,1 SNALL SEALL
307. /COM,
308. /COM, ENTER BOUNDARY CONDITIONS
309. /COM,
310. NSEL,X,R0
311. NT,ALL,MAG,0
312. NALL SEALL
313. NSEL,X,R6
314. NT,ALL,MAG,0
315. NALL SEALL
316. CE,1,0,1,MAG,1,1861,MAG,1
317. RP30,1,,1,,,1
318. /COM,
319. /COM, ENTER THE CURRENTS
320. /COM,
321. JAPL = 8.E6
322. JBPL = -4.0E6
323. JCPL = -4.0E6
324. JAM = -JAPL  SJBM = -JBPL  SJCM = -JCPL
325. KTEMP,-1
326. NALL SEALL
327. ESEL,MAT,5  STE,ALL,,JAPL
328. NALL SEALL
329. ESEL,MAT,6  STE,ALL,,JBPL S/COM,SHOULD BE
330. NALL SEALL
331. ESEL,MAT,7  STE,ALL,,JCPL
332. NALL SEALL
333. ESEL,MAT,8  STE,ALL,,JAM
334. NALL SEALL
335. ESEL,MAT,9  STE,ALL,,JBM
336. NALL SEALL
337. ESEL,MAT,10 STE,ALL,,JCM
338. NALL SEALL
339. KBC,0
340. ITER,10
341. LWRITE
342. ITER,-20,,2
343. CNVR,0.0001  SKBC,1
344. LWRITE SAFWRI
345. FINI
346. /EXEC
347. /INPUT,27
348. FINI
349. /EOF
```

APPENDIX G

## Experimental Thermal Investigation

To start to become familiar with techniques and problems to be encountered in future laboratory work a commercially available motor was obtained and subsequently opened i.e. the end bells removed. From this first phase it was observed that there were eight poles and twenty seven slots. Thus it is immediately clear that this is a fractional slot motor i.e. there is no integer by which the product of the number of phases and the number of poles will equal 27. It was interesting to see that the manufacturer had used extended end windings on *one* end of the motor and carefully formed them so that they fit tightly into the aluminum end bell (without however any potting). Based on our later work this is, no doubt, to facilitate heat removal. Next the end windings on one end were cut off more or less flush with the first laminations in the stator stack. A 600 dpi color scan was made of the end of the lamination stack and is enclosed as figure on p. 99 below. The numbers beside some of the slots denote the numbers of conductors in the various slots. From their varying numbers it is clear, as expected, that this fractional slot motor does not have identical coils. Thus its electrical balance is assured from careful design of the unbalanced windings. The diameter of the wire was measured several times and it approximates 25 AWG but not exactly.

Perhaps the wire is a metric size (this is a pure speculation). Three Hall effect devices were found to be cemented to the inside of the assembly where the magnetic flux from the rotor's permanent magnets can sweep over them. The angular distance between them corresponded to the standard required for electronic commutation purposes. Additional things to be noticed include the fact that there is no apparent effort made to encapsulate the wires in the slots. This is a little surprising because it is common commercial practice to vacuum impregnate the windings with insulating varnish after they are placed in the stator. In this instance where heat removal was pretty clearly a design feature the voids in the slots is a little puzzling (or perhaps it is felt that the large end turns and so forth are enough of a heat removal design feature to make the motor competitive). Analysis of the fuller slots showed that the fill factor achieved in this motor does not exceed 50% (a common number it appears). The stator laminations measured to be 25 mils thick. This is a little surprising because 14 mil material is generally available (10 mil material appears to be available in a few cases). However in the light of our core loss analysis perhaps core loss is just not that big a problem and possibly the thicker material is more easily fabricated than the thinner.

After this examination it was decided to perform a simple thermal test on the motor. The motor was fixed to the bottom of a plastic jar with RTV. Thermocouples were cemented along the length of the inside of the stator and to the copper end windings (black and white photographs). The first thermocouple was placed 1/4 inch up from the bottom of the stack, the second 3/8, third 3/4, fourth 1 1/8, fifth 1 1/2, and the last two on the copper at the top of the motor. With a known ambient temperature as an initial condition an ice and water combination was poured into the plastic jar i.e. surrounding the outside of the motor and the output of the thermocouples recorded on a floppy disk. The results of this exercise are presented in the multiline multicolored figure on p. 101 showing temperature at the various stations versus time.

While the exponential appearing changes in the various temperatures confirms the nature of the response and agrees with the lumped thermal circuit approach to modeling one thing stands out that is somewhat counterintuitive (at least to this author without the benefit of a thermal simulation of this configuration). That is the temperature of the copper followed the temperature of the iron without any appreciable time lag. While there is at present no explanation of this observed fact speculation must center on two things. The first speculation is that there is better than anticipated iron to copper wire thermal coupling (despite the visible voids in the slots). The second speculation is that the relatively small thermal capacitance of the copper (compared to the relatively massive iron presence) makes it possible for its temperature to track the iron temperature closely in time.

Several possibilities for instrumenting the fabricated motors arise from this experiment. To perform meaningful thermal characterization of the new motors temperature measurements must be made in several contexts. Of course thermal measurement wires should be wound with the main windings (this need only require a single strand). During laboratory tests essentially the same experiment described above should be run with refinements gained from this work. One experiment might involve thermocouples cemented to the iron and the copper as before. However instead of not only cooling the outer part of the stator and seeing how heat leaves the motor in an attempt to characterize the thermal circuit but also the copper winding would be energized to determine its temperature profile with time. Another test to be done is to spin the unenergized motor with another motor and measure its temperature rise and, if possible, the power transmitted into the motor. This test would establish the core loss caused by spinning the permanent magnets relative to the stator and confirm hopefully that it is a small contributor.
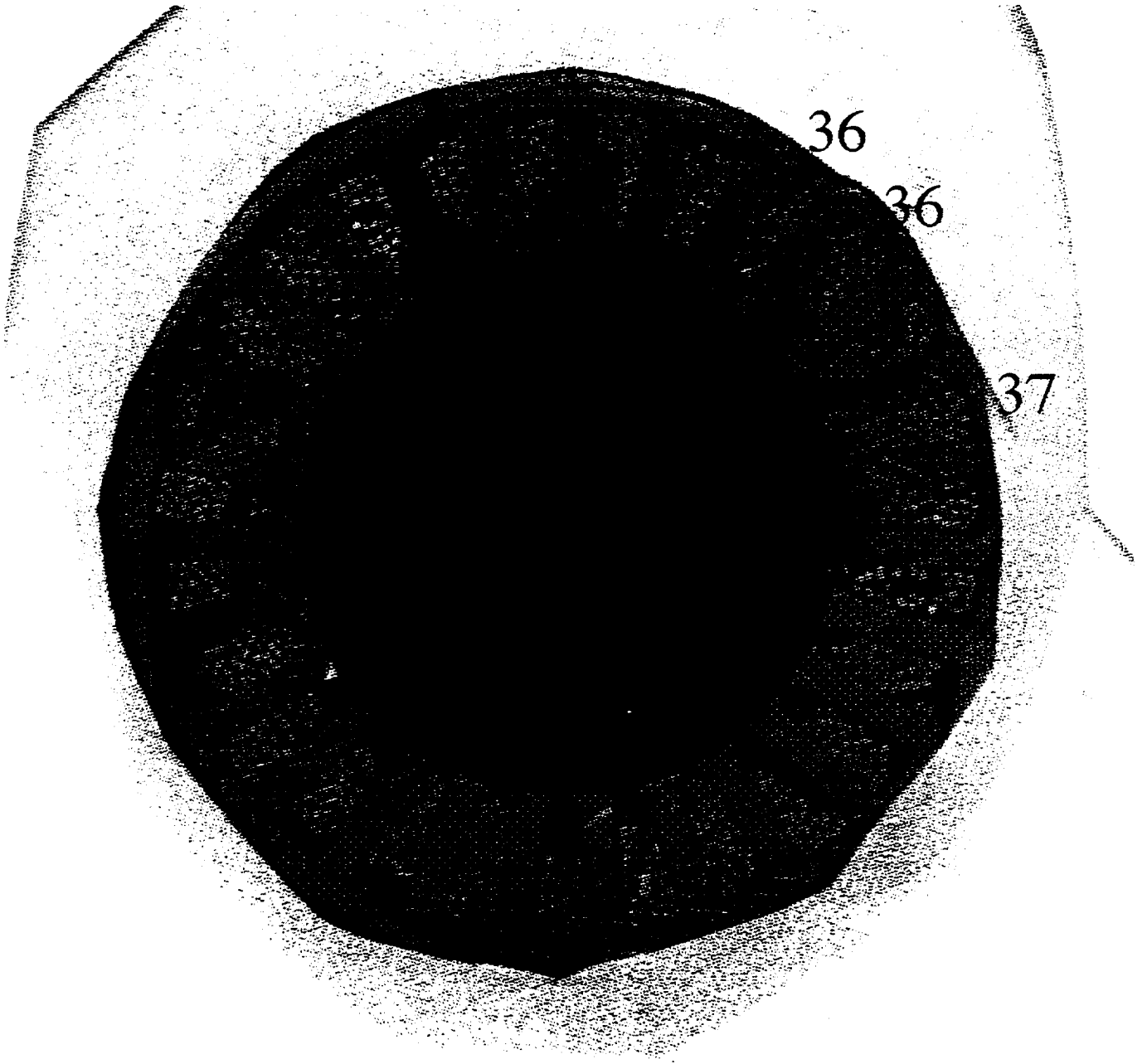
36
36
37

View of Motor Showing Thermocouple
Placement

Laboratory Setup For Thermal
Motor Tests

Degrees Celsius

Temperature vs Time Inland Motor

| | 0 | 5 | 10 | 15 | 20 | 25 |

57.068
114.136
171.204
228.272
285.34
342.408
399.476
456.544
513.612
570.68
627.748
684.816
741.884
798.952
856.02
913.088
970.156
1027.224
1084.292
1141.36
1198.428
1255.496
1312.564
1369.632
1426.7
1483.768
1540.836

Seconds

Ice and water introduced
around motor housing

Deg 3Celsius
Deg4Celsius
Deg5Celsius
Deg6Celsius
Deg7Celsius
Deg8Celsius

Measurement 9	Meas 3	Seconds	Deg 3Celsi	Deg4Celsiu	Deg5Celsius	Deg6Celsiu	Deg7Celsiu	Deg8Celsius
DC Volts								
1	0.028	2.594	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666
2	0.0279	5.188	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666
3	0.028	7.782	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666
4	0.0279	10.376	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666
5	0.0279	12.97	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666
6	0.0279	15.564	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666
7	0.0279	18.158	23.82157	23.5666	23.54185	23.5666	23.49237	23.5666
8	0.0279	20.752	23.82157	23.5666	23.54185	23.5666	23.49237	23.5666
9	0.0279	23.346	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666
10	0.0279	25.94	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666
11	0.0279	28.534	23.82157	23.5666	23.54185	23.5666	23.49237	23.5666
12	0.028	31.128	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666
13	0.028	33.722	23.82157	23.5666	23.54185	23.5666	23.49237	23.5666
14	0.028	36.316	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666
15	0.028	38.91	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666
16	0.0279	41.504	23.82157	23.5666	23.54185	23.5666	23.49237	23.5666
17	0.028	44.098	23.82157	23.5666	23.54185	23.5666	23.49237	23.5666
18	0.028	46.692	23.82157	23.5666	23.54185	23.5666	23.49237	23.5666
19	0.0279	49.286	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666
20	0.0279	51.88	23.82157	23.5666	23.54185	23.5666	23.49237	23.5666
21	0.028	54.474	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666

22	0.028	57.068	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666
23	0.028	59.662	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666
24	0.028	62.256	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666
25	0.028	64.85	23.82157	23.5666	23.54185	23.5666	23.49237	23.5666
26	0.028	67.444	23.82157	23.5666	23.54185	23.5666	23.49237	23.5666
27	0.028	70.038	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666
28	0.028	72.632	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666
29	0.028	75.226	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666
30	0.028	77.82	23.82157	23.59134	23.54185	23.5666	23.51711	23.5666
31	0.028	80.414	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666
32	0.028	83.008	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666
33	0.028	85.602	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666
34	0.028	88.196	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666
35	0.028	90.79	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666
36	0.0279	93.384	23.82157	23.59134	23.54185	23.5666	23.51711	23.5666
37	0.028	95.978	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666
38	0.028	98.572	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666
39	0.028	101.166	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666
40	0.028	103.76	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666
41	0.028	106.354	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666
42	0.028	108.948	23.82157	23.59134	23.54185	23.59134	23.51711	23.5666
43	0.0279	111.542	23.82157	23.59134	23.54185	23.5666	23.51711	23.5666
44	0.028	114.136	23.82157	23.59134	23.54185	23.5666	23.51711	23.5666
45	0.028	116.73	23.82157	23.59134	23.54185	23.5666	23.51711	23.5666
46	0.0279	119.324	23.82157	23.59134	23.54185	23.5666	23.51711	23.5666
47	0.0279	121.918	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666
48	0.028	124.512	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666
49	0.028	127.106	23.82157	23.59134	23.54185	23.5666	23.51711	23.5666
50	0.028	129.7	23.82157	23.59134	23.54185	23.59134	23.51711	23.5666
51	0.028	132.294	23.82157	23.59134	23.54185	23.5666	23.51711	23.5666
52	0.028	134.888	23.82157	23.59134	23.54185	23.5666	23.51711	23.5666
53	0.028	137.482	23.82157	23.59134	23.54185	23.5666	23.51711	23.5666
54	0.028	140.076	23.82157	23.59134	23.54185	23.5666	23.51711	23.5666
55	0.028	142.67	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666
56	0.028	145.264	23.82157	23.59134	23.54185	23.5666	23.51711	23.5666
57	0.028	147.858	23.82157	23.59134	23.54185	23.59134	23.51711	23.5666

58	0.028	150.452	23.82157	23.59134	23.54185	23.5666	23.51711	23.5666
59	0.028	153.046	23.82157	23.59134	23.5666	23.5666	23.51711	23.5666
60	0.028	155.64	23.82157	23.5666	23.5666	23.59134	23.51711	23.5666
61	0.028	158.234	23.82157	23.59134	23.54185	23.5666	23.51711	23.5666
62	0.028	160.828	23.82157	23.59134	23.54185	23.5666	23.51711	23.5666
