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Conceptual Requirements of the Superconducting Linear Induction Motor

Office of Research and
Development
Washington, DC 20590

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Prepared in cooperation with
New York State Energy Research and Development Agency
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DOT/FRA/NMI-92/19

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Final Report

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CONCEPTUAL REQUIREMENTS OF THE SUPERCONDUCTING LINEAR INDUCTION MOTOR

FINAL REPORT

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16. Abstract

This study is a feasibility and conceptual design study of a superconducting linear induction motor for Maglev applications. Superconducting materials are maturing to the extent that a superconducting linear motor can be built with existing niobium titanium superconducting technology.

Several motors were considered, with and without iron. There are advantages and disadvantages of eliminating iron in the motor. The guideway is less costly if iron is removed, but magnetic shielding is required around the motor to protect the passengers.

Parametric studies for the motors were made of the input power requirements, resistive losses and cost and weight. The result is that superconductors can increase motor efficiency by reducing the resistive losses of the windings. However, there are power losses and additional operating costs associated with keeping the magnet cold (at cryogenic temperatures) due to AC losses in the superconductor and from cryogenic losses in the dewar. As a consequence of the associated support equipment, a superconducting linear motor for a Maglev train is not as efficient or as practical as a conventional copper iron motor.

The study also examines superconducting linear motor designs using futuristic high-temperature superconducting materials. High-temperature superconducting materials are less sensitive to AC losses and are more economical to operate. As a consequence, superconducting linear motors incorporating high-temperature superconducting materials are likely to offer the advantages of efficiency and light weight, especially for designs not requiring iron.

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SCLIM Final Report

1. Executive Summary

There has been a great resurgence of interest in efficient, high speed transportation systems involving magnetically driven and levitated trains. Most of these systems are designed with linear synchronous motors (LSM) as a means of propulsion. The synchronous motors have a DC magnet (permanent or superconducting) on board. The train is propelled by a traveling AC wave under or at the side of the vehicle, which is generated by windings imbedded in the guideway.

Another approach for propulsion is a linear induction motor (LIM) approach, whereby the propulsion is formed by inducing eddy currents in the guideway. In this case a traveling wave is formed under the train by primary windings on the vehicle. The appeal of a linear induction motor is that the guideway is completely passive and, as a consequence, less expensive than guideways required for other linear motors.

The purpose of this study is to determine the feasibility of a linear motor based on superconducting materials. Several motors were examined in the study including iron based and non-iron (air core) motors. The key features of a superconducting linear motor are:

1. No resistive losses
2. High current capability
3. Light weight (for air core motors only)

Superconducting motor designs with iron cores at room temperature proved the most practical. Motors with cryogenically cooled iron cores are shown to be impractical because of the core losses. The most advanced superconducting motors, the air core motors, could be realized if the AC losses of the superconductor could be improved.

The study also includes a systems weight and cost analysis. Low temperature superconductors for this application are not economical because of AC losses, the expense of helium refrigeration, and the complexity of the cryogenic containers. The conclusion of the study is that high temperature superconductors (HTS) would be more economical and could reduce the resistive (I^2R) losses, which would improve the performance and range of operation of the linear motor.

2. Introduction

The objective of the study is to explore the feasibility of using superconductors in linear induction motors for transportation systems. The hope is that superconductors offer a more efficient motor design and that the advantages of the superconductor, i.e., high current and field operation, may lead to more compact motors or motors which can operate over a larger gap.

The scope of work in the contract requires that a baseline configuration be chosen in collaboration with the Volpe National Transportation System Center (VNTSC) and that a superconducting linear motor (SCLIM) design concept be generated and documented to meet the requirements of that baseline system. This has been accomplished. Specifically, a baseline requirement has been established and a conceptual design has been generated which meets the baseline requirements.

The tasks performed in this study include:

1. Establishment of baseline requirements.
2. Determination of the materials required to implement the design.
3. Completion of a conceptual design to meet the baseline requirements.
4. Completion of a cost estimate for the conceptual design.
5. Determination of the interface requirements

These tasks fulfill the contractual requirements as outlined in section 4 of the contract DTF R 53-91-C-0066.

The study begins by describing the baseline requirements and how they were derived. It continues with a description of the technologies used and the respective design rules of these technologies. Some work was done in outlining the important motor parameters of interest. Four generic motor designs were examined in detail including:

1. Copper-iron design
2. Superconducting warm iron
3. Superconducting cold iron
4. Superconducting air core designs

The superconducting designs are based on low temperature multifilamentary cabled NbTi superconducting materials which are state of the art and available commercially. More advanced high temperature superconductive materials were also considered in the studies because of recent advances in the technology.

Considerable work was spent on analyzing the motor parameters and interface requirements. In the process of doing this work, an exact solution for the air core motor performance parameters was derived. The methodology, which is based on the Poynting vector, may have application in other motor designs.

For the iron core design, we used the guidelines for linear motor design established by Nasar [1]. Following a recommendation from VNTSC, a conventional copper linear induction motor was designed to serve as a benchmark to compare superconducting motors.

3. Baseline Maglev Linear Motor Requirements

3.1 Source of Requirements

After many discussions with VNTSC we formed a set of requirements for thrust and drag forces representative of an existing train. The train recommended by VNTSC as a good candidate for the design of a superconducting linear induction motor was the Transrapid TR07. Those requirements are taken from reference [2].

3.2 Thrust Requirement

The Transrapid TR07 propulsion LSM motor thrust specification is shown in Figure 1. The motor thrust follows a constant thrust curve until the speed increases to 50 m/sec, at which speed it follows a constant power curve. At low speeds the thrust is 56 kN and decreases to 38 kN at the peak velocity 134 m/sec.

Another requirement of the train requested by VNTSC is that it propel the train at 0.1 G up a 3.5% grade. This requires more thrust than produced by the TR07. To achieve this specification, the TR07 thrust given in Figure 1 was scaled up by a factor of 1.2 This scaling results in a thrust requirement shown in Figure 1 which is the key baseline requirement for the linear motor design in this study.

3.3 Aerodynamic and Magnetic Drag

The typical aerodynamic drag curve increases with speed as shown in Figure 2, which is a simple example based on an analysis by Draper [3]. The magnitude of the magnetic drag curve depends on the guideway geometry and conductivity and the type of levitation. An example of the magnetic drag for an electrodynamic system (EDS) guideway is shown in Figure 3. The EDS magnetic drag can be reduced by removing material and forming ladderlike structures, which have a higher lift to drag ratio than continuous sheets [4]. For this study, the drag is assumed to be for an electromagnetic system (EMS) which is lower than an EDS.

In addition to the aerodynamic and magnetic drag, there is generator drag, which amounts to a few kilonewtons [5]. The Transrapid system TR07 has a combined aerodynamic, magnetic and generator drag curve shown in Figure 1, which is the basis of this study.

3.4 Acceleration and Grade

The acceleration profile was derived from the net force profile plotted in Figure 4. The net force is computed from the thrust requirement minus the total drag identified in Figure 1. The grade was assumed to be a maximum of 3.5%. Using the mass of the TR07, which is approximately 45 tonnes (one vehicle), the acceleration was computed from the net force F_{net} and mass m using,

$$a = F_{net}/m.$$

A plot of the acceleration profile is shown in Figure 5. At low speeds the acceleration is 0.1 g at 3.5% grade and tapers down to 0 g at maximum speed. The effect on the acceleration due to the positive grades (upward) and negative grades (downward) are shown in the figure. The grade produces about 0.0347 G of additional acceleration or deceleration to the train.

The parameters that drive the motor design are the maximum speed and thrust profiles. These parameters, in addition to the slip at maximum velocity (hereafter referred to as "max slip"), determine the drive current, frequency and size of the motor.

4.0 Technology Basis

4.1 Superconductor Selection

In the initial phases of the program, a linear motor was designed using state of the art, low loss AC superconductors as a baseline. These materials are manufactured by Alsthome, an affiliate of IGC. In the final phases of the project, we included the use of HTS materials, particularly bismuth compounds, which have exceptional properties and hold promise for future improvement. Although these materials are still under development, it is expected that in a few years the current density at 77K will be high enough to allow them to be used for Maglev applications.

4.2 Low T_c Superconducting Material Properties

The low T_c material properties used in this report are based on the most recent data from AC loss measurements on high performance, small coils [6]. The critical current follows a modified Bean model [15] as shown in Figure 6. From this data, one can estimate the AC losses of a low T_c conductor using the approximate formula:

$$P \text{ (watts)/m}^3) = 400 * B * f$$

This formula is derived in Appendix I. For linear induction motor applications, the field at the windings is less than 2 Tesla. At fields of 2 T and lower, current densities of 10,000 amp/cm^2 have been attained successfully for medium sized AC coils [6]. This current density is consistent with superconducting magnet designs presented in the study which were based on cryogenic stability criteria [7].

4.3 HTS Superconducting Material Properties

HTS materials are progressing to the point where it is expected that practical devices using HTS will be viable in the near future. Historical data indicates that the critical current for HTS materials like BSCCO (Bi-Pb-Sr-Ca-Cu-O Bi 2223) shall reach 10,000 amps per cm^2 in a few years, as shown in Figure 7. At this level of current density, a superconducting linear motor could be practical.

There are several advantages for using HTS conductors, including the promise of

1. Lower cryogenic operational costs
2. Simpler cryostat design
3. Larger AC loss margins
4. Lower motor fabrication costs

4.4 HTS Leads

High temperature superconductivity has matured to the extent that prototype low loss power leads are being developed for conventional low temperature superconducting magnets

[8]. The leads dramatically reduce the liquid helium boiloff and heatload by reducing the I^2R lead losses in the region between 4K and 77K.

The HTS leads are shown in Figure 8. The leads are constructed by wrapping superconducting tape around stainless steel tubing, which serves as a thermal stabilizer and protects the superconductor in the event of a quench. During a quench the current transfers from the superconductor to the brass tube, protecting the magnet from arcing and the leads from burnout.

For AC operation, some improvements of this lead design can be made to reduce eddy current losses and heatloads in the stabilizing materials. One approach is to wrap the leads in a bifilar configuration. One can also use high resistance materials in or near the superconducting portion of the leads.

4.5 Cryogenic Design Guidelines

The guidelines for the cryogenic design and heatload estimates are based on experience that IGC and others have had in building cryostats and cryogenic magnets.

There are several ways to support the propulsion magnets including tunions, straps and cylindrical posts. In this study we have restricted the analysis to cylindrical support systems for simplicity. A very effective cylindrical support system has been developed for the SSC program [9]. This support consists of a series of convoluted tubes as shown in Figure 9. This support carries very high axial loads (20,000 pounds) and transverse loads up to 10,000 pounds. In this study the supports consist of a number of cylindrical support systems similar to those developed for the SSC, mounted to carry the thrust in the horizontal direction.