63	0.0279	163.422	23.82157	23.5666	23.54185	23.5666	23.51711	23.5666
64	0.028	166.016	23.82157	23.59134	23.54185	23.5666	23.51711	23.5666
65	0.028	168.61	23.82157	23.59134	23.5666	23.59134	23.51711	23.5666
66	0.028	171.204	23.82157	23.59134	23.5666	23.59134	23.51711	23.5666
67	0.028	173.798	23.82157	23.59134	23.54185	23.59134	23.5666	23.59134
68	0.028	176.392	23.82157	23.59134	23.5666	23.59134	23.54185	23.59134
69	0.028	178.986	23.82157	23.51711	23.51711	23.61608	23.46762	23.59134
70	0.028	181.58	23.79629	23.59134	23.59134	23.59134	23.5666	23.59134
71	0.028	184.174	23.84685	23.59134	23.54185	23.59134	23.5666	23.59134
72	0.028	186.768	23.82157	23.59134	23.5666	23.61608	23.5666	23.64082
73	0.028	189.362	23.69515	23.51711	23.46762	23.51711	23.5666	23.51711
74	0.028	191.956	22.93663	21.6845	22.47737	22.99737	23.39339	23.02212
75	0.028	194.55	21.79886	20.27075	21.18866	22.22966	22.97261	22.27921
76	0.028	197.144	20.73694	19.20301	20.17147	21.51099	22.6012	21.56056
77	0.028	199.738	19.87728	18.38285	19.50109	20.84144	21.83321	20.84144
78	0.028	202.332	19.19462	17.88548	19.02909	20.29557	21.28785	20.1963
79	0.028	204.926	18.56252	17.33811	18.55688	19.42658	20.69259	19.42658
80	0.028	207.52	17.90514	16.64106	17.91036	18.2088	20.07218	18.706602
81	0.028	210.114	17.32361	15.99339	17.21367	16.93985	19.42658	17.98498
82	0.028	212.708	16.76736	15.51985	16.59125	15.91863	18.80543	17.28834
83	0.028	215.302	16.31225	15.14585	16.01831	15.29546	18.25853	16.74066
84	0.028	217.896	15.95828	14.8715	15.5697	14.8715	17.71135	16.24254
85	0.028	220.49	15.6043	14.64699	15.19572	14.62204	17.23856	15.84387
86	0.028	223.084	15.27561	14.39747	14.84656	14.44738	16.76557	15.49492
87	0.028	225.678	14.89635	14.17286	14.59709	14.3226	16.36709	15.17079
88	0.028	228.272	14.64352	13.97316	14.42242	14.22277	16.01831	14.92139
89	0.028	230.866	14.34011	13.74846	14.19782	14.09797	15.69433	14.67194
90	0.028	233.46	14.11255	13.57366	14.04805	13.99812	15.3952	14.44738
91	0.028	236.054	13.85971	13.39883	13.8733	13.89826	15.12091	14.24773
92	0.028	238.648	13.60688	13.19899	13.69852	13.72349	14.8715	14.02309
93	0.028	241.242	13.37932	12.99911	13.4238	13.37385	14.59709	13.74846

94	0.028	243.836	13.15177	12.69923	13.14902	12.92415	14.29765	13.39883
95	0.028	246.43	12.89893	12.32426	12.69923	12.47426	14.02309	13.07407
96	0.028	249.024	12.6208	11.92415	12.27425	12.07421	13.67355	12.69923
97	0.0279	251.618	12.36796	11.57393	11.92415	11.72404	13.34887	12.34926
98	0.028	254.212	12.14041	11.34873	11.64899	11.49887	13.04908	12.07421
99	0.028	256.806	11.91285	11.19857	11.4238	11.29868	12.77421	11.84911
100	0.0278	259.4	11.71058	11.02336	11.19857	11.09846	12.49926	11.59895
101	0.0271	261.994	11.50831	10.89819	11.04839	10.94826	12.29926	11.4238
102	0.0259	264.588	11.33132	10.74797	10.87316	10.77301	12.0492	11.24863
103	0.0249	267.182	11.12905	10.57269	10.72293	10.59773	11.84911	11.07342
104	0.024	269.776	10.95207	10.42242	10.54765	10.42242	11.64899	10.89819
105	0.0233	272.37	10.80036	10.27214	10.39738	10.27214	11.47385	10.77301
106	0.0227	274.964	10.64866	10.14688	10.22204	10.09678	11.32371	10.59773
107	0.022	277.558	10.47167	9.996559	10.04667	10.09678	11.12349	10.44747
108	0.0215	280.152	10.31997	9.871273	9.896331	9.72091	10.94826	10.29719
109	0.0209	282.746	10.19355	9.745972	9.745972	9.545462	10.82309	10.17193
110	0.0205	285.34	10.06713	9.620658	9.595593	9.395055	10.69789	10.04667
111	0.0201	287.934	9.94071	9.495329	9.445193	9.244627	10.54765	9.921389
112	0.0197	290.528	9.814291	9.395055	9.294772	9.069102	10.42242	9.796094
113	0.0194	293.122	9.713155	9.2697	9.169406	8.91863	10.27214	9.670785
114	0.019	295.716	9.586736	9.169406	9.044025	8.79322	10.14688	9.570528
115	0.0188	298.31	9.4856	9.044025	8.893549	8.64271	9.996559	9.445193
116	0.0185	300.904	9.384464	8.91863	8.743053	8.492179	9.871273	9.319844
117	0.0182	303.498	9.283329	8.79322	8.617623	8.341627	9.745972	9.19448
118	0.018	306.092	9.182193	8.692882	8.492179	8.241248	9.620658	9.094179
119	0.0177	308.686	9.081058	8.567447	8.366721	8.115761	9.495329	8.96879
120	0.0175	311.28	8.979922	8.441997	8.216152	7.965157	9.369985	8.868468
121	0.0173	313.874	8.878786	8.316533	8.065562	7.839639	9.219554	8.743053
122	0.017	316.468	8.777651	8.191055	7.965157	7.714106	9.119255	8.64271
123	0.0168	319.062	8.676515	8.090662	7.864744	7.613669	9.018947	8.542358
124	0.0165	321.656	8.600663	7.965157	7.714106	7.48811	8.893549	8.416906
125	0.0163	324.25	8.474244	7.839639	7.613669	7.387652	8.768137	8.316533
126	0.016	326.844	8.373108	7.714106	7.48811	7.262068	8.667796	8.241248
127	0.0158	329.438	8.297257	7.613669	7.387652	7.161589	8.567447	8.115761
128	0.0156	332.032	8.196121	7.48811	7.287186	7.061102	8.467088	8.015361
129	0.0155	334.626	8.094985	7.387652	7.161589	6.960606	8.366721	7.914952

130	0.0153	337.22	7.99385	7.262068	7.061102	6.8601	8.241248	7.814533
131	0.0151	339.814	7.892714	7.161589	6.960606	6.759585	8.140859	7.739213
132	0.0149	342.408	7.791579	7.061102	6.8601	6.659061	8.065562	7.638779
133	0.0148	345.002	7.715727	6.960606	6.759585	6.583662	7.965157	7.563447
134	0.0146	347.596	7.614591	6.8601	6.684193	6.508257	7.864744	7.462996
135	0.0145	350.19	7.513456	6.759585	6.583662	6.40771	7.789427	7.362537
136	0.0143	352.784	7.41232	6.659061	6.483121	6.307154	7.688997	7.287186
137	0.0142	355.378	7.336468	6.583662	6.40771	6.23173	7.588558	7.18671
138	0.0141	357.972	7.235333	6.483121	6.332294	6.156302	7.513223	7.111347
139	0.014	360.566	7.134197	6.40771	6.23173	6.080868	7.412768	7.035979
140	0.0138	363.16	7.033062	6.307154	6.156302	6.00543	7.33742	6.960606
141	0.0137	365.754	6.95721	6.23173	6.080868	5.904837	7.262068	6.885227
142	0.0136	368.348	6.856074	6.131158	5.980282	5.829386	7.18671	6.784714
143	0.0135	370.942	6.780223	6.030576	5.904837	5.75393	7.111347	6.709324
144	0.0134	373.536	6.679087	5.955134	5.829386	5.678468	7.035979	6.633928
145	0.0133	376.13	6.603235	5.879687	5.75393	5.628158	6.960606	6.558527
146	0.0132	378.724	6.5021	5.804234	5.678468	5.552688	6.885227	6.483121
147	0.0131	381.318	6.426248	5.728776	5.628158	5.477213	6.809843	6.40771
148	0.013	383.912	6.350396	5.678468	5.552688	5.426894	6.709324	6.332294
149	0.0129	386.506	6.274545	5.577845	5.477213	5.35141	6.659061	6.256872
150	0.0128	389.1	6.173409	5.502372	5.401733	5.275921	6.558527	6.181445
151	0.0127	391.694	6.097557	5.452054	5.326248	5.225593	6.508257	6.131158
152	0.0126	394.288	5.996422	5.376572	5.275921	5.175262	6.432848	6.055723
153	0.0125	396.882	5.945854	5.301085	5.200427	5.099761	6.357433	5.980282
154	0.0124	399.476	5.870002	5.250757	5.150095	5.049424	6.307154	5.929986
155	0.0123	402.07	5.794151	5.175262	5.099761	4.999085	6.256872	5.854537
156	0.0122	404.664	5.743583	5.124928	5.049424	4.948743	6.181445	5.804234
157	0.0121	407.258	5.667731	5.074593	4.999085	4.8984	6.131158	5.75393
158	0.012	409.852	5.591879	5.024255	4.923572	4.848054	6.080868	5.703623
159	0.0119	412.446	5.541312	4.948743	4.873227	4.797706	6.00543	5.653314
160	0.0118	415.04	5.46546	4.8984	4.82288	4.747355	5.955134	5.577845
161	0.0117	417.634	5.414892	4.848054	4.772531	4.671825	5.904837	5.52753
162	0.0116	420.228	5.33904	4.797706	4.722179	4.646647	5.854537	5.477213
163	0.0116	422.822	5.288473	4.747355	4.671825	4.596289	5.779082	5.401733
164	0.0115	425.416	5.237905	4.697002	4.621468	4.54593	5.728776	5.35141
165	0.0114	428.01	5.162053	4.646647	4.57111	4.495568	5.678468	5.301085

166	0.0113	430.604	5.111485	4.596289	4.520749	4.445203	5.628158	5.250757
167	0.0112	433.198	5.060917	4.54593	4.470386	4.42002	5.577845	5.200427
168	0.0111	435.792	5.01035	4.495568	4.42002	4.369652	5.52753	5.150095
169	0.011	438.386	4.934498	4.42002	4.369652	4.319282	5.477213	5.099761
170	0.0109	440.98	4.88393	4.394837	4.319282	4.26891	5.426894	5.049424
171	0.0108	443.574	4.833362	4.344468	4.294096	4.218535	5.401733	4.999085
172	0.0107	446.168	4.782795	4.294096	4.243723	4.193347	5.35141	4.973914
173	0.0106	448.762	4.732227	4.26891	4.218535	4.142969	5.301085	4.923572
174	0.0106	451.356	4.681659	4.218535	4.168158	4.117779	5.250757	4.873227
175	0.0105	453.95	4.656375	4.168158	4.117779	4.067397	5.200427	4.82288
176	0.0104	456.544	4.605807	4.142969	4.092588	4.042206	5.175262	4.772531
177	0.0103	459.138	4.555239	4.092588	4.042206	3.991821	5.124928	4.747355
178	0.0102	461.732	4.504672	4.067397	4.017013	3.966627	5.074593	4.697002
179	0.0101	464.326	4.479388	4.017013	3.966627	3.916239	5.024255	4.646647
180	0.0101	466.92	4.403536	3.966627	3.941433	3.891044	4.999085	4.596289
181	0.01	469.514	4.378252	3.941433	3.891044	3.840652	4.948743	4.57111
182	0.0099	472.108	4.327684	3.891044	3.865848	3.815455	4.923572	4.520749
183	0.0099	474.702	4.3024	3.865848	3.815455	3.765059	4.873227	4.470386
184	0.0098	477.296	4.251833	3.815455	3.790257	3.739861	4.82288	4.445203
185	0.0097	479.89	4.226549	3.790257	3.739861	3.714662	4.797706	4.42002
186	0.0097	482.484	4.175981	3.765059	3.714662	3.689462	4.747355	4.369652
187	0.0096	485.078	4.150697	3.714662	3.689462	3.664262	4.722179	4.344468
188	0.0095	487.672	4.100129	3.689462	3.664262	3.613859	4.697002	4.319282
189	0.0095	490.266	4.074845	3.664262	3.639061	3.588657	4.671825	4.26891
190	0.0094	492.86	4.024278	3.639061	3.613859	3.563455	4.621468	4.243723
191	0.0094	495.454	3.998994	3.613859	3.588657	3.538252	4.596289	4.218535
192	0.0093	498.048	3.97371	3.588657	3.538252	3.513048	4.57111	4.193347
193	0.0093	500.642	3.948426	3.563455	3.513048	3.487844	4.54593	4.142969
194	0.0092	503.236	3.923142	3.513048	3.487844	3.462639	4.520749	4.142969
195	0.0091	505.83	3.872574	3.513048	3.462639	3.437433	4.470386	4.092588
196	0.0091	508.424	3.84729	3.462639	3.437433	3.412227	4.445203	4.067397
197	0.009	511.018	3.822006	3.437433	3.412227	3.387021	4.42002	4.042206
198	0.009	513.612	3.796722	3.412227	3.387021	3.361813	4.394837	4.017013
199	0.0089	516.206	3.771439	3.387021	3.361813	3.336606	4.369652	3.991821
200	0.0089	518.8	3.720871	3.361813	3.336606	3.311397	4.344468	3.941433
201	0.0088	521.394	3.695587	3.336606	3.311397	3.286188	4.319282	3.916239

202	0.0088	523.988	3.670303	3.311397	3.286188	3.260979	4.26891	3.916239
203	0.0087	526.582	3.645019	3.286188	3.260979	3.235769	4.26891	3.865848
204	0.0087	529.176	3.619735	3.260979	3.235769	3.210558	4.218535	3.840652
205	0.0086	531.77	3.594451	3.235769	3.210558	3.185347	4.218535	3.815455
206	0.0086	534.364	3.569167	3.210558	3.185347	3.160135	4.193347	3.790257
207	0.0085	536.958	3.543883	3.185347	3.160135	3.134923	4.168158	3.765059
208	0.0085	539.552	3.5186	3.160135	3.134923	3.134923	4.142969	3.739861
209	0.0085	542.146	3.493316	3.134923	3.134923	3.10971	4.117779	3.714662
210	0.0084	544.74	3.468032	3.134923	3.084496	3.10971	4.092588	3.689462
211	0.0084	547.334	3.442748	3.10971	3.084496	3.084496	4.067397	3.689462
212	0.0084	549.928	3.417464	3.084496	3.084496	3.059282	4.042206	3.664262
213	0.0083	552.522	3.39218	3.059282	3.059282	3.034068	4.017013	3.639061
214	0.0083	555.116	3.366896	3.034068	3.034068	3.008853	3.991821	3.588657
215	0.0082	557.71	3.341612	3.034068	3.008853	2.983637	3.966627	3.588657
216	0.0082	560.304	3.316328	2.983637	2.983637	2.95842	3.941433	3.563455
217	0.0082	562.898	3.291044	2.983637	2.95842	2.933203	3.916239	3.538252
218	0.0081	565.492	3.265761	2.95842	2.933203	2.933203	3.891044	3.513048
219	0.0081	568.086	3.265761	2.933203	2.907986	2.907986	3.891044	3.487844
220	0.0081	570.68	3.240477	2.907986	2.882768	2.882768	3.865848	3.462639
221	0.008	573.274	3.215193	2.907986	2.882768	2.882768	3.840652	3.462639
222	0.008	575.868	3.189909	2.882768	2.857549	2.857549	3.840652	3.437433
223	0.008	578.462	3.189909	2.857549	2.857549	2.857549	3.815455	3.412227