The heatload analysis in this study is based on the guidelines listed in Table 1. These design rules are conservative in the sense that actual magnets have performed better than these estimates would have predicted. The justification of using these more conservative numbers is that additional factors relating to a traveling vehicle, such as slushing, will lead to higher heatloads than expected.

4.6 Cryostat Design

In all the designs presented, the cryostats are assumed to consist of welded aluminum or epoxy containers with epoxy support structures. On the bottom of the motor, the oscillating magnetic fields are highly concentrated and there the dewar must be "transparent" to the fields. This means that thin ribbed aluminum (designed for supporting a vacuum) or epoxy should be used. We have identified this structure as an AC window.

4.7 Voltage Breakdown Requirements

Electrical leads in cryogenic containers which contain helium gas arc or break down at lower voltages than those in dry air or nitrogen [10]. A plot of the voltage breakdown limits in gaseous nitrogen and helium is shown in Figure 10. In practice the maximum voltage across motor power leads of a helium based cryostat should be as low as possible (preferably below 2200 V). This is a very difficult requirement for low T_c air core motors, which have large leakage reactances.

4.8 Refrigeration

For developing the refrigeration interface requirements, it is assumed:

1. A refrigerator is carried on board.
2. The refrigeration power, weight, and costs are computed using Figures 17 and Appendix IV, Figures IV-1 and IV-2, which are based on commercially available ground based units. (Using modern designs, IGC's APD Cryogenics division estimates the weights could be reduced by a factor of two.)
3. There is adequate power on board for the refrigeration system.

The SCLIMs based on low T_c conductors are assumed to be operating at 4.2K. At 4.2K, it it takes 1000 watts of refrigeration to cool one watt of heat load according to Figure 17. HTS SCLIMs by contrast require only 100 watts of refrigeration per watt of heat load at 77K.

5.0 Motor Parameters

5.1 Parameters of Importance to Maglev Linear Motors

The measure of a good motor is its weight and power requirements for a given output. The larger the motor, the more material it contains and the higher the cost. The train is also more expensive because of the additional lift required. Weight and power requirements are the most important Maglev performance parameters and they also drive the cost of the system.

5.2 Guideway

The guideway costs are of major importance in a Maglev system. For a linear motor, the guideway consists of (i) an aluminum conductor into which current is induced and (ii) a back iron for carrying flux. For the air core system the back iron may or may not be necessary. For air core systems without back iron, the cost of the guideway can be greatly reduced compared to conventional iron core designs.

5.2.1 Gap

The guideway cost is influenced by the gap. The larger the gap, the less critical are the guideway tolerances and the lower the guideway costs.

The size of the motor and motor power are also driven by the gap size. As the gap increases, the motor power increases, as shown in Figure 11.

5.2.2 Track Thickness

Another factor which influences the cost of the guideway is the track thickness, which determines the volume of track conductor (usually aluminum). The track thickness also determines the drive current and power of the motor. For thin tracks the motor requires more input KVA than for thick ones, as shown in the parameter plots in Figure 12.

5.2.3 Backing Iron Thickness

For iron core designs, enough iron is required above and below the motor to pass the flux through the pole without saturation. The flux enters the backing iron and splits into forward and backward return paths. The higher the flux design, the larger the cross section and weight of iron required. Efficient designs have the minimum flux per pole.

5.3 Vehicle Cost

The impact of the motor weight, capital and operational costs on the vehicle cost is significant. An SCLIM costs more than a copper LIM because of the expensive cryogenic package surrounding the superconductor. A low T_c cryostat is more expensive than a high T_c cryostat because of the added complexity of helium refrigeration. The hope of using HTS materials is that the motor cost and complexity would be reduced by using liquid nitrogen cryogenics.

The operational cost tradeoff is not so clear. The largest operational expense of the copper linear motor is power. Superconductors reduce the copper I^2R losses and hence reduce the motor power requirements but also add a cryogenic cost. The cost of cryogenics appears as added costs of refrigeration or cryogenic fluids. The economics of the SCLIM hinge on the possible power savings and efficiency of the AC superconducting state, including refrigeration.

5.4 Power Factor

In addition to parameters which affect the operational cost directly such as total input power KVA, the power factor is very important for power generation and transmission efficiency. Power factors near unity are desired by the utilities. Systems whose power factors are appreciably smaller than one or that vary as a function of velocity should be compensated with load matching networks. Power stations usually cannot tolerate large fluctuations in power factor and will charge exorbitant rates if required to do so.

5.5 Weight

The added weight to a Maglev vehicle due to the LIM will consist of the weight of the motor, the power system and ancillary equipment. For the superconducting LIM, the ancillary equipment includes cryogenic refrigeration equipment. The power system weight is assumed to scale with the motor input power requirements and the refrigeration weight scales with the heatloads. The total weight of the motor system should be minimized to reduce the lifting requirements and the vehicle cost.

5.6 Size

For the purposes of this study, the size of the SCLIM should be small enough so that it can fit within the length of the Transrapid vehicle, which is 25 meters. The size of the train is determined by the synchronous speed and number of poles. In this study the number of poles was fixed to 8, which is long enough to minimize end effects [1].

5.7 Performance Parameters

In our parameter studies we have investigated the goodness factor, motor weight, input power and motor losses as measures of the motor performance.

5.7.1 Goodness Factor

The conventional definition of goodness factor is usually the ratio of the secondary reactance to the resistance. Goodness factors of 25 are usually indicative of a good motor [11]. Plots of the goodness factors are shown in Figure 13 for SCLIMs with core.

5.7.2 Motor Losses

There are several sources of motor losses including:

1. Conductor Losses.

   These are resistive losses in the copper designs and AC losses in the superconductor designs. The AC losses of the superconductor are worsened by the refrigeration requirement which adds more power and cost to the system. If refrigeration is on board, it appears as an additional load on the power system. If the refrigeration is ground based, then the cost of cryogenic liquids and their maintenance adds to the overall operational cost of the vehicle.

2. Core Losses.

   For linear motors with iron cores, there are two sources of loss form the core: eddy current loss and magnetic hysteresis loss. In conventional warm iron magnets, this loss is usually small compared to the input power. At low temperatures the eddy current losses will increase because the conductivity of the laminates will increase. We assume for this study the hysteresis losses are independent of temperature.

   In cold iron designs, the core losses become very significant because they add to the heatload at low temperature. A small amount of heating tolerable at room temperature becomes intolerable at low temperatures. The net effect is that additional refrigeration is required on the vehicle to keep the motor at cryogenic temperatures. If cryogenic liquids are used, then the cost and maintenance of the additional cryogens adds to the overall operational cost of the system.

5.8 Drive Strategies

Linear motors can be driven at constant frequency or at variable frequency. In the constant frequency mode, the thrust can be controlled by varying the motor current. The power systems for constant frequency motors are less demanding and power factor adjustments can be made with fixed components. This is particularly important for motors which have very low power factors. However, VNTSC's experience indicates that variable frequency operation may be the better choice because of motor efficiency and excessive track eddy heating which can lead to track buckling. Our analysis confirms that several megawatts can be transferred to the track via eddy current heating on start up with a constant frequency drive. We have therefore restricted our studies to variable frequency operation. The slip is adjusted so that the relative velocity between the vehicle and the synchronous velocity is held constant. The slip curves assumed in this study are shown in Appendix V, Figure V-1. In this mode of operation, the current is kept almost constant throughout the operating range, rising 25% at the lowest speeds.

6. Copper Iron Core Design

The first linear motor conceptual design chosen was a conventional copper linear motor, which was used as a benchmark to compare the performance of SCLIMs. The copper iron core design methodology follows that outlined by Nasar [1] and is described in Appendix II.

6.1 Design Assumptions

The copper iron motor design is based on the following assumptions:

1. The motor must meet the thrust requirements at all speeds.
2. The motor length is less than 10 meters, which is the maximum space assumed available in the vehicle.
3. The maximum frequency of operation of the motor considered was 180 Hz. The frequency of 180 Hz was thought to be low enough to take advantage of available commercial power equipment and also low enough to accommodate AC losses in superconductors, which increase dramatically at higher frequencies. Two motor designs were studied in detail, a 60 Hz motor and a 180 Hz motor.
4. The track thickness was assumed to be 3 mm unless otherwise stated. This was made small to reduce guideway costs.
5. The gap was assumed to be between 5 cm and 15 cm. The term "gap" as it appears in this study in this study refers to the gap between the iron in the motor and the back iron of the guideway.

6. The voltage available to drive the motor is restricted to 2200 rms volts three phase, so that no unusual high voltage insulation is required.

7. The copper current density is assumed to be 500 amps/cm^2, which is an aggressive design.

8. The number of poles of the motor is assumed to be eight. This is an adequate number of poles such that end effects can be neglected.

9. A three phase winding is assumed for simplicity. The phasing is described in Appendix III, Figure III-1. (The iron core designs and the air core designs have the same phasing.)

10. The slip is assumed to be 0.07 at maximum velocity unless otherwise specified.

11. The motor is operated at variable frequency, variable slip, constant relative velocity mode.

6.2 Parametric Study

The performance of various copper iron motors is presented in Appendix V, Figures V-I to V-27. In these plots, the intrinsic design parameters, such as the design frequency, gap, track thickness, and other motor parameters are varied. The performance is examined as a function of speed.

The length of the motor as a function of design slip and maximum design frequency (Fm) is shown in Figure V-2. As the plot indicates, as the slip is decreased the motor length is shortened. A slip of .07 has been selected for the design and it leads to a reasonable motor size. The plot also indicates that maximum frequencies below 60 Hz are not feasible unless the number of poles are reduced. The 60 Hz motor is longer than the 180 Hz motor.

The current demand on the motor as a function of velocity is shown in Figure V-3. The motor current is almost independent of speed, rising slightly at low speeds to accommodate the thrust curve in Figure 1. A LIM designed at 60 Hz requires less current than a 180 Hz motor.

6.3 Design Description

A typical copper iron linear induction motor conceptual design is shown in Figure 14. The motor consists of a three phase winding made of copper with slots in the iron. The iron core consists of 0.014" low loss iron laminates. Several motors were designed and are listed in

Appendix II, Tables II-1 through II-9. Summaries of designs at 60 Hz and 180 Hz with 10 cm and 15 cm gaps are shown in Table 2 and 3, respectively. The motors with a 10 cm gap are used as baseline designs for the copper iron and warm iron designs.

6.4 Interface Requirements

The interface requirements of both the 60 Hz and 180 Hz motors with a 10 cm gap are shown in Table 2.

The 60 Hz motor requires 135 kW cooling and draws 7.65 MVA at a maximum speed of 134 m/sec. The motor requires 2200 Vrms at 2007 Amps three phase and has a power factor of 0.78 at maximum speed.

The 180 Hz motor is similar to the 60 Hz motor except that the I^2R losses are lower, 80.3 kW as compared to 38.2 kW. The motor draws more power and requires higher current (2863 amps as apposed to 2007 amps) and has a power factor of 0.55.

6.5 Conclusions

Of the two motor designs studied in detail, the 180 Hz copper iron motor is lighter and smaller, but the 60 Hz motor is less expensive. Both the 60 Hz and 180 Hz motors can be used for comparison with their superconducting counterparts. The 180 Hz motor has a lower power factor and may need power factor compensation.

7. Warm Iron Designs

Two concepts for warm iron SCLIM were examined, an axial and transverse design. The axial warm iron design concepts were formed by replacing copper with superconductors in such a way that the iron is retained at room temperature. The magnetic designs of the copper iron and warm iron designs are very similar in design and performance.

The transverse design is a very practical design for fitting cryostats around iron cores, but it requires more iron than the axial design. As a consequence, the motor is not very useful for Maglev applications and was not considered in detail.

7.1 Design Assumption

The assumptions for the axial motor design are identical to the conventional copper iron LIM with the exception of the current density. A current density of 10,000 amps/cm^2 was assumed for the superconductor design. Because of the geometry, there is no penalty paid for the motor in terms of gap assuming the top iron cross section is sized large enough to carry the flux.

For the cryogenics it is assumed that the superconductor is operated at 4.2K and that HTS power leads are used to reduce the heatload at 4.2K.

7.2 Design Description

The axial warm iron design is shown in Figure 15. In Table 4, the warm iron design is compared to the copper iron design with a 10 cm gap.

The cryostat contains several vessels, a 4.2 K vessel which supports the superconductor and a helium storage region surrounded by a vacuum vessel and a liquid nitrogen jacketed reservoir. The entire cryostat is fabricated out of nonmetallic epoxy fiberglass composites, which eliminate eddy currents. The vessels in contact with helium have a thin layer of aluminum coating on the epoxy to prevent helium leakage. Cylindrical supports located at the outer boundary of the package suspend the entire superconducting winding bundle.

The winding consists of a multifilamentary superconductor wound and potted with reinforced epoxy fiberglass. The winding is a self standing structure attached to a liquid helium reservoir.

The AC losses of the superconductor are 24.7 W compared to 80.3 kW for I^2R losses in an equivalent copper motor.

7.2 Advantages and Disadvantages

There are several advantages of the warm iron design. Most of forces are transmitted through the iron and not the superconductor. Core losses are at room temperature and are low enough that they can be cooled with a chiller if necessary.

The disadvantage of this approach is that large slots must be cut into the iron to fit the cryostats which surround the superconductor. Extra iron must be added to compensate for the cuts to prevent saturation in the iron. The cryostat in this configuration is very tight fitting and requires very accurate and precise assembly to avoid thermal shorts in the vacuum spaces.

7.3 Interface Requirements

The 60 Hz warm iron SCLIM requires 7.65 MW and has a power factor of 0.78. In addition to this power 48 watts of refrigeration are required at 4.2K. Refrigeration systems require about 1000 watts to provide enough cooling at 4.2K (see Figure 17). This amounts to 48 kW of refrigeration power added to the power system. The voltage required to drive the motor is 2200 volts rms three phase. High temperature superconducting power leads have been assumed in the design to reduce the heatload.

7.4 Conclusions

A 60 Hz warm iron configuration for a SCLIM has been conceived which is similar in design to the copper iron core LIM. The design is practical but requires a very compact cryostat. The overall power requirements are about 87 kW lower than for a copper motor.

8. Cold Iron Design

A conceptual design for a cold iron SCLIM has been completed. The design is based on the fact that magnetic properties of iron are not very sensitive to low temperatures [12]. As a consequence the same methodology and design rules can be applied as in the case of the copper iron LIM.

8.1 Design Assumptions

The design assumptions are similar to those for the copper iron design with the following exceptions:

1. The current density is assumed to be 10,000 amps/cm^2 as in the warm iron SCLIM.
2. The cryostat requires material between the iron on the vehicle and the bottom of the train. The "effective gap" is held constant when comparing motors. The "effective gap" is defined as the real clearance between the bottom of the motor and the guideway. As a consequence, the gap for the cold iron motor is larger than the copper iron LIM or warm iron SCLIM.

3. The superconductor is operated at 4.2K and HTS power leads are attached to reduce cryogen consumption.

8.2 Design Description

The design for a cold iron SCLIM is shown in Figures 18 and 19. The design consists of a superconducting LIM packaged in a liquid helium cryostat. The motor is supported by cylindrical supports at each end. The supports are sized to carry the thrust of the motor as well as the weight of the iron core and superconductor. Both horizontal and vertical supports are shown. Because the horizontal support is very large (supporting the motor thrust), it can also carry the weight of the iron, eliminating the need for large vertical supports.

The cold mass consists of a three phase superconducting winding potted in a slotted iron core. The iron core is constructed of very thin laminate (0.014") to reduce eddy current losses.

The cryostat consists of an aluminum outer casing on the top and sides and a fiberglass AC window which allows flux to freely penetrate through the bottom without inducing eddy currents. The cryostat has provisions for liquid helium and liquid nitrogen vessels as well as a 20K shield to reduce the radiation losses. Five centimeters has been reserved for the cryostat bottom, which is adequate space for the shields and insulation.

The outer aluminum wall serves two purposes: (i) as a vacuum wall and (ii) as a magnetic field shield to attenuate the stray AC fields which emanate from the motor. (The AC fields are small because of the iron design, so the AC fields do not complicate the cryostat design.)

8.3 AC Losses in Cold Iron Superconducting Windings

The AC losses in the 60 Hz cold iron design run about 26.7 watts. as shown in Tables 5 and 6. This corresponds to a refrigeration load of 26.7 kW as indicated in Figure 17.

8.4 Cold Core Losses

The core losses are very important in the cold iron SCLIM because they represent a major heatload at cryogenic temperatures. In the case of a practical laminate (0.014") the losses at room temperature are 55 kW. At helium temperature the losses are estimated to be over 5 megawatts and are mainly due to eddy current losses which increase as the conductivity of iron increases at lower temperature. The magnetic hysteretic losses of the cold iron at 4.2K are very similar to those at room temperature [12].

Other cores such as ferrites could be considered for low temperature operation. Ferrite materials cannot be driven as hard as iron since they saturate at 0.4 T as opposed to iron, which saturates at 2 T [13]. Ferrites are brittle ceramics and require some reinforcement to prevent cracking under load. Ferrites have losses which are much smaller than iron (about a factor of 30) but not enough smaller that they can be neglected. A 60 Hz ceramic ferrite core SCLIM would have 175 kW of core loss at 4.2K, a huge heat load.

8.5 Conclusions

The cold iron SCLIM is not very practical because of the enormous heatloads due to core loss. Even with advanced ferrites the heat loads in a low T_c or high T_c motor would require megawatts of refrigeration.

9. Air Core Designs

To reduce the core losses and to eliminate the back iron in the guideway, a conceptual design for an air core motor was intitiated. The motor design is based on the analysis listed in Appendix III.

9.1 Design Assumptions

The design assumptions are similar to the copper iron core LIM and other iron core SCLIMs with the following comments:

1. The field at the windings are higher in the air core case than in the iron case for any equivalent geometry. This leads to higher AC losses.
2. The superconductor is operated at a higher field but the same current density is used. 10,000 amps/cm^2. This is a more aggressive design than used with other iron core SCLIM.
3. The cryostat is completely non-metallic.
4. The superconductor is assumed to be a low T_c conductor and a helium based cryostat is assumed.
5. The superconductor is operated at 4.2K and HTS power leads are attached to reduce cryogen consumption.

9.2 Design Description

A conceptual design of an air core SCLIM is shown in Figure 20, which includes the guideway back iron. The air core cryostat is identical to the cold iron core cryostat, except the iron core and aluminum casing are replaced by reinforced fiberglass composite forms to eliminate core losses and eddy current losses. The three phase superconducting winding is potted in a non-metallic composite form. The air core SCLIM windings require more structural support than the iron core designs because the full thrust of the motor is felt by the windings. (In the iron core designs, the forces are carried by the iron.) The supports used are cylindrical as in the cold iron SCLIM.

9.3 Interface Requirements

The air core motor requires more current and superconductor than the iron core motor. Details of a 60 Hz air core motor parameters with and without guideway back iron are shown in Tables 7 and 8, respectively. High temperature superconducting power leads will be required to reduce the heatload.

The air core motor with back iron requires 1006 volts rms at 5960 kA. The heat load at 4 K is 132 watts, adding approximately 132 kwatts of on board refrigeration power needs. The air core motor without iron requires more power and has a very low power factor. In addition, the refrigeration requirement is 2.9 times larger than the air core with back iron in the guideway.

9.4 Voltage Breakdown

To reduce the current in the air core motor leads, the number of turns in the motor should be increased so that the operational current is a few thousand amps or less. This reduces the heat load in the cryostat considerably. However, since the motor requires the same drive power (independent of the number of turns) the voltage would be have to be increased if the turns are increased. In some cases the voltage can be excessive and can lead to voltage breakdown in helium.

To solve this problem, we have developed a concept of distributed power factor optimization as shown in Figures 21 and 22. The voltage across the entire motor is reduced including series capacitive reactance in the winding such that the power factor is close to unity. By distributing the capacitive reactance along the winding, the voltage across any section is lowered, preventing voltage breakdown.

Two concepts were considered. In the first concept, shown in Figure 21, the distributed capacitance is located in the helium bath. The AC losses in the capacitors (represented by RC in Figure 21) will be a major heatload unless special low loss materials or superconductors are used in the capacitor.

The second concept, shown in Figure 22, brings the power correction capacitors out to the room temperature environment. The disadvantage of this design is that there are heatloads associated with power leads attaching the capacitors. (These leads are identified as R_L in Figure 22.) The advantage of this configuration is that the capacitors are accessible and can be variable or part of a switching network used to adjust for load changes as the vehicle changes speed.

9.5 AC Field Shielding

The air core SCLIM generates large external AC fringe fields which can be hazardous. Shielding may be necessary to protect train passengers. AC shielding can be accomplished by incorporating an aluminum or ferromagnetic shield around the motor. The aluminum shield must be located away from the motor, or eddy current heating will become a major problem. Laminated ferromagnetic shields can also be used, but they tend to be heavy, which is disadvantageous for the vehicle.

9.6 Conclusions

Several low T_c air core SCLIM concepts have been explored. The air core SCLIMs with guideways with back iron are more motors as compared to air core motors without guideway back iron.

All the air core approaches require more drive power than the iron core counterparts. Most of this power is used to drive flux. Since the flux is generated only from the current which is not amplified by the iron, more ampturns are required in this motor than in the iron core motors. This means the amount of superconductor required is larger and the AC losses are higher than in iron core designs.