224	0.008	581.056	3.164625	2.857549	2.83233	2.83233	3.790257	3.412227
225	0.0079	583.65	3.139341	2.83233	2.80711	2.80711	3.790257	3.387021
226	0.0079	586.244	3.114057	2.80711	2.80711	2.80711	3.765059	3.361813
227	0.0079	588.838	3.114057	2.80711	2.78189	2.78189	3.739861	3.336606
228	0.0078	591.432	3.088773	2.78189	2.78189	2.78189	3.739861	3.311397
229	0.0078	594.026	3.063489	2.756669	2.756669	2.756669	3.714662	3.311397
230	0.0078	596.62	3.038205	2.756669	2.731447	2.731447	3.689462	3.286188
231	0.0078	599.214	3.038205	2.731447	2.731447	2.731447	3.664262	3.260979
232	0.0077	601.808	3.012922	2.731447	2.706225	2.706225	3.664262	3.260979
233	0.0077	604.402	3.012922	2.706225	2.706225	2.706225	3.639061	3.235769
234	0.0077	606.996	2.987638	2.681002	2.681002	2.681002	3.613859	3.235769
235	0.0076	609.59	2.962354	2.681002	2.681002	2.681002	3.613859	3.210558
236	0.0076	612.184	2.962354	2.655779	2.655779	2.655779	3.588657	3.210558
237	0.0076	614.778	2.93707	2.655779	2.630555	2.630555	3.563455	3.185347

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238	0.0076	617.372	2.911786	2.630555	2.630555	2.630555	3.563455	3.160135
239	0.0075	619.966	2.911786	2.630555	2.605331	2.605331	3.538252	3.160135
240	0.0075	622.56	2.886502	2.605331	2.605331	2.605331	3.513048	3.134923
241	0.0075	625.154	2.886502	2.605331	2.605331	2.580106	3.513048	3.10971
242	0.0075	627.748	2.861218	2.580106	2.580106	2.580106	3.487844	3.10971
243	0.0075	630.342	2.861218	2.580106	2.55488	2.55488	3.487844	3.10971
244	0.0074	632.936	2.835934	2.55488	2.55488	2.55488	3.462639	3.084496
245	0.0074	635.53	2.81065	2.55488	2.55488	2.55488	3.462639	3.084496
246	0.0074	638.124	2.81065	2.529654	2.514518	2.529654	3.437433	3.059282
247	0.0074	640.718	2.81065	2.529654	2.511995	2.519563	3.437433	3.059282
248	0.0074	643.312	2.785366	2.517041	2.501905	2.50695	3.412227	3.034068
249	0.0073	645.906	2.785366	2.504427	2.489291	2.494336	3.412227	3.034068
250	0.0073	648.5	2.760083	2.496859	2.471632	2.489291	3.412227	3.008853
251	0.0073	651.094	2.760083	2.481723	2.461541	2.476677	3.387021	3.008853
252	0.0073	653.688	2.734799	2.471632	2.456495	2.466586	3.387021	2.983637
253	0.0073	656.282	2.734799	2.466586	2.443881	2.456495	3.361813	2.983637
254	0.0072	658.876	2.709515	2.456495	2.433789	2.448927	3.361813	2.95842
255	0.0072	661.47	2.709515	2.441358	2.428744	2.436312	3.336606	2.95842
256	0.0072	664.064	2.684231	2.433789	2.408561	2.431267	3.336606	2.933203
257	0.0072	666.658	2.684231	2.421175	2.398469	2.418652	3.336606	2.933203
258	0.0072	669.252	2.684231	2.418652	2.393423	2.413606	3.311397	2.933203
259	0.0071	671.846	2.658947	2.408561	2.380808	2.400992	3.311397	2.907986
260	0.0071	674.44	2.658947	2.400992	2.378285	2.395946	3.286188	2.907986
261	0.0071	677.034	2.633663	2.385854	2.368193	2.380808	3.286188	2.907986
262	0.0071	679.628	2.633663	2.375762	2.360624	2.378285	3.286188	2.882768
263	0.0071	682.222	2.633663	2.373239	2.348009	2.36567	3.260979	2.882768
264	0.0071	684.816	2.608379	2.363147	2.345486	2.358101	3.260979	2.882768
265	0.0071	687.41	2.608379	2.353055	2.33287	2.350532	3.235769	2.857549
266	0.007	690.004	2.608379	2.348009	2.325301	2.342963	3.235769	2.857549
267	0.007	692.598	2.583095	2.337917	2.315209	2.335393	3.235769	2.857549
268	0.007	695.192	2.583095	2.330347	2.307639	2.327824	3.210558	2.83233
269	0.007	697.786	2.583095	2.322778	2.305116	2.325301	3.210558	2.83233
270	0.007	700.38	2.557811	2.310162	2.2925	2.315209	3.210558	2.83233
271	0.007	702.974	2.557811	2.305116	2.279884	2.310162	3.185347	2.80711
272	0.007	705.568	2.532527	2.302593	2.277361	2.297547	3.185347	2.80711
273	0.0069	708.162	2.532527	2.295023	2.269791	2.295023	3.185347	2.78189

274	0.0069	710.756	2.532527	2.287454	2.267268	2.284931	3.160135	2.78189
275	0.0069	713.35	2.522414	2.272315	2.252129	2.277361	3.160135	2.78189
276	0.0069	715.944	2.517357	2.269791	2.242035	2.269791	3.160135	2.756669
277	0.0069	718.538	2.507244	2.259698	2.242035	2.262222	3.134923	2.756669
278	0.0069	721.132	2.504715	2.252129	2.231942	2.259698	3.134923	2.756669
279	0.0069	723.726	2.494602	2.247082	2.221849	2.249605	3.134923	2.756669
280	0.0069	726.32	2.487016	2.242035	2.224372	2.249605	3.10971	2.731447
281	0.0069	728.914	2.48196	2.236989	2.219325	2.236989	3.10971	2.731447
282	0.0068	731.508	2.469318	2.229419	2.201662	2.229419	3.10971	2.731447
283	0.0068	734.102	2.461733	2.224372	2.204185	2.229419	3.10971	2.706225
284	0.0068	736.696	2.459204	2.219325	2.196615	2.226895	3.10971	2.706225
285	0.0068	739.29	2.454147	2.214279	2.191568	2.214279	3.084496	2.706225
286	0.0068	741.884	2.446562	2.206709	2.183998	2.206709	3.084496	2.706225
287	0.0068	744.478	2.441505	2.201662	2.176428	2.204185	3.084496	2.681002
288	0.0068	747.072	2.436449	2.194092	2.171381	2.199138	3.059282	2.681002
289	0.0068	749.666	2.43392	2.189045	2.16381	2.194092	3.059282	2.681002
290	0.0068	752.26	2.421278	2.186521	2.158763	2.183998	3.059282	2.681002
291	0.0067	754.854	2.41875	2.181475	2.15624	2.183998	3.034068	2.655779
292	0.0067	757.448	2.413693	2.173904	2.148669	2.176428	3.034068	2.655779
293	0.0067	760.042	2.40358	2.173904	2.146146	2.173904	3.034068	2.655779
294	0.0067	762.636	2.40358	2.166334	2.143622	2.16381	3.034068	2.655779
295	0.0067	765.23	2.398523	2.158763	2.133528	2.166334	3.008853	2.630555
296	0.0067	767.824	2.395994	2.15624	2.125958	2.153716	3.008853	2.630555
297	0.0067	770.418	2.383352	2.15624	2.131005	2.15624	3.008853	2.630555
298	0.0067	773.012	2.378296	2.151193	2.123434	2.153716	3.008853	2.630555
299	0.0067	775.606	2.380824	2.146146	2.115863	2.146146	3.008853	2.630555
300	0.0067	778.2	2.373239	2.136052	2.105769	2.138575	3.008853	2.630555
301	0.0067	780.794	2.37071	2.133528	2.108292	2.136052	2.983637	2.605331
302	0.0067	783.388	2.363125	2.125958	2.100722	2.133528	2.983637	2.605331
303	0.0066	785.982	2.35554	2.125958	2.095674	2.125958	2.983637	2.605331
304	0.0066	788.576	2.353012	2.12091	2.095674	2.125958	2.983637	2.605331
305	0.0066	791.17	2.350483	2.118387	2.08558	2.123434	2.983637	2.605331
306	0.0066	793.764	2.347955	2.11334	2.088103	2.11334	2.983637	2.605331
307	0.0066	796.358	2.337841	2.110816	2.088103	2.110816	2.983637	2.580106
308	0.0066	798.952	2.34037	2.108292	2.08558	2.110816	2.95842	2.580106
309	0.0066	801.546	2.34037	2.100722	2.080533	2.108292	2.95842	2.580106

310	0.0066	804.14	2.332785	2.105769	2.078009	2.105769	2.95842	2.580106
311	0.0066	806.734	2.327728	2.103245	2.067914	2.095674	2.95842	2.580106
312	0.0066	809.328	2.322671	2.100722	2.070438	2.090627	2.95842	2.580106
313	0.0066	811.922	2.327728	2.095674	2.062867	2.098198	2.95842	2.580106
314	0.0066	814.516	2.325199	2.098198	2.060343	2.090627	2.95842	2.580106
315	0.0066	817.11	2.325199	2.090627	2.06539	2.088103	2.95842	2.55488
316	0.0066	819.704	2.312558	2.093151	2.060343	2.08558	2.933203	2.55488
317	0.0066	822.298	2.315086	2.088103	2.055296	2.08558	2.933203	2.55488
318	0.0066	824.892	2.310029	2.08558	2.055296	2.083056	2.933203	2.55488
319	0.0065	827.486	2.307501	2.083056	2.052772	2.078009	2.933203	2.55488
320	0.0065	830.08	2.304972	2.080533	2.047724	2.075485	2.933203	2.580106
321	0.0065	832.674	2.302444	2.072961	2.045201	2.070438	2.95842	2.580106
322	0.0065	835.268	2.297387	2.072961	2.045201	2.078009	2.983637	2.580106
323	0.0065	837.862	2.29233	2.070438	2.040153	2.072961	3.008853	2.580106
324	0.0065	840.456	2.289802	2.067914	2.037629	2.072961	3.034068	2.580106
325	0.0065	843.05	2.29233	2.06539	2.035106	2.070438	3.008853	2.580106
326	0.0065	845.644	2.289802	2.060343	2.030058	2.067914	3.008853	2.580106
327	0.0065	848.238	2.282217	2.062867	2.032582	2.070438	3.034068	2.580106
328	0.0065	850.832	2.27716	2.060343	2.030058	2.070438	3.059282	2.605331
329	0.0065	853.426	2.274632	2.060343	2.027534	2.072961	3.084496	2.605331
330	0.0065	856.02	2.269575	2.055296	2.032582	2.078009	3.10971	2.605331
331	0.0065	858.614	2.272103	2.052772	2.027534	2.067914	3.10971	2.605331
332	0.0065	861.208	2.269575	2.045201	2.02501	2.06539	3.10971	2.605331
333	0.0065	863.802	2.269575	2.047724	2.027534	2.070438	3.134923	2.605331
334	0.0065	866.396	2.264518	2.042677	2.02501	2.067914	3.134923	2.605331
335	0.0065	868.99	2.26199	2.045201	2.017439	2.067914	3.134923	2.605331
336	0.0065	871.584	2.26199	2.042677	2.014915	2.067914	3.134923	2.605331
337	0.0065	874.178	2.26199	2.037629	2.012391	2.055296	3.10971	2.580106
338	0.0065	876.772	2.256933	2.040153	2.009868	2.052772	3.084496	2.580106
339	0.0065	879.366	2.256933	2.035106	2.014915	2.052772	3.059282	2.55488
340	0.0065	881.96	2.251876	2.037629	2.014915	2.050248	3.059282	2.55488
341	0.0065	884.554	2.249348	2.030058	2.00482	2.045201	3.034068	2.55488
342	0.0065	887.148	2.246819	2.032582	2.00482	2.042677	3.008853	2.529654
343	0.0064	889.742	2.244291	2.027534	2.00482	2.050248	2.983637	2.529654
344	0.0064	892.336	2.251876	2.027534	2.002296	2.042677	3.008853	2.529654
345	0.0064	894.93	2.246819	2.02501	2.002296	2.052772	3.034068	2.580106

346	0.0064	897.524	2.239234	2.022487	1.999772	2.047724	3.059282	2.55488	
347	0.0064	900.118	2.244291	2.022487	1.992201	2.040153	3.059282	2.55488	
348	0.0064	902.712	2.239234	2.019963	1.994725	2.047724	3.034068	2.55488	
349	0.0064	905.306	2.236706	2.019963	1.997248	2.035106	3.008853	2.529654	
350	0.0064	907.9	2.234177	2.014915	1.987153	2.032582	3.008853	2.522086	
351	0.0064	910.494	2.234177	2.019963	1.989677	2.02501	2.983637	2.517041	
352	0.0064	913.088	2.231649	2.014915	1.984629	2.02501	2.95842	2.509473	
353	0.0064	915.682	2.231649	2.017439	1.984629	2.02501	2.95842	2.501905	
354	0.0064	918.276	2.229121	2.007344	1.979581	2.017439	2.933203	2.499382	
355	0.0064	920.87	2.224064	2.009868	1.982105	2.017439	2.933203	2.491814	
356	0.0064	923.464	2.224064	2.00482	1.974533	2.012391	2.933203	2.489291	
357	0.0064	926.058	2.226592	2.002296	1.969486	2.002296	2.907986	2.489291	
358	0.0064	928.652	2.221535	1.999772	1.966962	2.00482	2.907986	2.4792	
359	0.0064	931.246	2.221535	2.00482	1.966962	2.00482	2.907986	2.4792	
360	0.0064	933.84	2.226592	1.999772	1.966962	2.007344	2.907986	2.471632	
361	0.0064	936.434	2.219007	2.002296	1.966962	2.002296	2.882768	2.469109	
362	0.0064	939.028	2.216479	1.999772	1.964438	1.997248	2.882768	2.469109	
363	0.0064	941.622	2.211422	1.992201	1.95939	1.999772	2.882768	2.466586	
364	0.0064	944.216	2.21395	1.994725	1.961914	1.994725	2.882768	2.469109	
365	0.0064	946.81	2.21395	1.989677	1.95939	1.992201	2.882768	2.461541	
366	0.0064	949.404	2.211422	1.987153	1.954342	1.994725	2.882768	2.459018	
367	0.0064	951.998	2.208894	1.992201	1.954342	1.992201	2.857549	2.461541	
368	0.0064	954.592	2.208894	1.987153	1.951818	1.992201	2.857549	2.461541	
369	0.0064	957.186	2.203837	1.987153	1.951818	1.987153	2.857549	2.453972	
370	0.0064	959.78	2.203837	1.982105	1.94677	1.989677	2.857549	2.456495	
371	0.0064	962.374	2.19878	1.979581	1.944246	1.984629	2.857549	2.448927	
372	0.0064	964.968	2.19878	1.984629	1.949294	1.987153	2.857549	2.448927	
373	0.0064	967.562	2.201308	1.977057	1.941722	1.982105	2.857549	2.446404	
374	0.0064	970.156	2.19878	1.977057	1.939198	1.979581	2.857549	2.448927	
375	0.0064	972.75	2.19878	1.977057	1.941722	1.982105	2.857549	2.448927	
376	0.0064	975.344	2.201308	1.974533	1.939198	1.979581	2.857549	2.446404	
377	0.0064	977.938	2.196252	1.977057	1.94677	1.977057	2.857549	2.443881	
378	0.0064	980.532	2.191195	1.969486	1.936674	1.979581	2.857549	2.441358	
379	0.0064	983.126	2.188666	1.966962	1.941722	1.974533	2.83233	2.438835	
380	0.0064	985.72	2.193723	1.969486	1.93415	1.97201	2.83233	2.438835	
381	0.0064	988.314	2.191195	1.969486	1.936674	1.966962	2.83233	2.436312	

382	0.0064	990.908	2.186138	1.974533	1.929102	1.964438	2.83233	2.438835