There are also other problems associated with air core SCLIMs. Because of the poor power factor and high power required to drive the motor, voltage breakdown in the cryostat is a major concern. This problem can be minimized by use of distributed capacitance reactance as described in section 9.5. Most of these approaches add heat loss to the system.

The final difficulty with air core SCLIMs is AC shielding. Because of the high leakage flux on top of the motor, aluminum or ferromagnetic shielding must be employed for the safety of the passengers. The aluminum shield must be positioned far enough away from the motor to prevent eddy current heating. This takes up valuable vehicle space. Another approach is to use ferromagnetic shielding, which adds to the weight of the vehicle.

10. HTS Application Studies

There is much excitement with the discovery of HTS compounds. In the not too distant future, these materials shall be available for limited applications like power leads. The use of HTS power leads has been factored into our analysis of low temperature SCLIMs, and they are a key factor in reducing the refrigeration requirements.

There has been a steady increase in the performance of HTS conductors. Figure 2 shows the trend of improvement. Based on that trend, HTS conductors will be available in a few years which meet the need of air core and iron core SCLIMs.

SCLIM using HTS materials would be similar in design to the low temperature designs except that the cryostats would be liquid nitrogen (77K) based rather than liquid helium (4.2K) based. (This assumes that the improvement in the materials would come from improvements of current density at 77K.)

HTS SCLIMs would offer several advantages:

1. Lower refrigeration power requirements. From Figure 17 the power requirements for a given heat load at 77K is 100 times lower than at 4 K.
2. Less complex cryostats. There would be only one vessel and vacuum wall in the cryostat.
3. More compact cryostats. Because of the fewer thermal shields and vessels, the HTS cryostats could be made smaller.
4. Lower cryogenic and operation costs. Liquid nitrogen is less expensive and carries away more heat per liter. Hence the cryogenic consumption is lower. Also the refrigeration systems for liquid nitrogen are more efficient than for liquid helium.

5. The coils would be thermally more stable because of the higher specific heats at liquid nitrogen temperature.
6. The superconductor is more tolerant of AC losses at 77K because of the higher specific heats.
7. The dry nitrogen environment is less susceptible to high voltage breakdown.

In summary, all SCLIM concepts presented in this report would benefit greatly when HTS conductors become available.

11. Cost and Weight Comparisons

In Appendix IV a detailed estimate of costs and weights and heatloads is given for several SCLIMs. (The liquid nitrogen weights and costs were excluded in the study.) The tables indicate that low T_c solutions are heavier or more expensive than the equivalent copper iron core LIM's. The weight increase is primarily due to the power supply and refrigeration requirements. The air core SCLIM, for example, is a very lightweight motor but requires a large refrigerator to cool the AC losses in the superconductor. The air core SCLIM has a larger winding cross-section than the iron core SCLIMs and this accounts for the higher AC losses.

The study indicates that the smaller 180 Hz copper iron LIM is the lightest of the iron core motors studied. The input power and cost are higher than for the 60 Hz copper iron motor.

For HTS SCLIM, the most practical design is the warm iron SCLIM. The weight and costs would be comparable to an equivalent copper iron core LIM.

12. Conclusions

Several promising SCLIM concepts were explored in some detail.

A comparison table is shown in Table 9. The most attractive concept is the warm iron SCLIM. The cold iron SCLIM is impractical because of core losses. The air core concepts are not attractive because of the larger currents required, the mechanical loads borne by the superconductor and the additional shielding requirements.

The advantages of the warm iron concept are:

1. It takes advantage of iron and does not increase the iron-iron gap.

2. It provides a good environment for the superconductor, i.e., low fields and forces. As a consequence, motors with a large number of amp turns could be constructed.

3. It is self shielded for the most part and requires very little external shielding.

With the advent of HTS compounds and compact cryostats, the warm iron SCLIM would be a very appealing choice for Maglev applications.

The remaining question is how does warm iron SCLIM compare to the copper iron designs. The performance of the motors is similar and the guideway required is the same. The advantage of the warm iron SCLIM is that more ampturns could be incorporated in the motor without the associated heat. The motor would run cooler and could be easily designed to sustain large overcurrents from braking, etc., without overheating. This would be particularly true of HTS warm iron SCLIMS.