383	0.0064	993.502	2.188666	1.969486	1.929102	1.97201	2.83233	2.428744
384	0.0064	996.096	2.18361	1.966962	1.929102	1.966962	2.83233	2.428744
385	0.0064	998.69	2.188666	1.966962	1.931626	1.977057	2.80711	2.426221
386	0.0064	1001.284	2.18361	1.966962	1.929102	1.97201	2.83233	2.431267
387	0.0064	1003.878	2.186138	1.966962	1.924054	1.969486	2.83233	2.428744
388	0.0064	1006.472	2.18361	1.966962	1.929102	1.969486	2.83233	2.431267
389	0.0063	1009.066	2.186138	1.964438	1.929102	1.969486	2.83233	2.428744
390	0.0063	1011.66	2.186138	1.966962	1.93415	1.966962	2.83233	2.421175
391	0.0063	1014.254	2.186138	1.964438	1.926578	1.95939	2.83233	2.421175
392	0.0063	1016.848	2.176024	1.961914	1.92153	1.954342	2.83233	2.421175
393	0.0063	1019.442	2.178553	1.95939	1.924054	1.95939	2.83233	2.421175
394	0.0063	1022.036	2.181081	1.95939	1.919006	1.951818	2.80711	2.413606
395	0.0063	1024.63	2.178553	1.961914	1.924054	1.956866	2.80711	2.413606
396	0.0063	1027.224	2.176024	1.95939	1.92153	1.951818	2.80711	2.413606
397	0.0063	1029.818	2.176024	1.95939	1.919006	1.954342	2.80711	2.413606
398	0.0063	1032.412	2.181081	1.95939	1.919006	1.956866	2.80711	2.403515
399	0.0063	1035.006	2.18361	1.956866	1.919006	1.949294	2.80711	2.413606
400	0.0063	1037.6	2.176024	1.956866	1.916482	1.956866	2.83233	2.431267
401	0.0063	1040.194	2.173496	1.954342	1.92153	1.95939	2.857549	2.438835
402	0.0063	1042.788	2.176024	1.956866	1.919006	1.954342	2.857549	2.433789
403	0.0063	1045.382	2.170968	1.956866	1.911434	1.956866	2.857549	2.428744
404	0.0063	1047.976	2.168439	1.951818	1.913958	1.954342	2.83233	2.423698
405	0.0063	1050.57	2.173496	1.954342	1.913958	1.954342	2.83233	2.421175
406	0.0063	1053.164	2.173496	1.954342	1.913958	1.951818	2.83233	2.423698
407	0.0063	1055.758	2.170968	1.954342	1.913958	1.94677	2.83233	2.413606
408	0.0063	1058.352	2.168439	1.954342	1.90891	1.94677	2.80711	2.408561
409	0.0063	1060.946	2.170968	1.954342	1.911434	1.949294	2.80711	2.416129
410	0.0063	1063.54	2.170968	1.954342	1.911434	1.956866	2.80711	2.421175
411	0.0063	1066.134	2.170968	1.954342	1.911434	1.951818	2.83233	2.421175
412	0.0063	1068.728	2.170968	1.951818	1.916482	1.951818	2.83233	2.421175
413	0.0063	1071.322	2.168439	1.956866	1.911434	1.956866	2.83233	2.423698
414	0.0063	1073.916	2.168439	1.954342	1.911434	1.951818	2.83233	2.421175
415	0.0063	1076.51	2.170968	1.956866	1.913958	1.949294	2.83233	2.421175
416	0.0063	1079.104	2.170968	1.956866	1.913958	1.954342	2.83233	2.418652
417	0.0063	1081.698	2.170968	1.951818	1.906386	1.949294	2.83233	2.416129

418	0.0063	1084.292	2.165911	1.949294	1.911434	1.94677	2.83233	2.413606
419	0.0063	1086.886	2.170968	1.951818	1.913958	1.944246	2.80711	2.411083
420	0.0063	1089.48	2.168439	1.951818	1.906386	1.941722	2.80711	2.411083
421	0.0063	1092.074	2.176024	1.94677	1.90891	1.94677	2.80711	2.408561
422	0.0063	1094.668	2.165911	1.949294	1.90891	1.94677	2.80711	2.408561
423	0.0063	1097.262	2.170968	1.951818	1.90891	1.949294	2.80711	2.408561
424	0.0063	1099.856	2.170968	1.954342	1.90891	1.941722	2.80711	2.403515
425	0.0063	1102.45	2.165911	1.951818	1.90891	1.941722	2.80711	2.406038
426	0.0063	1105.044	2.176024	1.954342	1.911434	1.949294	2.80711	2.403515
427	0.0063	1107.638	2.165911	1.951818	1.90891	1.941722	2.80711	2.408561
428	0.0063	1110.232	2.170968	1.951818	1.90891	1.949294	2.80711	2.403515
429	0.0063	1112.826	2.165911	1.951818	1.90891	1.944246	2.78189	2.403515
430	0.0063	1115.42	2.168439	1.951818	1.906386	1.939198	2.80711	2.408561
431	0.0063	1118.014	2.163383	1.94677	1.906386	1.94677	2.80711	2.408561
432	0.0063	1120.608	2.165911	1.954342	1.90891	1.944246	2.80711	2.406038
433	0.0063	1123.202	2.168439	1.949294	1.903862	1.941722	2.78189	2.408561
434	0.0063	1125.796	2.165911	1.949294	1.906386	1.941722	2.80711	2.403515
435	0.0063	1128.39	2.168439	1.951818	1.901338	1.941722	2.78189	2.406038
436	0.0063	1130.984	2.170968	1.951818	1.901338	1.944246	2.78189	2.400992
437	0.0063	1133.578	2.163383	1.951818	1.903862	1.94677	2.78189	2.408561
438	0.0063	1136.172	2.165911	1.954342	1.901338	1.941722	2.78189	2.406038
439	0.0063	1138.766	2.168439	1.951818	1.90891	1.944246	2.78189	2.406038
440	0.0063	1141.36	2.170968	1.951818	1.901338	1.94677	2.78189	2.406038
441	0.0063	1143.954	2.165911	1.949294	1.901338	1.941722	2.78189	2.411083
442	0.0063	1146.548	2.170968	1.954342	1.906386	1.939198	2.78189	2.413606
443	0.0063	1149.142	2.168439	1.954342	1.903862	1.941722	2.78189	2.416129
444	0.0063	1151.736	2.170968	1.954342	1.906386	1.944246	2.78189	2.408561
445	0.0063	1154.33	2.165911	1.954342	1.903862	1.941722	2.78189	2.408561
446	0.0063	1156.924	2.165911	1.951818	1.901338	1.951818	2.78189	2.411083
447	0.0063	1159.518	2.165911	1.951818	1.90891	1.944246	2.78189	2.408561
448	0.0063	1162.112	2.165911	1.951818	1.911434	1.94677	2.78189	2.408561
449	0.0063	1164.706	2.165911	1.954342	1.906386	1.941722	2.78189	2.400992
450	0.0063	1167.3	2.168439	1.949294	1.90891	1.944246	2.78189	2.406038
451	0.0063	1169.894	2.168439	1.951818	1.90891	1.944246	2.78189	2.400992
452	0.0063	1172.488	2.168439	1.951818	1.906386	1.941722	2.78189	2.411083
453	0.0063	1175.082	2.168439	1.956866	1.906386	1.941722	2.78189	2.406038

454	0.0063	1177.676	2.170968	1.956866	1.906386	1.941722	2.78189	2.403515
455	0.0063	1180.27	2.176024	1.954342	1.906386	1.94677	2.78189	2.408561
456	0.0063	1182.864	2.165911	1.954342	1.90891	1.951818	2.78189	2.406038
457	0.0063	1185.458	2.168439	1.956866	1.903862	1.941722	2.78189	2.408561
458	0.0063	1188.052	2.170968	1.956866	1.911434	1.94677	2.78189	2.408561
459	0.0063	1190.646	2.165911	1.954342	1.90891	1.94677	2.78189	2.411083
460	0.0063	1193.24	2.170968	1.954342	1.90891	1.941722	2.78189	2.406038
461	0.0063	1195.834	2.170968	1.951818	1.906386	1.944246	2.78189	2.403515
462	0.0063	1198.428	2.168439	1.954342	1.90891	1.94677	2.78189	2.406038
463	0.0063	1201.022	2.168439	1.951818	1.903862	1.941722	2.78189	2.400992
464	0.0063	1203.616	2.170968	1.951818	1.906386	1.939198	2.78189	2.403515
465	0.0063	1206.21	2.170968	1.956866	1.906386	1.939198	2.78189	2.411083
466	0.0063	1208.804	2.165911	1.956866	1.911434	1.944246	2.78189	2.411083
467	0.0063	1211.398	2.176024	1.956866	1.90891	1.939198	2.78189	2.411083
468	0.0063	1213.992	2.170968	1.95939	1.90891	1.944246	2.78189	2.411083
469	0.0063	1216.586	2.170968	1.954342	1.911434	1.941722	2.78189	2.408561
470	0.0063	1219.18	2.170968	1.961914	1.90891	1.944246	2.78189	2.408561
471	0.0063	1221.774	2.176024	1.956866	1.90891	1.944246	2.78189	2.408561
472	0.0063	1224.368	2.173496	1.95939	1.906386	1.949294	2.78189	2.408561
473	0.0063	1226.962	2.181081	1.95939	1.913958	1.944246	2.78189	2.406038
474	0.0063	1229.556	2.173496	1.95939	1.903862	1.94677	2.78189	2.408561
475	0.0063	1232.15	2.170968	1.961914	1.906386	1.944246	2.78189	2.408561
476	0.0063	1234.744	2.181081	1.956866	1.911434	1.944246	2.78189	2.408561
477	0.0063	1237.338	2.173496	1.95939	1.913958	1.94677	2.78189	2.408561
478	0.0063	1239.932	2.176024	1.95939	1.90891	1.941722	2.78189	2.408561
479	0.0063	1242.526	2.176024	1.966962	1.90891	1.94677	2.78189	2.413606
480	0.0063	1245.12	2.176024	1.95939	1.906386	1.944246	2.78189	2.408561
481	0.0063	1247.714	2.178553	1.961914	1.911434	1.941722	2.78189	2.416129
482	0.0063	1250.308	2.178553	1.961914	1.911434	1.944246	2.78189	2.416129
483	0.0063	1252.902	2.178553	1.964438	1.916482	1.944246	2.78189	2.413606
484	0.0063	1255.496	2.178553	1.964438	1.906386	1.949294	2.78189	2.416129
485	0.0063	1258.09	2.181081	1.966962	1.90891	1.94677	2.78189	2.413606
486	0.0063	1260.684	2.181081	1.964438	1.919006	1.941722	2.78189	2.413606
487	0.0063	1263.278	2.173496	1.964438	1.913958	1.94677	2.78189	2.416129
488	0.0063	1265.872	2.178553	1.969486	1.913958	1.954342	2.78189	2.426221
489	0.0063	1268.466	2.181081	1.961914	1.913958	1.954342	2.80711	2.426221

490	0.0063	1271.06	2.186138	1.964438	1.913958	1.954342	2.80711	2.433789
491	0.0063	1273.654	2.181081	1.969486	1.919006	1.954342	2.80711	2.433789
492	0.0063	1276.248	2.178553	1.969486	1.913958	1.954342	2.80711	2.428744
493	0.0063	1278.842	2.186138	1.969486	1.916482	1.954342	2.80711	2.431267
494	0.0063	1281.436	2.188666	1.966962	1.92153	1.951818	2.80711	2.433789
495	0.0063	1284.03	2.188666	1.97201	1.913958	1.951818	2.80711	2.426221
496	0.0063	1286.624	2.186138	1.97201	1.916482	1.954342	2.80711	2.426221
497	0.0063	1289.218	2.186138	1.969486	1.924054	1.956866	2.80711	2.431267
498	0.0063	1291.812	2.18361	1.97201	1.919006	1.951818	2.80711	2.433789
499	0.0063	1294.406	2.188666	1.974533	1.916482	1.95939	2.80711	2.426221
500	0.0063	1297	2.193723	1.97201	1.919006	1.951818	2.80711	2.426221
501	0.0063	1299.594	2.191195	1.97201	1.924054	1.954342	2.80711	2.426221
502	0.0063	1302.188	2.186138	1.977057	1.92153	1.951818	2.80711	2.426221
503	0.0063	1304.782	2.186138	1.97201	1.966962	1.979581	2.80711	2.413606
504	0.0063	1307.376	2.186138	1.977057	1.929102	1.951818	2.80711	2.428744
505	0.0063	1309.97	2.191195	1.979581	1.931626	1.954342	2.80711	2.428744
506	0.0063	1312.564	2.196252	1.977057	1.919006	1.939198	2.80711	2.428744
507	0.0063	1315.158	2.193723	1.979581	1.919006	1.931626	2.80711	2.426221
508	0.0063	1317.752	2.196252	1.987153	1.913958	1.936674	2.80711	2.4236698
509	0.0063	1320.346	2.196252	1.982105	1.916482	1.929102	2.80711	2.421175
510	0.0063	1322.94	2.19878	1.984629	1.92153	1.936674	2.80711	2.428744
511	0.0063	1325.534	2.19878	1.987153	1.924054	1.93415	2.80711	2.426221
512	0.0063	1328.128	2.201308	1.989677	1.919006	1.94677	2.80711	2.433789
513	0.0063	1330.722	2.203837	1.989677	1.926578	1.944246	2.83233	2.456495
514	0.0063	1333.316	2.203837	1.989677	1.919006	1.999772	2.857549	2.484246
515	0.0063	1335.91	2.224064	2.012391	2.047724	2.08558	2.95842	2.529654
516	0.0063	1338.504	2.219007	2.055296	2.037629	2.115863	3.034068	2.605331
517	0.0063	1341.098	2.246819	2.100722	2.067914	2.191568	3.134923	2.681002
518	0.0063	1343.692	2.272103	2.146146	2.148669	2.302593	3.235769	2.756669
519	0.0063	1346.286	2.304972	2.196615	2.224372	2.428744	3.361813	2.83233
520	0.0063	1348.88	2.350483	2.259698	2.30007	2.511995	3.513048	2.933203
521	0.0063	1351.474	2.413693	2.34044	2.383331	2.580106	3.639061	3.008853
522	0.0063	1354.068	2.487016	2.421175	2.428744	2.630555	3.739861	3.059282
523	0.0063	1356.662	2.557811	2.496859	2.491814	2.706225	3.840652	3.134923
524	0.0063	1359.256	2.608379	2.55488	2.55488	2.731447	3.916239	3.185347
525	0.0063	1361.85	2.658947	2.605331	2.605331	2.80711	3.991821	3.260979

526	0.0063	1364.444	2.734799	2.681002	2.681002	2.907986	4.067397	3.361813
527	0.0063	1367.038	2.785366	2.731447	2.756669	2.95842	4.168158	3.437433
528	0.0063	1369.632	2.81065	2.80711	2.80711	2.983637	4.243723	3.538252
529	0.0063	1372.226	2.886502	2.857549	2.857549	3.059282	4.369652	3.639061
530	0.0063	1374.82	2.962354	3.059282	2.983637	3.160135	4.470386	3.765059
531	0.0063	1377.414	3.164625	3.437433	3.134923	3.286188	4.57111	3.891044
532	0.0063	1380.008	3.442748	3.815455	3.412227	3.538252	4.697002	4.092588
533	0.0063	1382.602	3.695587	4.017013	3.639061	3.739861	4.848054	4.26891
534	0.0063	1385.196	3.897858	4.117779	3.840652	3.916239	4.973914	4.445203
535	0.0063	1387.79	4.049561	4.168158	4.017013	4.092588	5.124928	4.57111
536	0.0063	1390.384	4.125413	4.243723	4.092588	4.193347	5.275921	4.722179
537	0.0063	1392.978	4.201265	4.294096	4.168158	4.319282	5.426894	4.82288
538	0.0063	1395.572	4.251833	4.344468	4.319282	4.42002	5.552688	4.8984
539	0.0063	1398.166	4.327684	4.394837	4.495568	4.621468	5.653314	4.973914
540	0.0063	1400.76	4.403536	4.470386	4.646647	4.772531	5.728776	5.049424
541	0.0063	1403.354	4.454104	4.520749	4.747355	4.848054	5.804234	5.099761
542	0.0064	1405.948	4.529956	4.57111	4.747355	4.82288	5.854537	5.150095