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FIGURES

FIG V-1. SLIP AS A FUNCTION OF VELOCITY USED IN THE PARAMETRIC STUDY

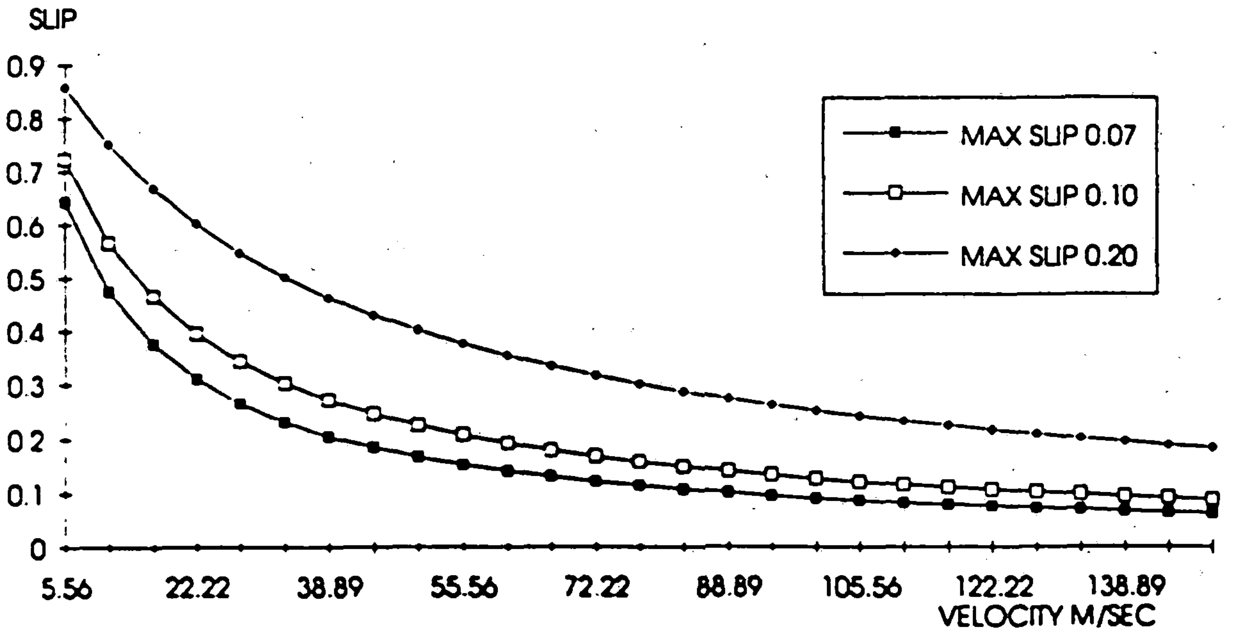


FIG V-2. EIGHT POLE MOTOR LENGTH VS MAX FREQUENCY OF OPERATION

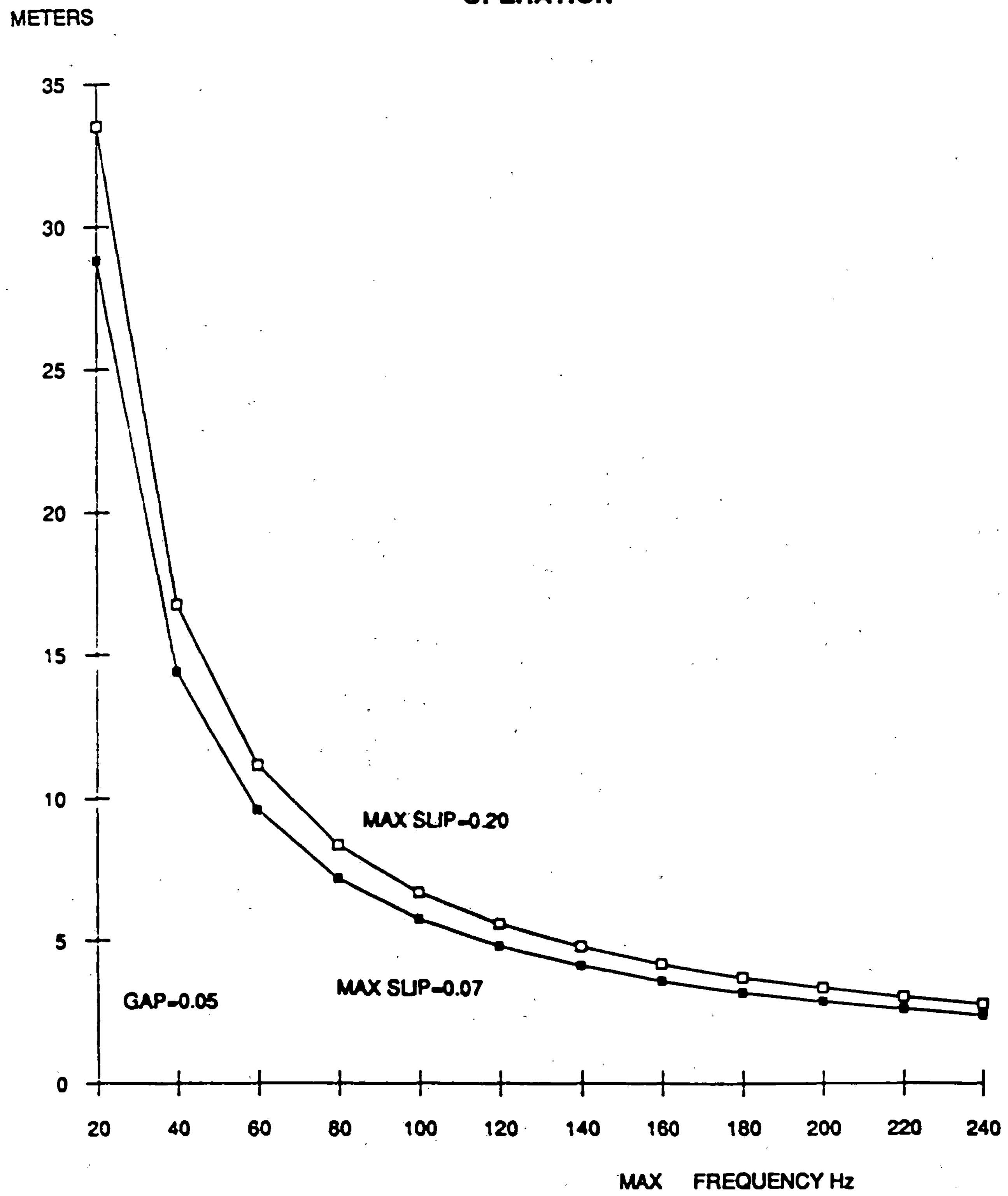


FIG V-3. CURRENT VS VELOCITY AT DIFFERENT MAX FREQUENCIES

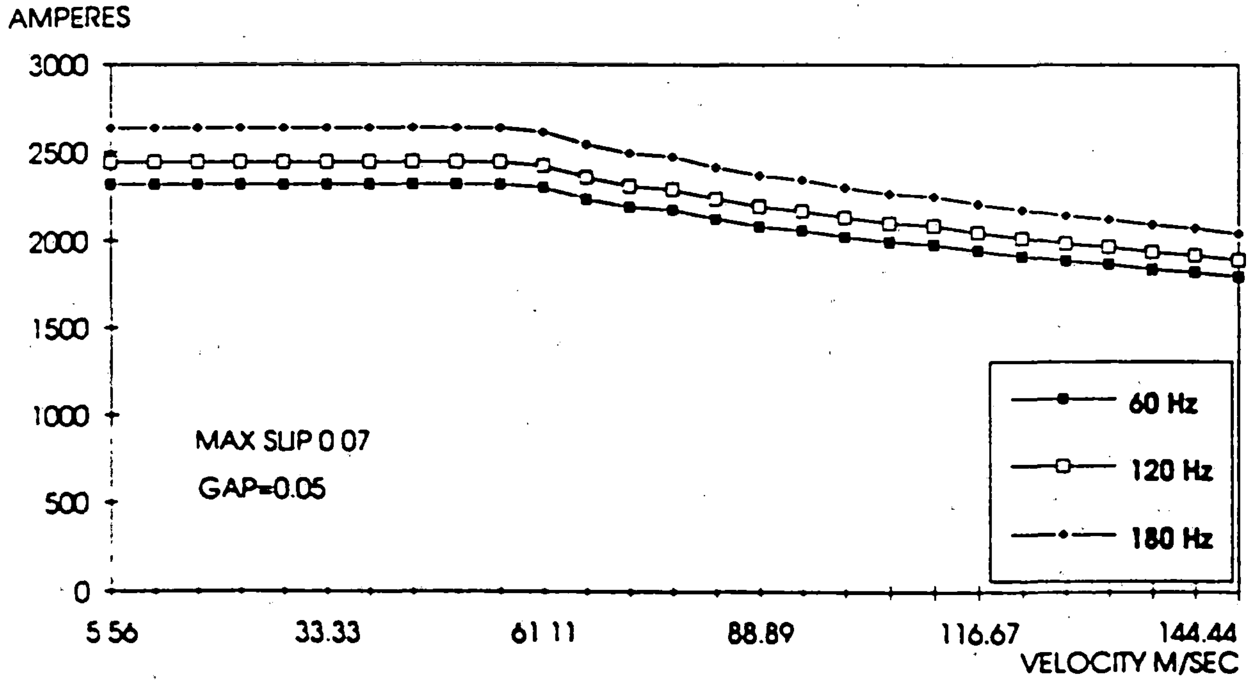


FIG V- 4. CURRENT VS VELOCITY AT DIFFERENT MAX SLIPS.