543	0.0064	1408.542	4.555239	4.596289	4.722179	4.848054	5.904837	5.200427
544	0.0064	1411.136	4.605807	4.621468	4.772531	4.8984	5.980282	5.275921
545	0.0064	1413.73	4.631091	4.671825	4.797706	4.923572	6.030576	5.301085
546	0.0064	1416.324	4.681659	4.697002	4.82288	4.923572	6.030576	5.326248
547	0.0065	1418.918	4.706943	4.722179	4.848054	4.948743	6.00543	5.326248
548	0.0065	1421.512	4.732227	4.747355	4.873227	4.973914	5.955134	5.35141
549	0.0066	1424.106	4.782795	4.797706	4.8984	4.973914	5.929986	5.35141
550	0.0067	1426.7	4.808078	4.82288	4.923572	4.999085	5.904837	5.376572
551	0.0067	1429.294	4.833362	4.848054	4.948743	5.024255	5.879687	5.401733
552	0.0068	1431.888	4.88393	4.8984	4.999085	5.074593	5.854537	5.426894
553	0.0069	1434.482	4.934498	4.923572	5.024255	5.099761	5.829386	5.426894
554	0.0069	1437.076	4.959782	4.973914	5.049424	5.124928	5.804234	5.452054
555	0.007	1439.67	5.01035	4.999085	5.099761	5.150095	5.804234	5.477213
556	0.007	1442.264	5.035634	5.024255	5.124928	5.200427	5.804234	5.502372
557	0.0071	1444.858	5.060917	5.049424	5.175262	5.225593	5.804234	5.52753
558	0.0073	1447.452	5.111485	5.099761	5.200427	5.250757	5.804234	5.552688
559	0.0076	1450.046	5.136769	5.124928	5.225593	5.275921	5.829386	5.577845
560	0.0078	1452.64	5.162053	5.150095	5.250757	5.301085	5.829386	5.603002
561	0.008	1455.234	5.187337	5.175262	5.250757	5.326248	5.829386	5.628158

562	0.0082	1457.828	5.237905	5.200427	5.301085	5.35141	5.854537	5.653314
563	0.0083	1460.422	5.263189	5.250757	5.326248	5.376572	5.854537	5.678468
564	0.0083	1463.016	5.288473	5.275921	5.35141	5.401733	5.879687	5.703623
565	0.0084	1465.61	5.313756	5.301085	5.401733	5.452054	5.879687	5.728776
566	0.0085	1468.204	5.364324	5.326248	5.426894	5.452054	5.904837	5.75393
567	0.0085	1470.798	5.389608	5.35141	5.452054	5.502372	5.929986	5.779082
568	0.0086	1473.392	5.414892	5.401733	5.477213	5.52753	5.929986	5.804234
569	0.0087	1475.986	5.440176	5.426894	5.502372	5.552688	5.955134	5.829386
570	0.0087	1478.58	5.46546	5.452054	5.52753	5.577845	5.980282	5.854537
571	0.0087	1481.174	5.516028	5.477213	5.552688	5.603002	5.980282	5.879687
572	0.0088	1483.768	5.541312	5.502372	5.577845	5.628158	6.00543	5.904837
573	0.0088	1486.362	5.566595	5.52753	5.603002	5.653314	6.030576	5.929986
574	0.0088	1488.956	5.591879	5.552688	5.628158	5.678468	6.055723	5.955134
575	0.0089	1491.55	5.617163	5.603002	5.653314	5.703623	6.080868	5.980282
576	0.0089	1494.144	5.642447	5.603002	5.678468	5.728776	6.080868	6.00543
577	0.0089	1496.738	5.667731	5.628158	5.703623	5.75393	6.106014	6.030576
578	0.009	1499.332	5.693015	5.653314	5.728776	5.779082	6.131158	6.055723
579	0.009	1501.926	5.718299	5.678468	5.75393	5.804234	6.156302	6.080868
580	0.0091	1504.52	5.743583	5.703623	5.779082	5.829386	6.181445	6.106014
581	0.0091	1507.114	5.768867	5.75393	5.804234	5.854537	6.206588	6.131158
582	0.0091	1509.708	5.794151	5.779082	5.829386	5.879687	6.23173	6.156302
583	0.0092	1512.302	5.844718	5.804234	5.879687	5.929986	6.256872	6.181445
584	0.0092	1514.896	5.870002	5.829386	5.904837	5.955134	6.282013	6.206588
585	0.0092	1517.49	5.895286	5.854537	5.929986	5.980282	6.307154	6.256872
586	0.0093	1520.084	5.92057	5.879687	5.929986	6.00543	6.307154	6.256872
587	0.0093	1522.678	5.945854	5.904837	5.980282	6.030576	6.332294	6.282013
588	0.0093	1525.272	5.971138	5.929986	6.00543	6.030576	6.357433	6.307154
589	0.0094	1527.866	5.996422	5.955134	6.030576	6.080868	6.382572	6.332294
590	0.0094	1530.46	6.021706	5.980282	6.055723	6.106014	6.40771	6.357433
591	0.0094	1533.054	6.04699	6.00543	6.080868	6.131158	6.432848	6.382572
592	0.0095	1535.648	6.072273	6.030576	6.106014	6.156302	6.457985	6.40771
593	0.0095	1538.242	6.097557	6.055723	6.131158	6.181445	6.483121	6.432848
594	0.0095	1540.836	6.122841	6.080868	6.156302	6.206588	6.508257	6.457985
595	0.0096	1543.43	6.148125	6.106014	6.181445	6.23173	6.508257	6.483121
596	0.0096	1546.024	6.173409	6.131158	6.23173	6.256872	6.533393	6.508257
597	0.0096	1548.618	6.198693	6.156302	6.23173	6.282013	6.583662	6.533393

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598	0.0096	1551.212	6.223977	6.181445	6.282013	6.332294	6.608795	6.558527
599	0.028	1553.806	6.249261	6.206588	6.307154	6.357433	6.633928	6.608795
600	0.028	1556.4	6.274545	6.23173	6.332294	6.357433	6.633928	6.608795
601	0.0279	1558.994	6.299829	6.256872	6.357433	6.382572	6.659061	6.633928
602	0.028	1561.588	6.325112	6.282013	6.382572	6.40771	6.684193	6.659061
603	0.0279	1564.182	6.350396	6.307154	6.382572	6.432848	6.709324	6.684193

Appendix H

Motor Magnet Restraint

During this Delivery Order Professor Campbell taught a senior level design course in engineering. The interest of one of his students, Mr. Daniel DeHaye, was piqued by the problem of shrink fitting thin, metallic, non megnetic tubing over the rotor magnets to prevent them coming loose from the rotor especially during high speed motor operation (where failures have been reported occuring in other designs). Thus Mr. DeHaye pursued an investigation of this problem (albeit the 4 pole design) for his class project.

His final report is presented in this appendix. Only the color figures have been added to his original work to aid in interpretation. The ANSYS system used for this analysis is a dimension limited one resident on a Hewlett Packard machine at UAH. It will be seen that he has solved the problems of not only the stresses and strains but also of including the effects of rotation and the temperature to which it is required to heat the sleeve prior to placing it over the rotor. His results show this is a very feasible approach to magnet retention.

Mr. DeHaye's figure of 15-20% cost of Shuttle refurbishment due to hydraulics is too high. However it is substantial and a NASA effort to cut or eliminate it is actively underway.

Motor Magnet Restraint

ME 465

Final Report

3-12-93

David DeHaye

I. Problem description

This project is part of an effort by the Research Institute (RI) and the University of Alabama in Huntsville (UAH) to design a 3 inch permanent magnet motor. The objectives of my project were to define a methodology for the design of magnet restraints to be used on permanent magnet motors, and to use this methodology to design magnet restraints for the RI/UAH motor. The RI/UAH motor is designed to be used on an electromechanical thrust vector control actuator. The electromechanical system is intended to replace hydraulic systems that can be expensive to maintain. For example, each time a space shuttle is refurbished, 15-20% of the cost comes from the hydraulic systems. Therefore, my project will contribute to a design effort that could save a large amount of money. The magnet restraint is being designed to overcome problems with motors that use magnets that are bonded to the rotor using adhesives. The problem with using a motor that has glued on magnets is that at high rpm the centrifugal forces involved can cause the magnets to break free from the rotor at the bond line. The restraint being designed is a non-magnetic sleeve that will be shrink fitted over the magnets to hold them onto the rotor. By using finite element modeling (FEM), a shrink fit can be designed so that the magnets are always in compression at their bases. This will ensure that the magnets will not break free from the rotor.

II. Design options considered

When I started to work on this project, the method of restraint had already been decided. A non-magnetic sleeve will be shrunk over the magnets to hold them in place. However, the method of performing the design was not specified. There are at least three methods that could have been used to perform the design. It could have been done by hand, but this method might give inaccurate results and it would require that the entire process be

repeated for different motor configurations, such as a larger motor or a different number of magnets. The second method is to write a fill in the blanks computer program. This would be an automation of the process done by hand. The accuracy of the results would be no better, but once the program is written, the analysis could be repeated quickly for different motor configurations. The third method is to use an FEM computer program such as ANSYS. This method should provide accurate results and after the model is first defined, only a few lines of the input file will need to be changed to account for different variables. I chose to use ANSYS to do the design of the motor magnet restraint.

III. Reasons for selection of design method

I chose to do the design of the motor magnet restraint using ANSYS. There are a number of reasons why I chose this design method. I am familiar with the program, and the results are probably more accurate than the results I would get using other methods. Also, different motor configurations can be analyzed by changing a few lines in the input file. Another reason is that the shrink fit is easy to simulate using ANSYS. This is done by using an interface element that can specify an interference fit between two adjacent elements. These reasons lead me to believe that the use of ANSYS is the best method for doing the design.

IV. Design description

A. Design overview

Figure I shows what the cross section of a typical permanent magnet motor looks like. The magnets are glued to the rotor and can break loose at high rpm. This problem is going to be fixed by designing retaining sleeves that will be shrunk over the magnets to hold them onto the rotor. An element plot of the restraint and motor can be seen in figure

2. The bands of thin elements at the outside edge of the circle represent the retaining sleeve. The rest of the elements represent the magnets, the rotor, and the motor shaft.

The design of the retaining sleeve for the 3 inch RI/UAH motor was done using ANSYS. Titanium was used for the sleeve because it is light in weight, relatively stiff, non-magnetic, and has a high yield strength. I found that by using an interference fit of one part in a thousand, and a sleeve thickness of 1 mm, the magnets would stay in compression at their bases at 20,000 rpm. This setup gives a factor of safety of 6.5. This amount of interference will require that the sleeve be heated to about 110°C (200°F) above the temperature of the motor to do the shrink fit. This should be acceptable if the sleeve is always at the same temperature as the motor and magnets. If the temperature of the sleeve should raise above the temperature of the motor, the shrink fit could loosen. If this is a potential problem, the shrink fit could be made with a greater interference so that at operating temperatures it keeps the magnets in compression at their bases. I ran the problem using a 1 mm thick titanium sleeve and the interference that comes from a 210°C (380°F) shrink fit. The factor of safety for this configuration was 3.4. For both of these configurations, the magnets remain in compression at their bases, the factor of safety is good, the sleeve is adequately thin, and the shrink fit temperatures are reasonable. Therefore, a titanium sleeve of 1 mm in thickness should be adequate to retain the magnets on the 3 inch RI/UAH motor. Also, the use of ANSYS as the method for doing the design seemed to be successful.

B. Task descriptions

There were two tasks required to finish this project. The first was to write an input file for ANSYS to do the design of the restraint. The second was to run the program for various motor configurations and analyze the data that was generated by the program.

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The input file for ANSYS and a description of the variables that can be modified is shown in appendix A. In writing the input file I encountered mostly minor problems. The biggest problem that I had was in coming up with a way to simulate the interference fit between the sleeve and the motor. I discussed this problem with Dr. Campbell and he called the technical support people at ANSYS. They suggested that an interface element be used. This type of element is used between surfaces that can make and break contact with each other. The attractive feature of this element is that it allows for an interference to be specified between two adjacent elements. By placing these elements between the inside of the retaining sleeve and the outside of the magnets, a shrink fit can be simulated. To see if this type of element could be used to simulate a shrink fit, I tested it on a simple problem. The test problem was a press fit of a ring onto a shaft. The results obtained using ANSYS and the interface element were within five percent of the textbook answer. This convinced me that interface elements could be used to simulate the shrink fit of the restraint over the motor and magnets.

I ran the problem for several motor configurations and analyzed the output. The output is in the form of stress plots and stress tables. For each configuration the first step in analyzing the restraint system was to make sure that the magnets remained in compression at their bases. I did this by looking at the stresses for the nodes on the bases of the magnets. If the stresses in the radial direction are compressive for all of these nodes, then the magnets must be in compression at their bases. A listing of the stresses for the nodes at the base of the magnets in the 3 inch RI/UAH motor is given in appendix B. This listing is for a titanium sleeve that is 1 mm thick and has an interference of one part in a thousand. SX is the stress in the radial direction and the units are in pascals. Once it has been determined that the magnets are in compression at their bases, it is necessary to determine whether the sleeve can tolerate the stresses involved. For each configuration the maximum stress intensity is found by making a plot

of the stress intensity. A stress intensity plot for the 3 inch RI/UAH motor is shown in figure 3. The maximum and minimum stress intensities are marked by an MX and MN on the plot. To the side of the plot, the values for MX and MN are given in pascals. The factor of safety is determined by dividing the yield strength of the sleeve material by MX. In this case, titanium has a yield strength of 830 MPa. Therefore, the safety factor = $\frac{830.0 \text{MPa}}{127.8 \text{MPa}} = 6.5$, which is acceptable.

This design process was done for several other motor configurations. Some interesting results were obtained by doing this. For a motor that is roughly twice as big in diameter as the RI/UAH motor, the factor of safety using a I mm thick titanium sleeve was found to be 1.75. The interference fit had to be increased to about one part in 250 to keep the magnets in compression at their bases. This made the maximum stress intensity go up and the factor of safety go down. This also means that the sleeve would have to be about 420°C (750°F) above the temperature of the motor to do the shrink fit. These results indicate that the use of a shrink fitted retaining sleeve might be limited to smaller motors. I had one interesting problem in doing the analysis of the RI/UAH motor. The manufacturers data for the magnets gave a modulus of elasticity that was about one thousand times less than that of steel. I thought that this was too low and the company was called to find out whether a mistake had been made. They said that this was the correct value, so I ran the problem using this modulus of elasticity. A stress intensity plot of the motor and restraint showed that it had deformed into an almost square shape. This plot is shown in figure 4. Another call was made to the company and this time they said that the value given was a thousand times too low. This problem took about a week to resolve and it is a good example of why you should always check your data and facts.

C. Design integration

There were several constraints and requirements that had to be satisfied for the successful completion of this project, these are listed below.

1) The material for the sleeve has to be non-magnetic.

2) The sleeve must be as thin as possible so that the air gap of the motor is not affected.

3) The magnets should remain in compression at their bases.

4) The temperature required to perform the shrink fit should be low enough that the magnets will not be adversely affected.

5) The method used for the design should be adaptable to other motor configurations.

6) The RI/UAH motor should be able to withstand speeds up to 20,000 rpm.

D. Design safety

If the retaining sleeve were to fail in service it would cause the electromechanical thrust vector control actuator to stop working. This could result in a scrubbed flight or possibly even the crash of the vehicle that it was used in. In either case, the monetary cost would be very high. If the vehicle crashed, this could cause injuries or death. However, the design will probably go through a great deal of testing before it will ever be used on an actual launch vehicle. Therefore, if the retaining sleeve does fail, the costs will be limited to the cost of a prototype and the cost of testing.

V. Summary

I believe that the two main objectives of this project have been met. The first objective was to define a methodology for the design of magnet restraints to be used on permanent magnet motors. I did this by using ANSYS to do the design. It gives accurate results and it is easy to handle different motor configurations by changing the input file of the program. The second objective was to use this methodology to do a design of a magnet restraint for the 3 inch RI/UAH motor. I used ANSYS to design a restraint for this motor and determined that a 1 mm thick titanium sleeve will work. Therefore, I think that this project was a success. If I were to do it over again, I would not do it differently, but I could have used more time. With extra time I could have investigated the possibility of using a thinner sleeve.
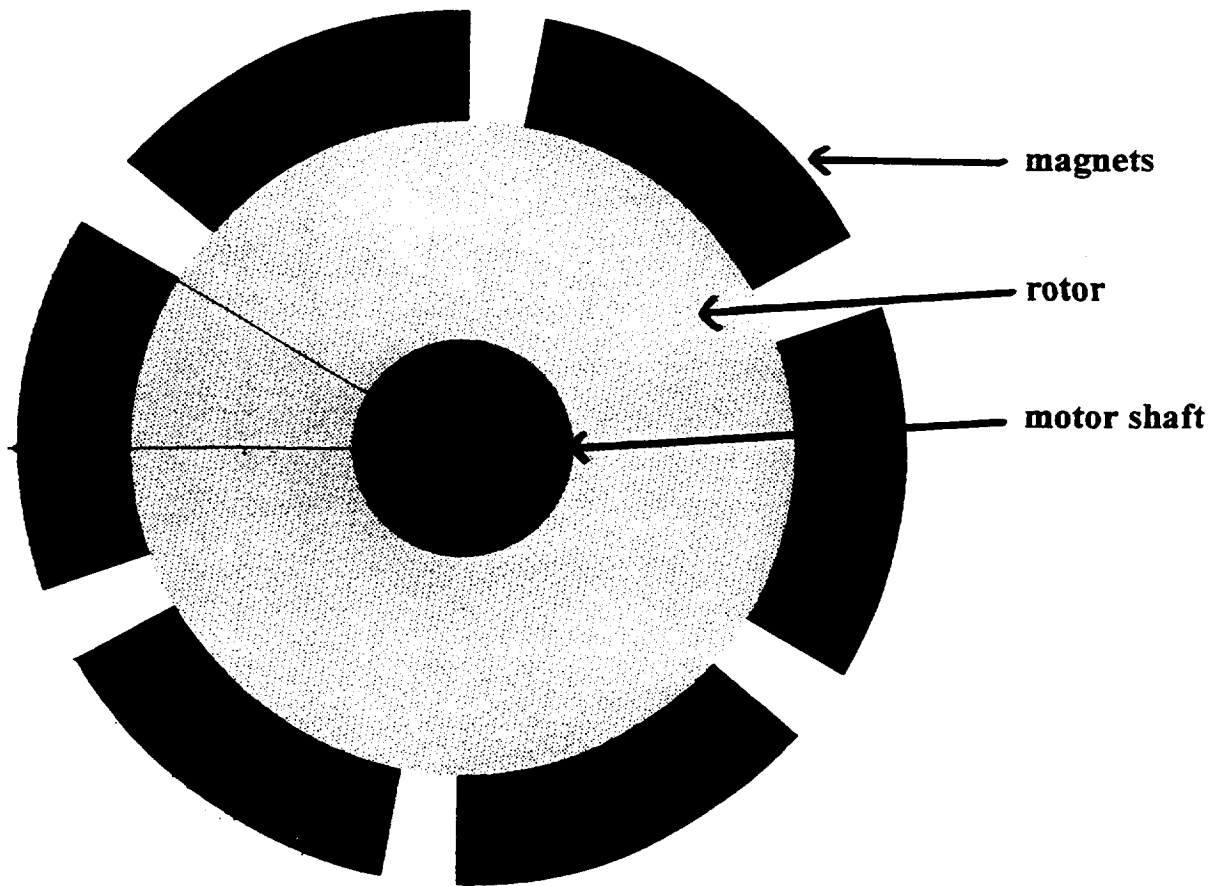
Figure 1.

Motor Cross Section
Showing Finite Elements
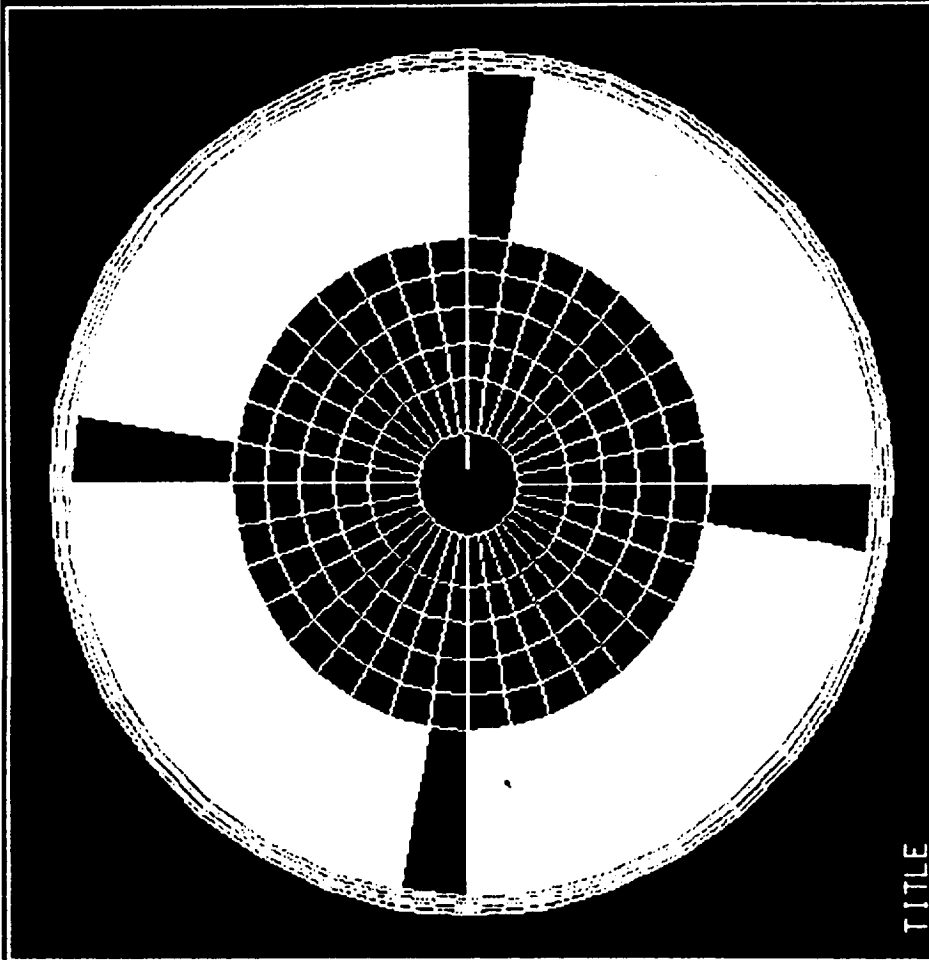
ANSYS 4.4A
MAR 5 1993
16:10:04
PREP7 ELEMENTS
MAT NUM

ZU =1
DIST=0.02288

TITLE
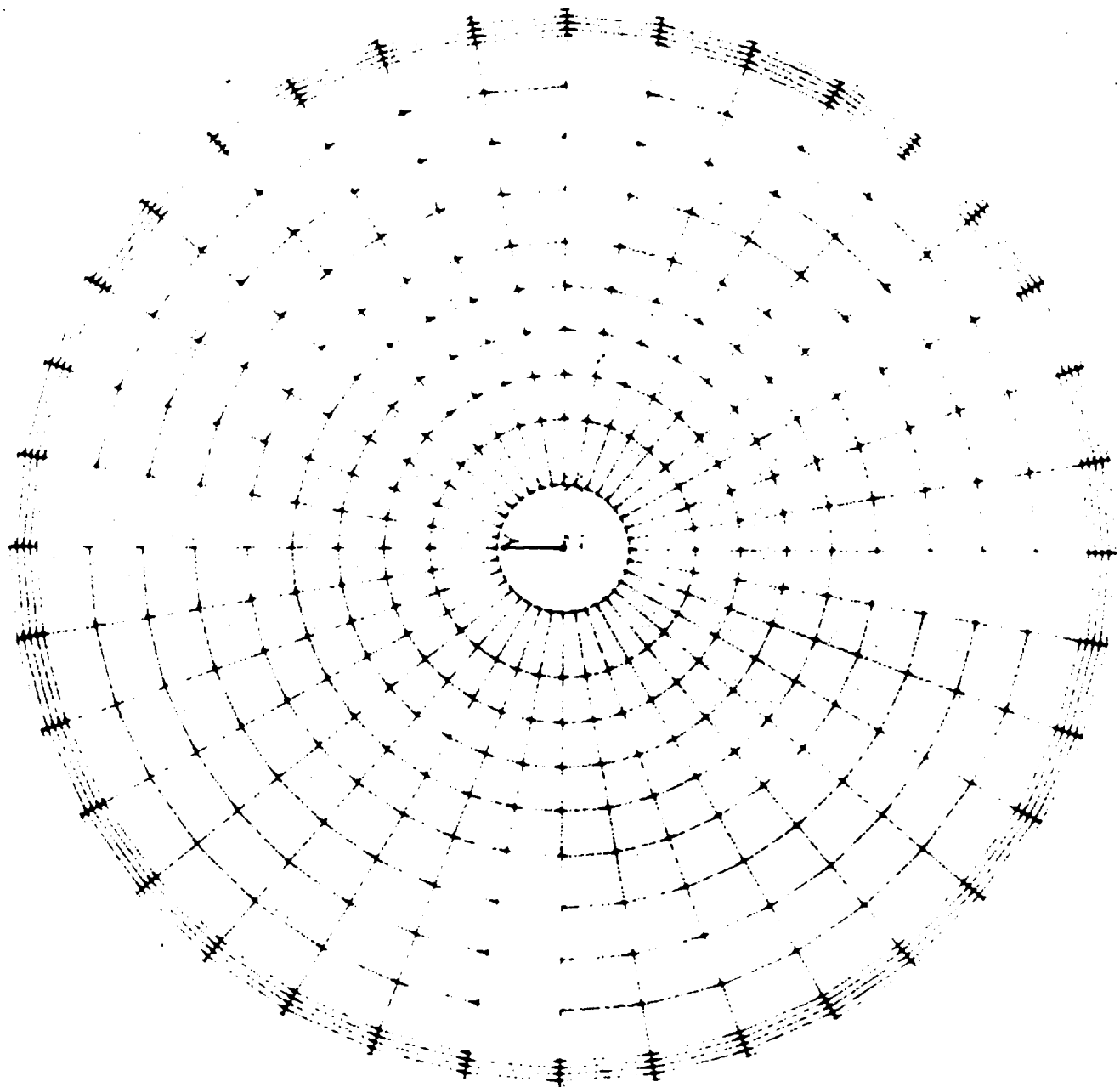
Figure 2.