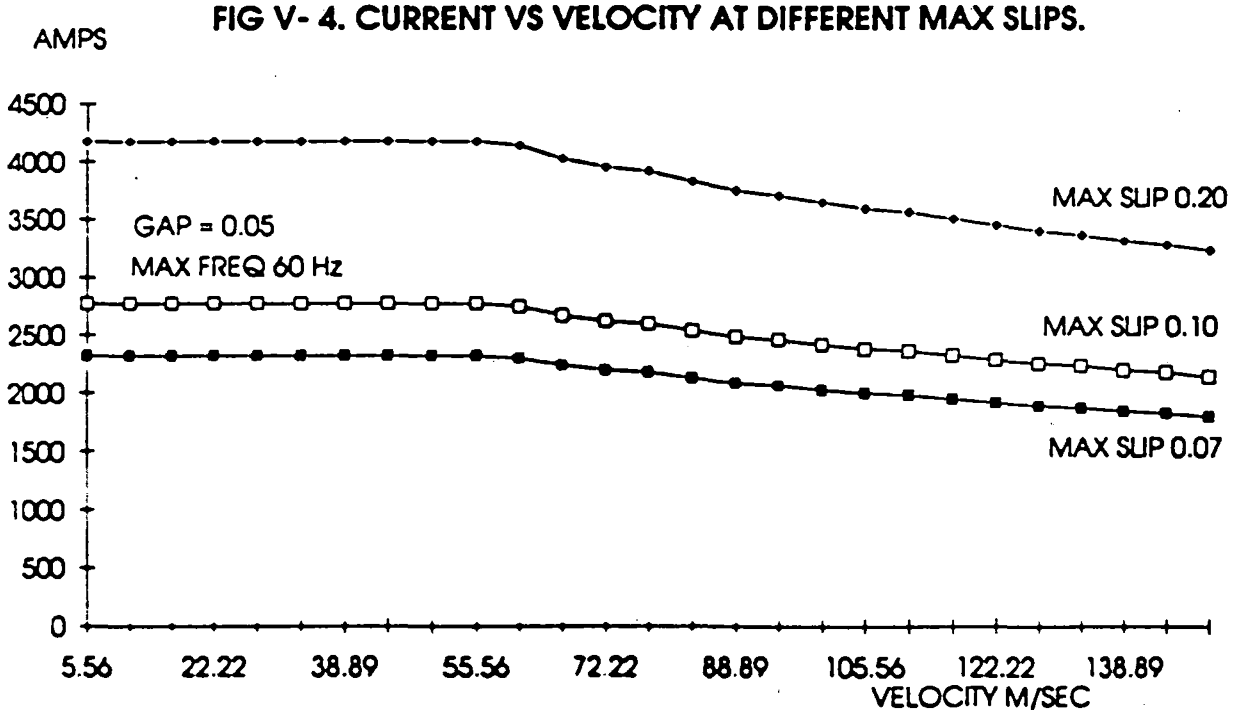


FIG V-5. INPUT POWER VS VELOCITY AT DIFFERENT MAX SLIPS

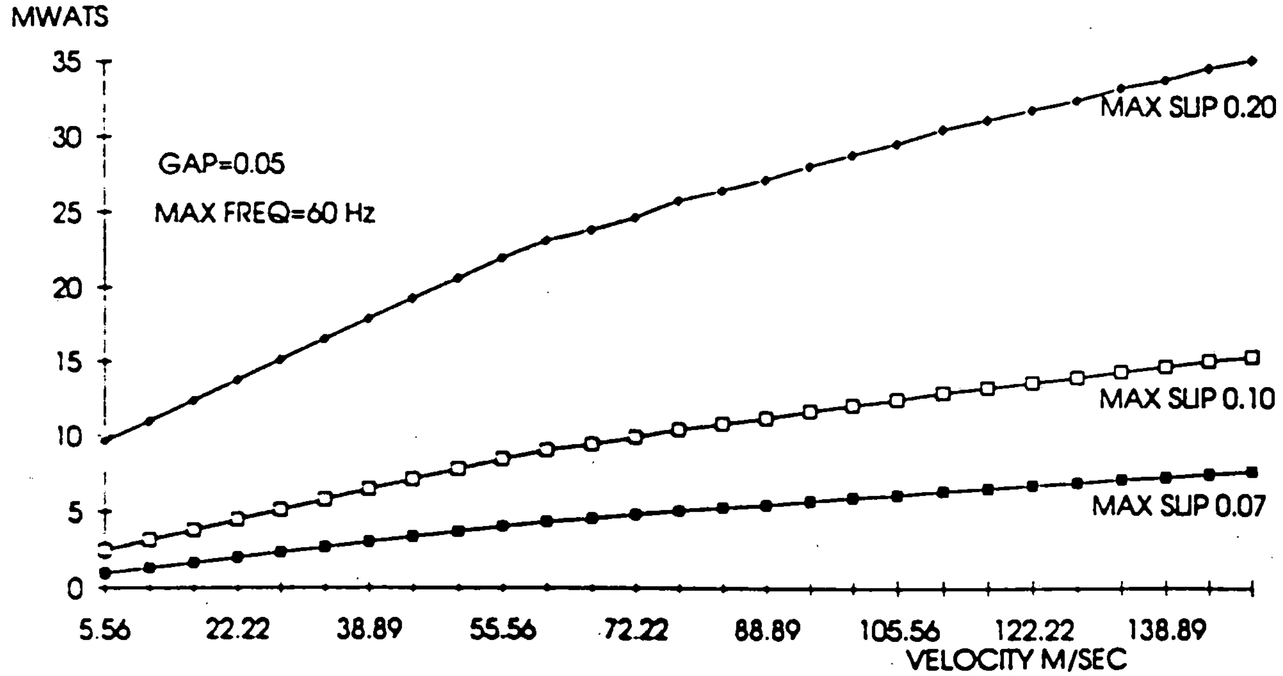


FIG V-6. CURRENT VS VELOCITY AT DIFFERENT GAPS AT 60 Hz

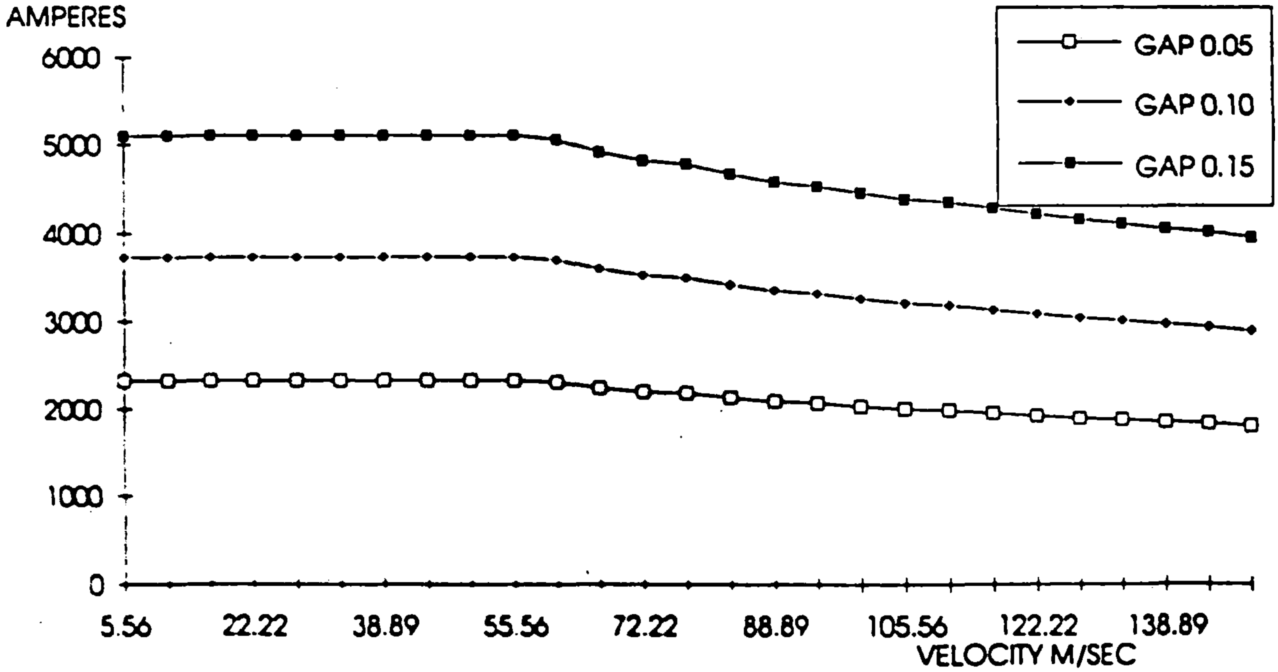
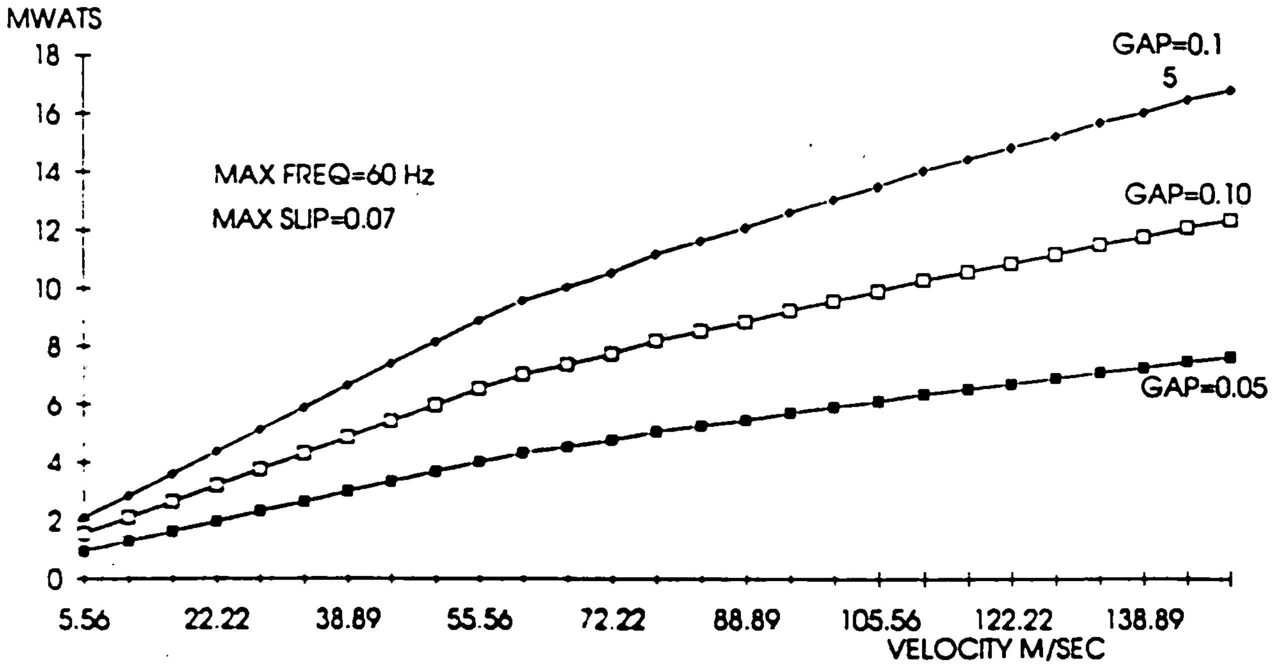


FIG V-7. INPUT POWER VS VELOCITY AT DIFFERENT GAPS



Appendix IV
Cost, Weight, and Heat Analysis Study for SCLIMs

The data attached represents a cost comparison for various SCLIMs compared to a conventional copper iron core LIM. The tables are based on the following assumptions:

Assumptions of the motor design:

1. The motor design data comes from the analysis in Appendix II for all motors except for the aircore motor.
2. The aircore motor data comes from the analysis in Appendix III.
3. The design thrust is 44.5 kN at 134 m/sec, higher than the requirement of 42.7 kN indicated by Figure 1. By increasing the thrust, the design current is such that the motor meets the requirements over the whole velocity range.
4. The conductor is assumed to be a square cross section.

Assumptions for the heat loads:

1. Table I was used to estimate the radiation and support heat loads.
2. Iron core losses were estimated from Reference 12 using 0.014" laminates.
3. The iron core properties are given by Reference 12. The core losses are estimated on the properties of laminated steel used in electrical applications from Reference 12. At 60 Hz and a temperature of 300K, the eddy current loss fraction was 65% and the magnetic hysteresis loss fraction was 35%. It was assumed that the hysteresis losses were independent of temperature, and the eddy current losses were proportional to the conductivity of iron at a given temperature. Iron resistivity (the inverse of the conductivity) drops by 167 from room temperature to 4K [12]. We assumed the resistivity of iron at 77K is 0.1 of the room temperature value.
4. For HTS motors the iron core losses are assumed to be at 80K.

Assumptions of weight and cost:

1. The cryostat is assumed to have a uniform density of 2000 kg/m^3.
2. The conventional copper iron core motors are estimated to cost $100/kg.
3. Superconductor based systems are estimated at $100/kg. This assumption is based on production costs and not prototype costs.
4. The refrigeration costs are assumed to follow Figure IV-1, which is based on commercial refrigeration systems [14]. For most examples this cost is about $12,000 per watt. We checked with IGC APD Division which manufactures refrigeration systems as to whether the table reflects current refrigeration costs. (The tables were

published in 1967.) They suggested we use those values although new technologies are available which could reduce refrigeration costs and weight. The technologies require development funding.

5. The refrigeration system is sized according to the 4K heat load and is assumed to be large enough to accommodate the 80K heat load as well.
6. The refrigeration weights are assumed to follow Figure IV-2, which is based on Reference 14.
7. Power supply weight are based computed on the basis of 0.40 kg/watt.
8. Power supply costs are based on an estimate of $0.10/watt.
9. These cost values are for crude cost calibration only and are not necessarily supported by quotations.

Table IV-1
Weight and Cost Estimates for 60 Hz LIM and SCLIM

Motor Type	copper	warm Fe	cold Fe	air core	units
Frequency	60	60	60	60	Hz
Gap	10	10	10	10	cm
Current density	500	10,000	10,000	10,000	amps/cm^2
Current	2007	2007	2163	5970	amps
Wire cross section	4.014	0.2007	0.2153	0.597	cm^2
No. poles	8	8	8	8	
No. of motor turns	32	32	32	32	
Turns per pole	4	4	4	4	
Bundle cross section per pole	16.056	0.8028	0.8652	2.388	cm^2
2 bundles cross section	32.112	1.6056	1.7304	4.776	cm^2
Bundle dimensions (assume square)	5.667	1.267	1.315	2.185	cm
Internal cryostat					
Cryostat dw		4			cm
Cryostat dh		4			cm
Cryo dw + bundle	5.667	5.267	1.315	2.185	cm
Cryo dh + bundle	5.667	5.267	1.315	2.185	cm
Slot area	32.112	[illegible]	1.7304	4.776	cm^2
Aspect Hs/Ws	2	2	2	2	
Slot width (Ws)	4.007	3.724	0.930	1.545	cm
Slot height (Hs)	8.014	7.449	1.860	3.091	cm
Pole pitch	1.2	1.2	1.2	1.2	meters
Ratio slot width/pitch	0.33	0.31	0.008	0.013	
Motor flux density	0.109	0.109	0.109		Tesla
Iron sat	2	2	2		Tesla
Eff pole 1 (minus slots	107.98	108.83	117.21	115.36	cm
Ratio pole/eff pole	0.011113	0.011026	0.010238	0.010401	
Current Increase required	1.111	1.103	1.024	1.040	percent

Table IV-1
Weight and Cost Estimates for 60 Hz LIM and SCLIM (cont'd)

Motor Type	copper	warm Fe	cold Fe	air core	units
Core back iron thickness	0.0327	0.0327	0.0327	0	cm
Core height	0.113	0.107	0.051	0.031	meters
Core width	1.44	1.44	1.44	1.44	meters
Core length	9.6	9.6	9.6	9.6	meters
Core volume (including slots)	1.560	1.482	0.709	0.427	m^3
Slot volume	0.046	0.040	0.002	0.007	m^3
Iron volume	1.514	1.442	0.707	0.420	m^3
Winding volume	0.108	0.094	0.006	0.016	m^3
Density of iron	7700	7700	7700	2000	kg/m^3
Density of winding	8900	8900	8900	8900	kg/m^3
Weight (assuming all iron)	12011	11410	5461	854	kg
Weight of iron	11655	11102	5442	841	kg
Weight of winding	965	833	52	143	kg
Weight of core + winding	12620	11935	5494	984	kg
External dimensions					
Core + bundle width	1.480	1.477	1.449	1.455	meters
Core + bundle length	9.640	9.637	9.609	9.615	meters
		4			
External Cryostat					
Cryo dh		0	5	5	cm
Cryo dw		5	5	5	cm
Cryo dl		5	5	5	cm
Motor height	0.113	0.107	0.151	0.131	m
Motor width	1.48	1.58	1.55	1.56	m
Motor length	9.64	9.74	9.71	9.72	m
Motor volume	1.610	1.646	2.276	1.978	m^3
Core volume	1.560	1.482	0.709	0.427	m^3
Cryostat volume	0.050	0.164	1.567	1.551	m^3

Table IV-1
Weight and Cost Estimates for 60 Hz LIM and SCLIM (cont'd)

Motor Type	copper	warm Fe	cold Fe	air core	units
Cryostat density	2000	2000	2000	2000	kg/m^3
Ex cryostat weight	100	329	3134	3012	kg
Motor weight	12720	12264	8627	4086	kg
Motor cost per kg	10	100	100	150	
Motor cost	0.127	1.226	0.863	0.613	$ million
Heat load at 4K	135,000*	31	5,300,000	132	watts
Refrig cost/watt	0.4	12,000	12,000	12,000	$/watt
Refrig cost	0.054	0.372	excessive	1.584	$ million
Refrig weight/watt	0.04	66	66	66	kg/watt
Refrig weight	5400	2046	excessive	8712	kg
Power supply power	7.65	7.65	8.24	10.4	MVA
Power supply weight/kW	0.4	0.4	0.4	0.4	kg/kW
Power supply weight	3060	3060	3296	4160	kg
Power supply cost/watt	0.1	0.1	0.1	0.1	$/MVA
Power supply cost	0.765	0.765	0.824	1.04	$ million
Total weight	21.18	17.37	excessive	16.96	tonnes
Total cost	0.946	2.363	excessive	3.327	$ million
					cm
Cost per kg	44.674	136.062	181.82	190.878	$/kg