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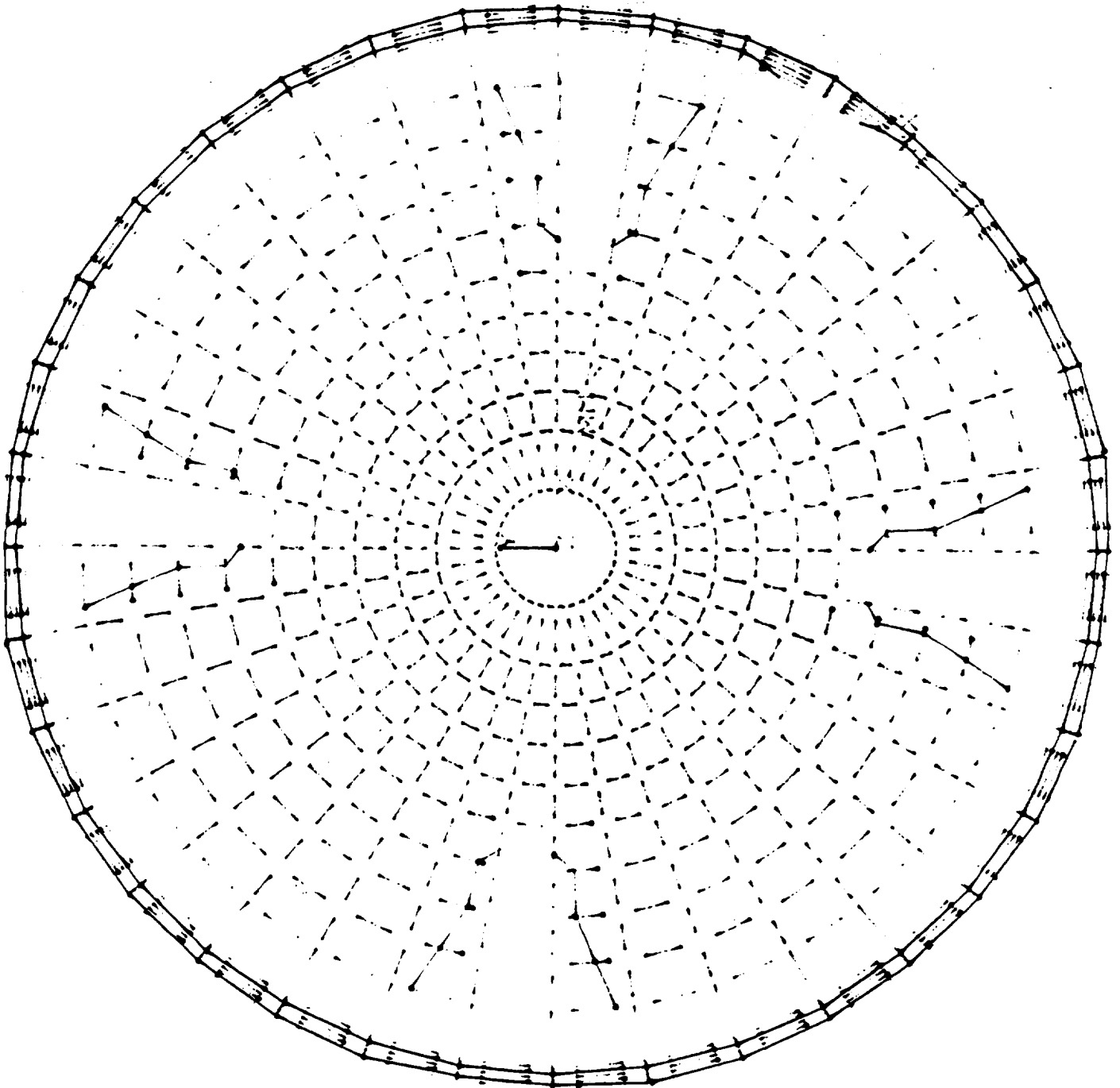
Figure 3.

Rotor Stress Plot

ANSYS 4.4A
MAR 24 1993
16:33:22
POST1 STRESS
STEP=1
ITER=10
SIGE (AVG)
DMX =0.196E-04
SMN =937961
SMX =0.112E+09
SMXB=0.124E+09

ZV =1
DIST=0.02288
937961
0.250E+07
0.500E+07
0.750E+07
0.100E+08
0.104E+09
0.108E+09
0.112E+09

MOTOR MAGNET RESTRAINT
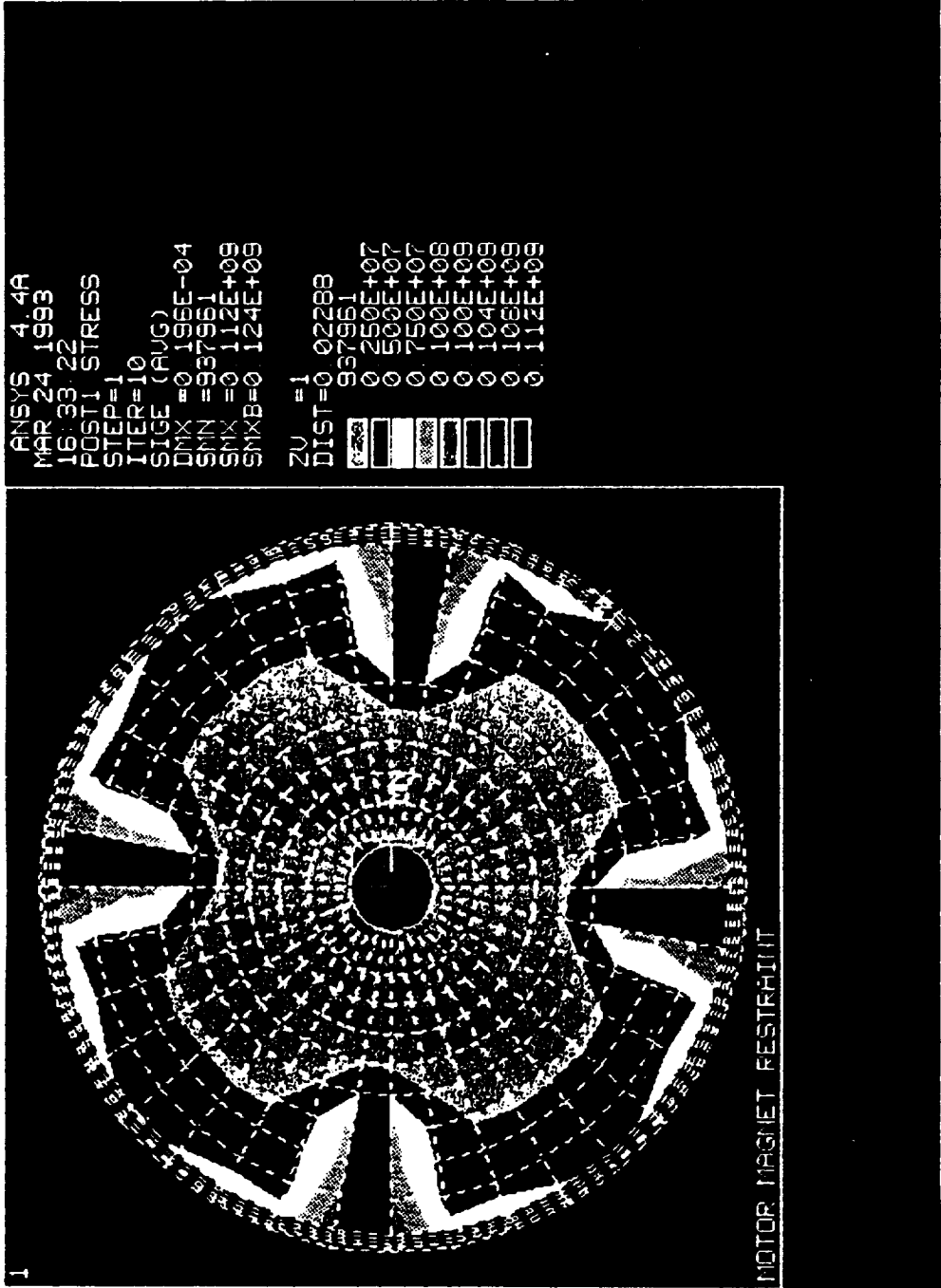
Enlarged View of Stresses In Titanium Sleeve
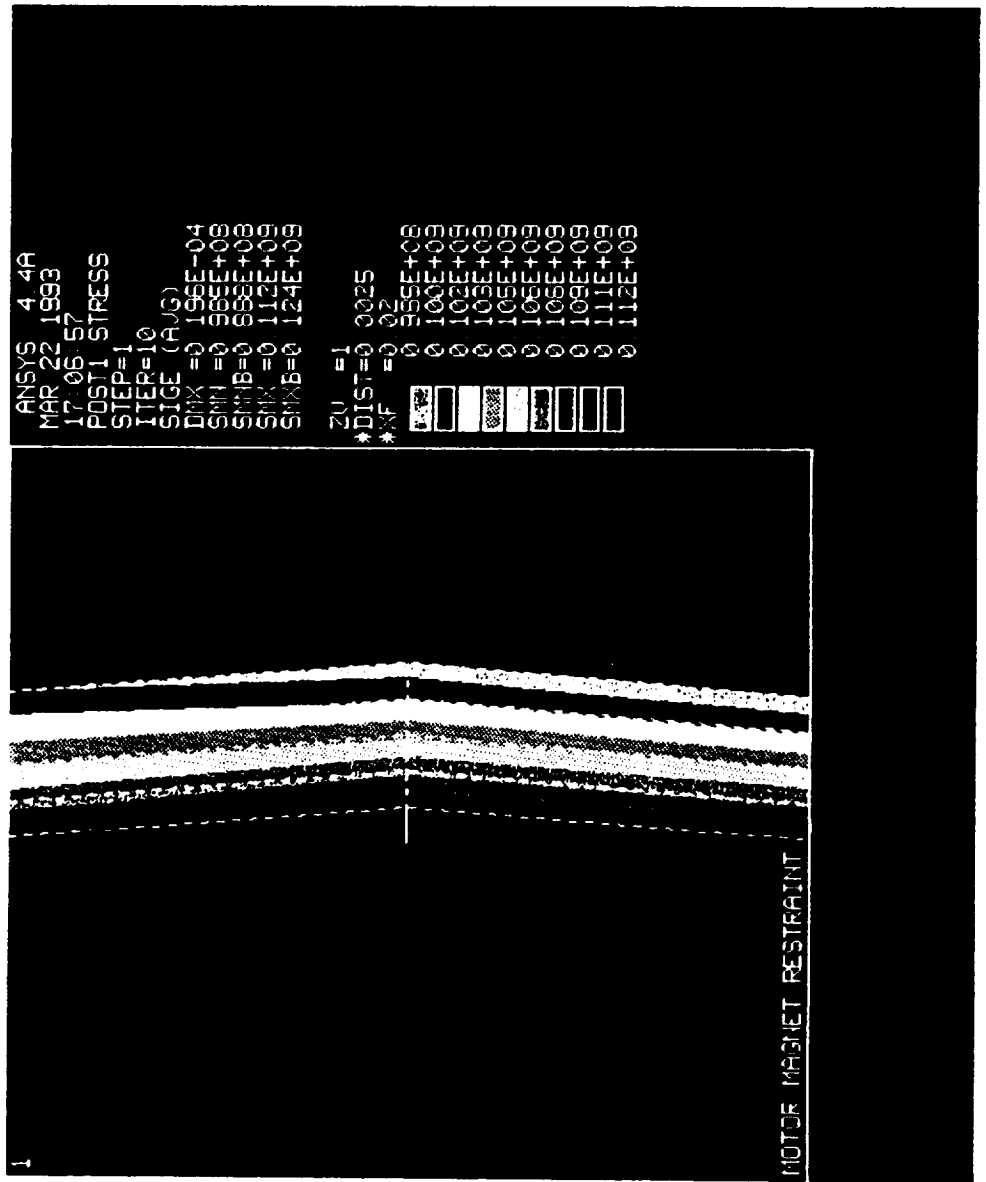
ANSYS 4.0
MAR 1 1991
18:45:17
POST1 STRESS
STEP=1
ITER=10
SI (AVG)

ZV=1
DIST=.027
MX=.99628226
MN=.368607
ICON=2
VMIN=33.55146
VINC=3308650
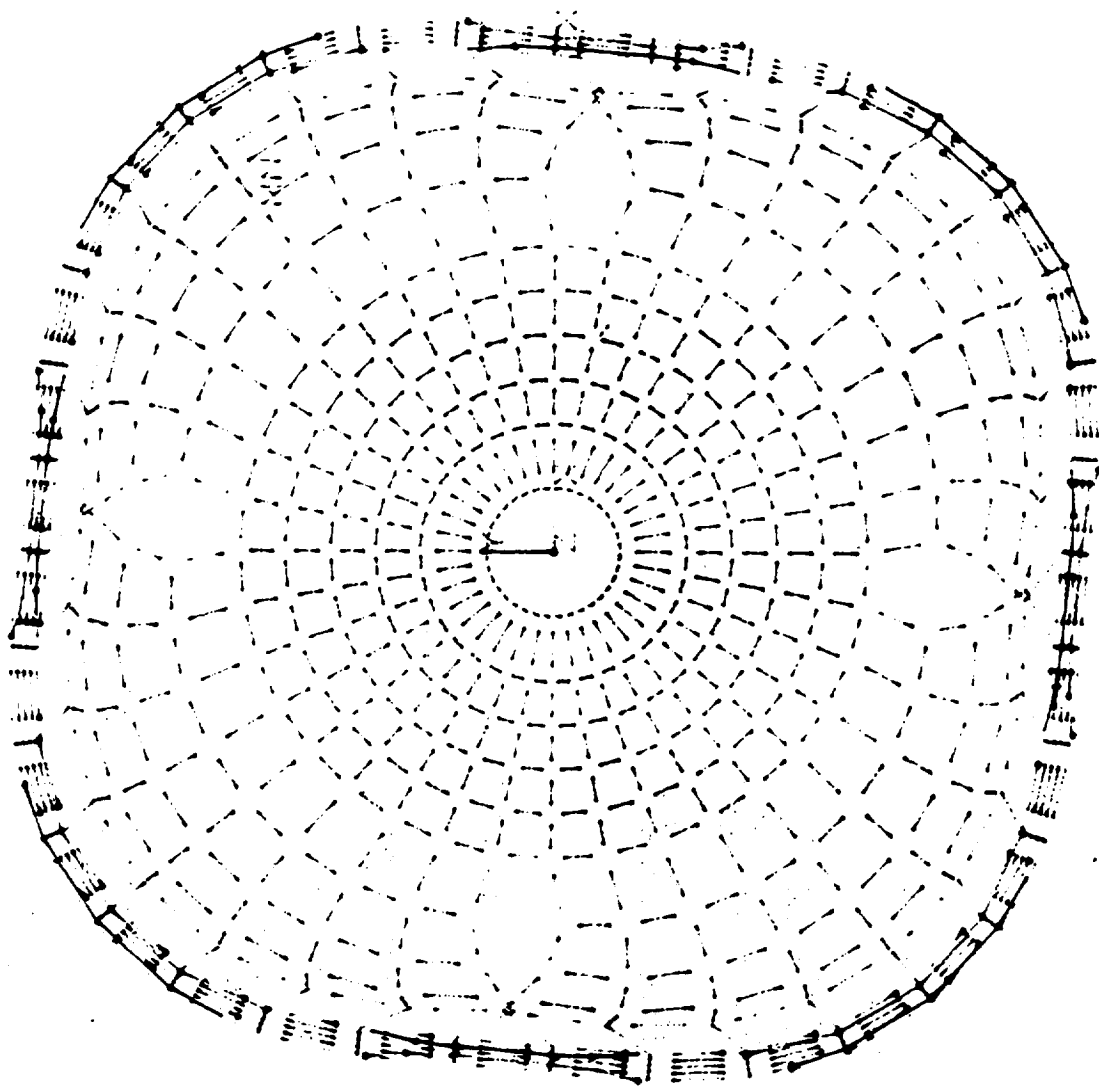
MOTOR MAGNET RESTRAINT

Figure 4.