* at room temperature

Table IV-2
Weight and Cost Estimates for 120 Hz LIM and SCLIM

Motor Type	copper	warm Fe	cold Fe	air core	units
Frequency	120	120	120	120	Hz
Gap	10	10	10	10	cm
Current density	500	10,000	10,000	10,000	amps/cm^2
Current	2365	2365	2863	8900	amps
Wire cross section	4.73	0.237	0.286	0.597	cm^2
No. poles	8	8	8	8	
No. of motor turns	32	32	32	32	
Turns per pole	4	4	4	4	
Bundle cross section per pole	18.92	0.946	1.1452	3.56	cm^2
2 bundles cross section	37.84	1.892	2.2904	7.12	cm^2
Bundle dimensions (assume square)	6.151	1.375	1.513	2.668	cm
Internal cryostat					
Cryostat dw		4			cm
Cryostat dh		4			cm
Cryo dw + bundle	6.151	5.375	1.513	2.668	cm
Cryo dh + bundle	6.151	5.375	1.513	2.668	cm
Slot area	37.84	28.896	2.290	7.12	cm^2
Aspect Hs/Ws	2	2	2	2	
Slot width (Ws)	4.35	3.89	1.07	1.89	cm
Slot height (Hs)	8.70	7.60	2.14	3.77	cm
Pole pitch	0.6	0.6	0.6	0.6	meters
Ratio slot width/pitch	0.072	0.063	0.018	0.031	
Motor flux density	0.22	0.22	0.22		Tesla
Iron sat	2	2	2		Tesla
Eff pole l (minus slots	46.95	48.60	56.79	54.34	cm
Ratio pole/eff pole	0.012779	0.012346	0.010565	0.011041	
Current Increase required	1.278	1.235	1.057	1.104	percent

Table IV-2
Weight and Cost Estimates for 120 Hz LIM and SCLIM (cont'd)

Motor Type	copper	warm Fe	cold Fe	air core	units
Core backiron thickness	0.033	0.033	0.033	0	cm
Core height	0.120	0.109	0.054	0.038	meters
Core width	0.72	0.72	0.72	0.72	meters
Core length	4.8	4.8	4.8	4.8	meters
Core volume (including slots)	0.415	0.377	0.188	0.130	m^3
Slot volume	0.027	0.021	0.002	0.005	m^3
Iron volume	0.387	0.356	0.186	0.125	m^3
Winding volume	0.064	0.049	0.004	0.012	m^3
Density of iron	7700	7700	7700	2000	kg/m^3
Density of winding	8900	8900	8900	8900	kg/m^3
Weight (assuming all iron)	3193	2901	1448	261	kg
Weight of iron	2983	2741	1435	251	kg
Weight of winding	572	436	34	107	kg
Weight of core + winding	3555	3177	1469	358	kg
External dimensions					
Core + bundle width	0.763	0.757	0.731	0.739	meters
Core + bundle length	4.843	4.838	4.811	4.819	meters
		4			
External Cryostat					
Cryo dh		0	5	5	cm
Cryo dw		5	5	5	cm
Cryo dl		5	5	5	cm
Motor height	0.120	0.109	0.154	0.138	m
Motor width	0.763	0.858	0.831	0.839	m
Motor length	4.843	4.938	4.911	4.919	m
Motor volume	0.444	0.462	0.630	0.568	m^3
Core volume	0.415	0.377	0.188	0.130	m^3
Cryostat volume	0.029	0.085	0.442	0.438	m^3

Table IV-2
Weight and Cost Estimates for 120 Hz LIM and SCLIM (cont'd)

Motor Type	copper	warm Fe	cold Fe	air core	units
Cryostat density	2000	2000	2000	2000	kg/m^3
Ex cryostat weight	58.1	170.3	883.7	875.8	kg
Motor weight	3613	3347	2353	1233	kg
Motor cost per kg	10	100	100	150	
Motor cost	0.036	0.335	0.235	0.185	$ million
Heat load at 4K	73,894*	57	5,300,000	383	watts
Refrig cost/watt	0.4	12,000	12,000	12,000	$/watt
Refrig cost	0.029	0.684	excessive	4.596	$ million
Refrig weight/watt	0.04	66	66	66	kg/watt
Refrig weight	2956	3762	excessive	25,278	kg
Power supply power	9.01	9.01	10.91	21.53	MVA
Power supply weight/kW	0.4	0.4	0.4	0.4	kg/kW
Power supply weight	3604	3604	4364	8162	kg
Power supply cost/watt	0.1	0.1	0.1	0.1	$/MVA
Power supply cost	0.901	0.901	1.091	2.153	$ million
Total weight	10.17	10.71	excessive	35.12	tonnes
Total cost	0.967	1.920	excessive	6.934	$ million
Cost per kg	95.026	179.192	181.819	197.419	$/kg

* at room temperature

Table IV-3
Weight and Cost Estimates for 180 Hz LIM and SCLIM

Motor Type	copper	warm Fe	cold Fe	air core	units
Frequency	180	180	180	180	Hz
Gap	10	10	10	10	cm
Current density	500	10,000	10,000	10,000	amps/cm^2
Current	2863	2863	3750	13,260	amps
Wire cross section	5.726	0.286	0.375	1.326	cm^2
No. poles	8	8	8	8	
No. of motor turns	32	32	32	32	
Turns per pole	4	4	4	4	
Bundle cross section per pole	22.904	1.145	1.5	5.304	cm^2
2 bundles cross section	45.808	2.2904	3	10.608	cm^2
Bundle dimensions (assume square)	6.768	1.513	1.732	3.257	cm
Internal cryostat					
Cryostat dw		4			cm
Cryostat dh		4			cm
Cryo dw + bundle	6.768	5.513	1.732	3.257	cm
Cryo dh + bundle	6.768	5.513	1.732	3.257	cm
Slot area	45.808	30.398	3	10.608	cm^2
Aspect Hs/Ws	2	2	2	2	
Slot width (Ws)	4.79	3.90	1.22	2.30	cm
Slot height (Hs)	9.57	7.80	2.45	4.61	cm
Pole pitch	0.4	0.4	0.4	0.4	meters
Ratio slot width/pitch	4.786	3.899	1.224	2.303	
Motor flux density	0.327	0.327	0.327		Tesla
Iron sat	2	2	2		Tesla
Eff pole 1 (minus slots	25.64	28.30	36.33	33.09	cm
Ratio pole/eff pole	0.0156	0.014	0.011	0.121	
Current Increase required	1.560	1.413	1.101	0.012	percent

Table IV-3
Weight and Cost Estimates for 180 Hz LIM and SCLIM (cont'd)

Motor Type	copper	warm Fe	cold Fe	air core	units
Core backiron thickness	0.0327	0.0327	0.0327	0	cm
Core height	0.128	0.111	0.057	0.046	meters
Core width	0.48	0.48	0.48	0.48	meters
Core length	3.2	3.2	3.2	3.2	meters
Core volume (including slots)	0.197	0.170	0.088	0.071	m^3
Slot volume	0.022	0.015	0.001	0.005	m^3
Iron volume	0.175	0.155	0.086	0.066	m^3
Winding Volume	0.052	0.035	0.003	0.012	m^3
Density of iron	7700	7700	7700	2000	kg/m^3
Density of winding	8900	8900	8900	8900	kg/m^3
Weight (assuming all iron)	1519	1309	676	141	kg
Weight of iron	1349	1197	665	131	kg
Weight of winding	464	307	30	107	kg
Weight of core + winding	1814	1504	695	238	kg
External dimensions					
Core + bundle width	0.528	0.519	0.492	0.503	meters
Core + bundle length	3.248	3.239	3.212	3.223	meters
		4			
External Cryostat					
Cryo dh		0	5	5	cm
Cryo dw		5	5	5	cm
Cryo dl		5	5	5	cm
Motor height	0.128	0.111	0.157	0.146	m
Motor width	0.528	0.619	0.592	0.603	m
Motor length	3.248	3.339	3.312	3.323	m
Motor volume	0.220	0.229	0.308	0.293	m^3
Core volume	0.197	0.170	0.088	0.071	m^3
Cryostat volume	0.023	0.059	0.221	0.222	m^3

Table IV-3
Weight and Cost Estimates for 180 Hz LIM and SCLIM (cont'd)

Motor Type	copper	warm Fe	cold Fe	air core	units
Cryostat density	2000	2000	2000	2000	kg/m^3
Ex cryostat weight	45.8	117.5	441.0	443.9	kg
Motor weight	1860	1621	1136	682	kg
Motor cost per kg	10	100	100	150	
Motor cost	0.019	0.162	0.114	0.102	$ million
Heat load at 4K	38,000*	114	excessive	320	watts
Refrig cost/watt	0.4	12,000	12,(00	12,000	$/watt
Refrig cost	0.152	1.368	excessive	3.84	$ million
Refrig weight/watt	0.04	66	66	66	kg/watt
Refrig weight	1520	7524	excessive	21,210	kg
Power supply power	10.91	10.91	14.26	45.39	MVA
Power supply weight/kW	0.4	0.4	0.4	0.4	kg/kW
Power supply weight	4364	4364	5704	18, 156	kg
Power supply cost/watt	0.1	0.1	0.1	0.1	$/MVA
Power supply cost	1.091	1.091	1.426	4.539	$ million
Total weight	7.74	13.51	excessive	39.96	tonnes
Total cost	1.125	2.621	excessive	8.481	$ million
Cost per kg	145.253	194.024	181.818	212.256	$/kg

* at room temperature

Table IV-4
Heat Load Summary (60 Hz)

	copper	warm Fe	cold Fe	air core	units
Gap	10	10	15	15	cm
Current	2007	2007	2163	5970	amps
300K Heat					
Core mass	15,602	15,488			kg
Core loss/kg	3.52	3.52			watts/kg
Core losses	54,919	54,518			watts
I^2R	80,324	0			
Total (330K)	135.24	54.52			kW
80K Heat					
Cryostat		12.86	86	86	watts
Heatload/amp		0.3	0.3	0.3	
Leads		602.1	648.9	1791	watts
Total (80K)	0	614.96	734.9	1877	watts
(HTS only)					
Core mass			13,082		kg
Core loss/kg			35.2		watts/kg
Core losses			460,486		watts
AC losses		2.5	2.7	10.6	watts
Total (80K)	0	617.46	461,224	1887.6	watts
4K Heat					
Cryostat		0.023	8	8	watts
Heatload/amp		0.003	0.003	0.003	
Leads		6.021	6.489	17.91	watts
Core mass			13,082		kg
Core loss/kg			402.6		watts/kg
Core losses			5,266,813		watts
AC losses		25	27	106	watts
Total (4K)	0	31.044	5,266,854	131.91	watts