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Appendix A.

Program listing

material properties.
EX = modulus of elasticity
DENS = density
NUXY = Poissons ratio

material 1 = motor shaft
material 2 = rotor
material 3 = magnets
material 4 = retaining sleeve

inner radius of the motor shaft.

radius of the motor shaft

radius from the center of the motor
shaft to the outside of the rotor

radius from the center of the motor
To the outside of the magnets

same as above plus a very small distance.

radius from the center of the moti
To the outside of the restrainin
sleeve.

amount of radial interference

```
OMEGA...[2005]
```

angular velocity of the motor in radians per second.

Appendix B.

Nodal stresses at magnet bases

LOAD STEP   1 ITERATION=   10 SECTION= 1
TIME=   .00000E+00   LOAD CASE= 1

THE FOLLOWING X,Y,Z STRESSES ARE IN COORDINATE SYSTEM   1

NODE	SX	SY	SZ	SXY	SYZ	SXZ	SIG
	SIG2	SIG3	SI	SIGE			
235	-.6214E+07	-.5086E+07	-.3188E+07	.8262E+06	-.1349E-05	.4942E-05	-.30
E+07	-.3555E+07	-.7882E+07	.4831E+07	.4604E+07			
240	-.6210E+07	-.5084E+07	-.3186E+07	-.8232E+06	.3258E-13	.1197E-12	-.30
E+07	-.3553E+07	-.7878E+07	.4029E+07	.4602E+07			
245	-.4694E+07	-.2517E+07	-.2016E+07	-.2422E+06	.3408E-06	.3743E-05	-.20
E+07	-.2440E+07	-.4771E+07	.2755E+07	.2574E+07			
250	-.3256E+07	-.2202E+07	-.1525E+07	.1295E+06	.2661E-06	-.2303E-05	-.15
E+07	-.2129E+07	-.3329E+07	.1804E+07	.1592E+07			
255	-.2691E+07	-.2036E+07	-.1321E+07	.1162E+06	-.1511E-06	.1283E-05	-.13
E+07	-.1980E+07	-.2747E+07	.1426E+07	.1238E+07			
260	-.2553E+07	-.1986E+07	-.1267E+07	4093.	.8751E-09	-.2748E-06	-.12
E+07	-.1957E+07	-.2581E+07	.1314E+07	.1146E+07			
265	-.2685E+07	-.2050E+07	-.1323E+07	-.1135E+06	.0000E+00	.0000E+00	-.13
07	-.1991E+07	-.2744E+07	.1421E+07	.1233E+07			
270	-.3262E+07	-.2220E+07	-.1532E+07	-.2068E+06	.3106E-06	.2599E-05	-.15
E+07	-.2142E+07	-.3339E+07	.1808E+07	.1594E+07			
275	-.4725E+07	-.2534E+07	-.2029E+07	.2356E+06	.4540E-06	-.5193E-05	-.20
E+07	-.2458E+07	-.4801E+07	.2771E+07	.2588E+07			
280	-.6278E+07	-.5098E+07	-.3209E+07	.8331E+06	-.1423E-05	.5243E-05	-.30
E+07	-.3586E+07	-.7930E+07	.4861E+07	.4629E+07			

MAXIMUMS
NODE	280	280	280	280	190	190	2
	280	280	280	280			
VALUE	-.6278E+07	-.5098E+07	-.3209E+07	.8331E+06	-.1472E-05	.5397E-05	-.3
0E+07	-.3586E+07	-.7930E+07	.4861E+07	.4629E+07			

LOAD STEP   1 ITERATION=   10 SECTION=   1
TIME=   .00000E+00   LOAD CASE=   1

THE FOLLOWING X,Y,Z STRESSES ARE IN COORDINATE SYSTEM   1

NODE	SX	SY	SZ	SXY	SYZ	SXZ	SIG
	SIG2	SIG3	SI	SIGE			
170	-.2553E+07	-.1976E+07	-.1265E+07	46.75	-.1607E-10	.4429E-06	-.1?
E+07	-.1949E+07	-.2581E+07	.1316E+07	.1147E+07			
175	-.2691E+07	-.2033E+07	-.1320E+07	-.1124E+06	.4808E-07	.5863E-06	-.1?
E+07	-.1978E+07	-.2746E+07	.1426E+07	.1238E+07			
180	-.3257E+07	-.2201E+07	-.1525E+07	-.1968E+06	.2957E-06	.2602E-05	-.1?
E+07	-.2129E+07	-.3329E+07	.1804E+07	.1592E+07			
185	-.4695E+07	-.2518E+07	-.2017E+07	.2447E+06	.4355E-06	-.4767E-05	-.20
E+07	-.2441E+07	-.4772E+07	.2756E+07	.2574E+07			
190	-.6215E+07	-.5089E+07	-.3189E+07	.8254E+06	-.1472E-05	.5397E-05	-.3?
E+07	-.3556E+07	-.7885E+07	.4833E+07	.4606E+07			
195	-.6215E+07	-.5089E+07	-.3189E+07	-.8256E+06	.1290E-16	.4729E-16	-.3?
·07	-.3557E+07	-.7885E+07	.4833E+07	.4606E+07			
200	-.4695E+07	-.2518E+07	-.2017E+07	-.2448E+06	.4367E-06	.4777E-05	-.2?
E+07	-.2441E+07	-.4772E+07	.2756E+07	.2574E+07			
205	-.3257E+07	-.2201E+07	-.1525E+07	.1967E+06	.3502E-06	-.3083E-05	-.1?
E+07	-.2129E+07	-.3329E+07	.1804E+07	.1592E+07			
210	-.2691E+07	-.2033E+07	-.1320E+07	.1124E+06	-.1689E-06	.2060E-05	-.1?
E+07	-.1978E+07	-.2746E+07	.1426E+07	.1238E+07			
215	-.2553E+07	-.1976E+07	-.1265E+07	59.76	-.2556E-10	.5511E-06	-.1?
?+07	-.1948E+07	-.2581E+07	.1316E+07	.1147E+07			
220	-.2691E+07	-.2033E+07	-.1320E+07	-.1123E+06	.3858E-07	.4712E-06	-.1?
E+07	-.1977E+07	-.2746E+07	.1426E+07	.1238E+07			
225	-.3256E+07	-.2200E+07	-.1525E+07	-.1965E+06	.2556E-06	.2253E-05	-.1?
?+07	-.2129E+07	-.3328E+07	.1804E+07	.1592E+07			
230	-.4694E+07	-.2517E+07	-.2016E+07	.2450E+06	.4721E-06	-.5160E-05	-.2?
E+07	-.2440E+07	-.4772E+07	.2755E+07	.2574E+07			

PRINT   ALL   NODAL STRESSES PER NODE

***** POST1 NODAL STRESS LISTING *****

LOAD STEP   1 ITERATION=   10 SECTION=   1
TIME=   .80000E+00   LOAD CASE=   1

THE FOLLOWING X,Y,Z STRESSES ARE IN COORDINATE SYSTEM   1

NODE	SX	SY	SZ	SXY	SYZ	SXZ	SIG
	SIG2	SIG3	SI	SIGE			
105	-.6160E+07	-.5080E+07	-.3171E+07	-.8160E+06	.1416E-05	.5185E-05	-.30
	-.3530E+07	-.7845E+07	.4808E+07	.4586E+07			
110	-.4669E+07	-.2505E+07	-.2006E+07	-.2497E+06	.4265E-06	.4550E-05	-.20
	-.2427E+07	-.4748E+07	.2742E+07	.2561E+07			
115	-.3250E+07	-.2188E+07	-.1519E+07	.1899E+06	.3459E-06	-.3335E-05	-.15
	-.2120E+07	-.3319E+07	.1799E+07	.1588E+07			
120	-.2691E+07	-.2023E+07	-.1317E+07	.1100E+06	-.1653E-06	.2064E-05	-.13
	-.1970E+07	-.2744E+07	.1427E+07	.1239E+07			
125	-.2555E+07	-.1969E+07	-.1263E+07	649.6	.0000E+00	.0000E+00	-.12
	.1943E+07	-.2581E+07	.1318E+07	.1149E+07			
130	-.2692E+07	-.2030E+07	-.1319E+07	-.1107E+06	-.2368E-07	-.2935E-06	-.13
	-.1975E+07	-.2747E+07	.1427E+07	.1239E+07			
135	-.3258E+07	-.2200E+07	-.1525E+07	-.1950E+06	.2537E-06	.2254E-05	-.15
	-.2129E+07	-.3329E+07	.1804E+07	.1592E+07			
140	-.4696E+07	-.2520E+07	-.2017E+07	.2464E+06	.3286E-06	-.3572E-05	-.20
	-.2442E+07	-.4774E+07	.2757E+07	.2575E+07			
145	-.6219E+07	-.5093E+07	-.3191E+07	.8272E+06	-.1164E-05	.4260E-05	-.30
	-.3559E+07	-.7890E+07	.4836E+07	.4608E+07			
150	-.6215E+07	-.5092E+07	-.3190E+07	-.8249E+06	.1144E-18	.4194E-18	-.30
	-.3557E+07	-.7886E+07	.4834E+07	.4607E+07			
155	-.4695E+07	-.2519E+07	-.2017E+07	-.2446E+06	.3994E-06	.4374E-05	-.20
	-.2441E+07	-.4773E+07	.2756E+07	.2574E+07			
160	-.3257E+07	-.2201E+07	-.1525E+07	.1969E+06	.3794E-06	-.3337E-05	-.15
	-.2129E+07	-.3329E+07	.1804E+07	.1592E+07			
165	-.2691E+07	-.2033E+07	-.1320E+07	.1125E+06	-.1464E-06	.1784E-05	-.13
	-.1978E+07	-.2746E+07	.1426E+07	.1238E+07			

APPENDIX I

Inertia Considerations

Mention has already been made in the main body of the report about inertia concerns. For ready refernece are listed immediately below the results of optimizing the motor, spur gear, roller screw configuration for maximum acceleration.

$$
\left(\left(1 \rightarrow \frac{ \mathrm{Sqrt}\left(\dfrac{4\ Jm\ \mathrm{Sqrt}(Jrs)}{\mathrm{Sqrt}(Jp)} + 4\ \mathrm{Sqrt}(Jp)\ \mathrm{Sqrt}(Jrs) + 8\ Jrs \right)\ PI }{ \mathrm{Sqrt}(J1) } \right., \right.
$$

$$
\left. n \rightarrow \frac{Jrs^{1/4}}{Jp^{1/4}} \right), \quad \left(1 \rightarrow \right.
$$

The various Js in the formulas represent the various inertis and reflected masses in the system. The spur gear ratio is denoted by n and the roller screw ratio by 1. See the original work for all the definitions. These results make it plain that the interrelationships are subtle.

The following material exerpted from the previous report is included to lend some heuristic insight into the foregoing relationships.

It has been stated elsewhere in this report that to obtain maximum possible performance from a motor, gear train and load combination it is necessary to match carefully the motor to the load by careful selection of a gear ratio between the two and then repeat the matching process for a number of differing motors to ascertain the best possible load acceleration performance. The results may be counter intuitive to a casual observer because in many minds it is natural to think in terms of the motor and its speed and acceleration rather than the speed and acceleration of the load. In the present design environment it is possible to select motors of the same rated horsepower with different available torque capacities because of different speeds at which the motors are rated (and they therefore have differing attendant polar mass moments of inertia) as well as being able to select independently the gear ratio(s). Thus in the present case only the load is a fixed quantity - and it is the load in whose motion one is intrerested. The results of this procedure are presented in this report for the multipass gear train case but a simpler example will perhaps help to cement the principles involved.

Consider the case of a motor coupled to a load by a simple one pass gear train. Now examine the accelerations of the motor and the load. The system inertia referred to the motor shaft will be given by

$$Jtm = Jm + Jl/n^2$$

while the system inertia referred to the load is given by

$$Jtl = n^2 Jm + Jl$$

Where n is a step down gear ratio from the motor to the load and is greater than one in magnitude, Jt denotes a total inertia either at the load (1) or the motor (m), JM is the motor rotor inertia and Jl is the load inertia.

The expression for the motor acceleration is given by

$$accel(m)=T/Jtm=T/(Jm+Jl/n^2)$$

and the load acceleration is

$$accel(1)=T\,n/(Jl+Jm\,n^2)$$

where T is the torque available from the motor.

Inspection of these expressions show immediately that to maximize the acceleration of a given motor n should be made as large as possible; in the limit the motor becomes uncoupled from the load (Jl/n^2 approaches 0). Finding the maximum acceleration of the load is a more tedious matter but if the derivative of the load acceleration is taken with respect to n and the results set to zero the results become

$$n=SquareRoot[Jl.Jm]$$

$$accel(1)max=T/(2\,SquareRoot[Jl\,Jm]).$$

Thus even in the simplest case finding the correct match of inertias through gear train ratio selection is more involved than maximizing the motor acceleration. And in this case for a given load different motors with different maximum torques and different inertias will

produce different maximum load acceleration (which is desired for maximum bandwidth or speed of response). In this maximized load acceleration case the acceleration of the motor will be (by simple substitution) expressed by

$$accel(m)=T/(2\ Jm)$$

which is certainly lower than could be achieved by a higher gear ratio (as n approaches infinity accel(m) approaches T/Jm).

It is hoped that the simple example discussed above will help the intuitive reasoning process concerning motor and gear ratio selection for a given load. Hopefully it lends insight into why the multipass gear case is somewhat involved to optimize with respect to load acceleration and motor-gear train selection, as has been done in this report.

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