Table IV-5
Heat Load Summary (120 Hz)

	copper	warm Fe	cold Fe	air core	units
Gap	10	10	15	15	cm
Current	2365	2365	2863	8900	amps
300K Heat					
Core mass	2481	1570			kg
Core loss/kg	10.84	10.84			watts/kg
Core losses	26,894	17,019			watts
I^2R	47,000	0			
Total (330K)	73.894	17.019			kW
80K Heat					
Cryostat		6.9	21.5	21.5	watts
Heatload/amp		0.3	0.3	0.3	
Leads		709.5	858.9	2670	watts
Total (80K)	0	716.4	880.4	2691.5	watts
(HTS only)					
Core mass			1570		kg
Core loss/kg			35.2		watts/kg
Core losses			55,264		watts
AC losses		5	5.8	35.3	watts
Total (80K)	0	721.4	56,150.2	2726.8	watts
4K Heat					
Cryostat		0.007	2.07	2.07	watts
Heatload/amp		0.003	0.003	0.003	
Leads		7.095	8.589	26.7	watts
Core mass			1570		kg
Core loss/kg			1182		watts/kg
Core losses			1,855,740		watts
AC losses		50	58	353	watts
Total (4K)	0	57.102	1,855,808	381.77	watts

Table IV-6
Heat Load Summary (180 Hz)

	copper	warm Fe	cold Fe	air core	units
Gap	10	10	15	15	cm
Current	2863	2863	3750	13,650	amps
300K Heat					
Core mass	643	643			kg
Core loss/kg	19.73	19.73			watts/kg
Core losses	12,686.39	12686.39			watts
I^2R	38,000	0			
Total (330K)	50.686	12.686			kW
80K Heat					
Cryostat		4.78	10.09	90.2	watts
Heatload/amp		0.3	0.3	0.3	
Leads		858.9	1125	4095	watts
Total (80K)	0	863.68	1135.09	4185.2	watts
(HTS only)					
Core mass			507		kg
Core loss/kg			35.2		watts/kg
Core losses			17,846.4		watts
AC losses		10.6	13.9	27.8	watts
Total (80K)	0	874.28	18,995.39	4213	watts
4K Heat					
Cryostat		0.004	0.979	0.979	watts
Heatload/amp		0.003	0.003	0.003	
Leads		8.589	11.25	40.95	watts
Core mass			13,082		kg
Core loss/kg			2,149.6		watts/kg
Core losses			28,121,067		watts
AC losses		106	139	278	watts
Total (4K)	0	114.593	28,121,218	319.929	watts

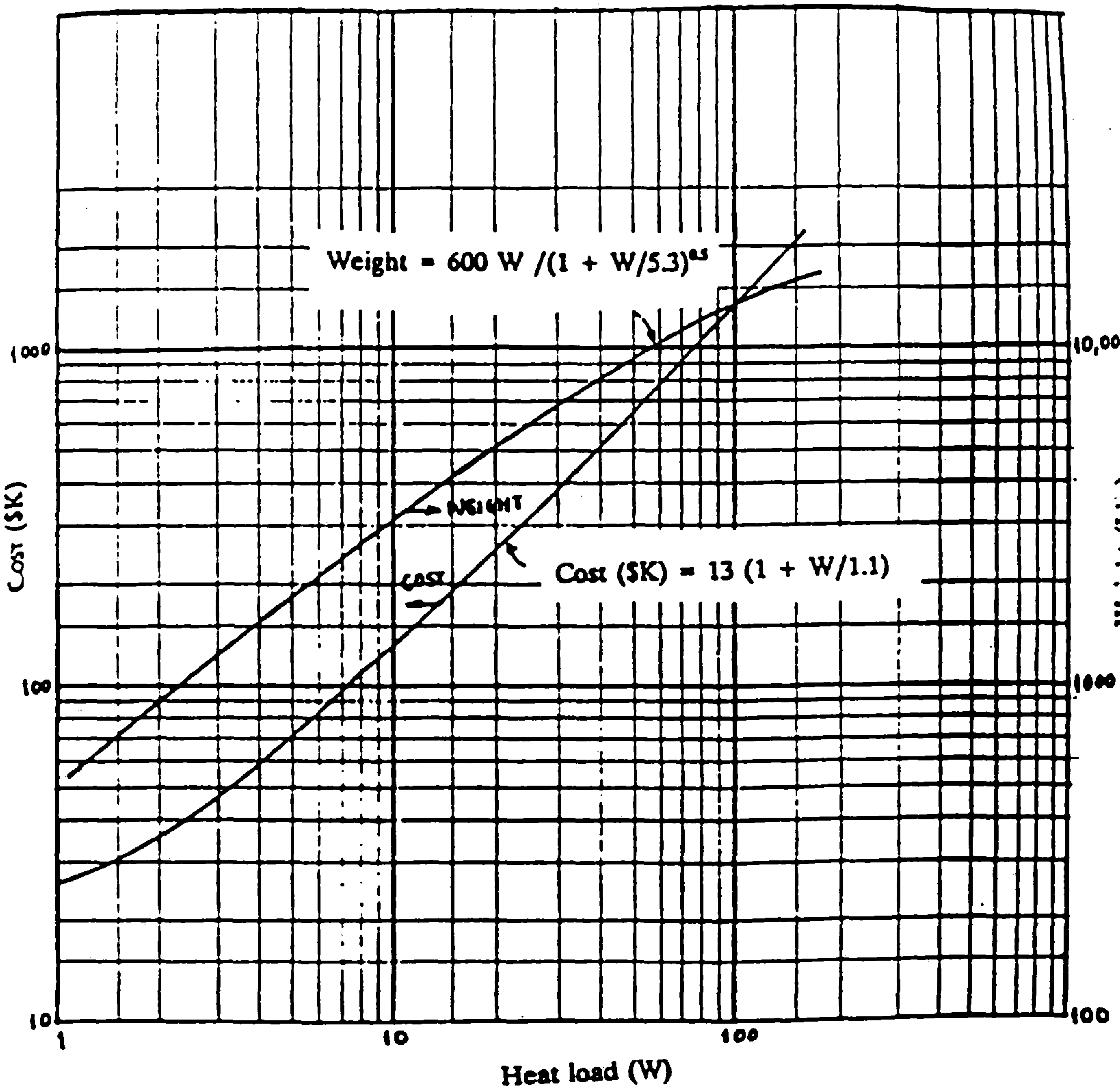


FIG IV-1. HELIUM REFRIGERATOR WEIGHT AND COST AS A FUNCTION OF HEAT LOAD

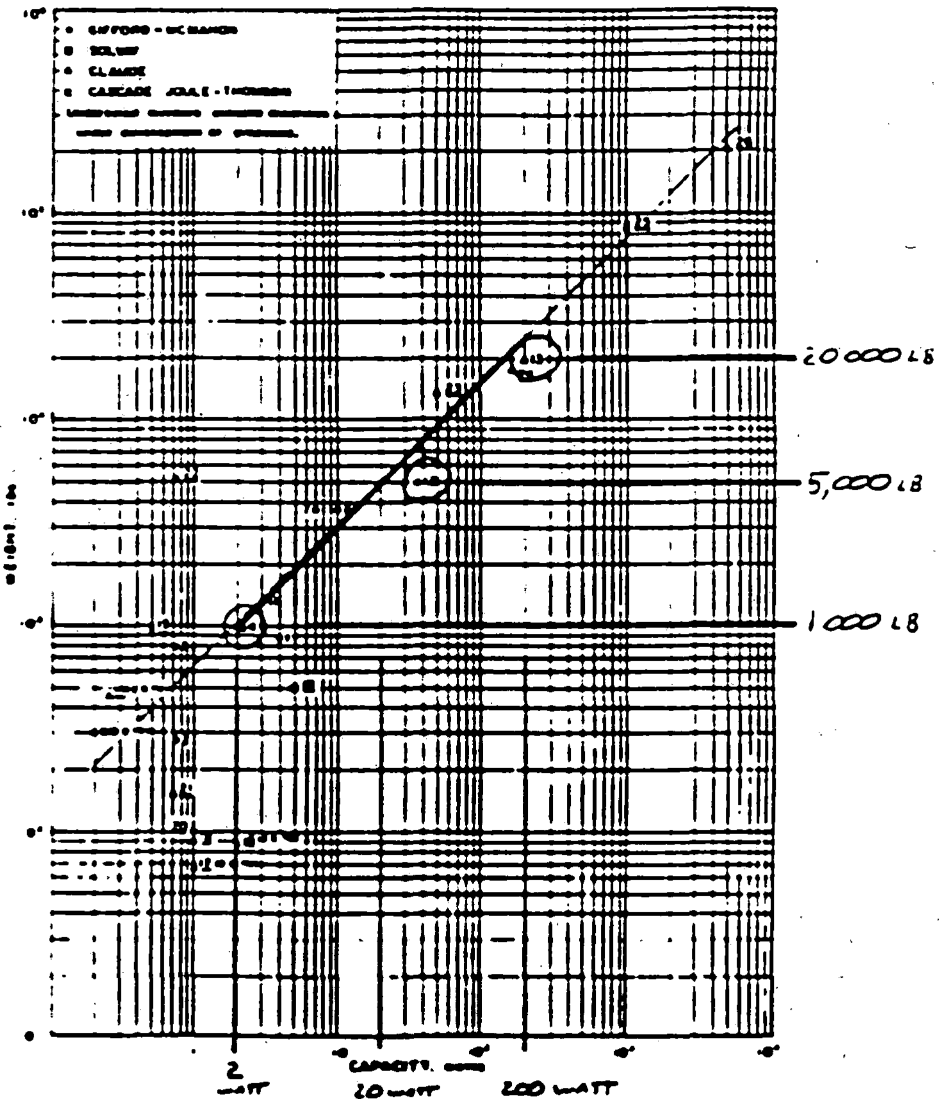


FIG IV-2. WEIGHT OF LIQUID HELIUM TEMPERATURE REFRIGERATORS

Appendix V
Parametric Studies of Various SCLIM and LIM Iron Core Designs

The purpose of the study was to determine the effect of changing key parameters in the design on the overall performance of the motor. This data was used to select the baseline designs and to identify any problems associated with the designs selected.

The assumptions of the design are listed in section 6.1. For copper LIM designs the current density is assumed to be 500 amps/cm^2. For the superconducting magnet designs a current density of 10,000 amps/cm^2 was selected. AC losses were estimated using the formulation in Appendix I.

One of the findings of the study is that a constant slip operation leads to high current and high starting powers, higher than necessary. By examining the equations for the field and for eddy current losses, a "constant relative velocity" scenario was developed which reduces the current and input power requirements as well as keeps the eddy current dissipation in the track low. This operation requires variable frequency and variable slip. The slip profile as a function of velocity is shown in Figure V-1. In this mode the motor current is almost independent of speed, rising 25% at low speeds (see, for example, Figure V-3). This can be accommodated by the superconductor since at low speeds the drive frequency is lower.

The constant relative velocity operation was adopted in the parametric study.

Appendix V Figures

FIG V-8. I*I*R LOSSES VS VELOCITY AT 3 DIFFERENT MAX FREQUENCIES

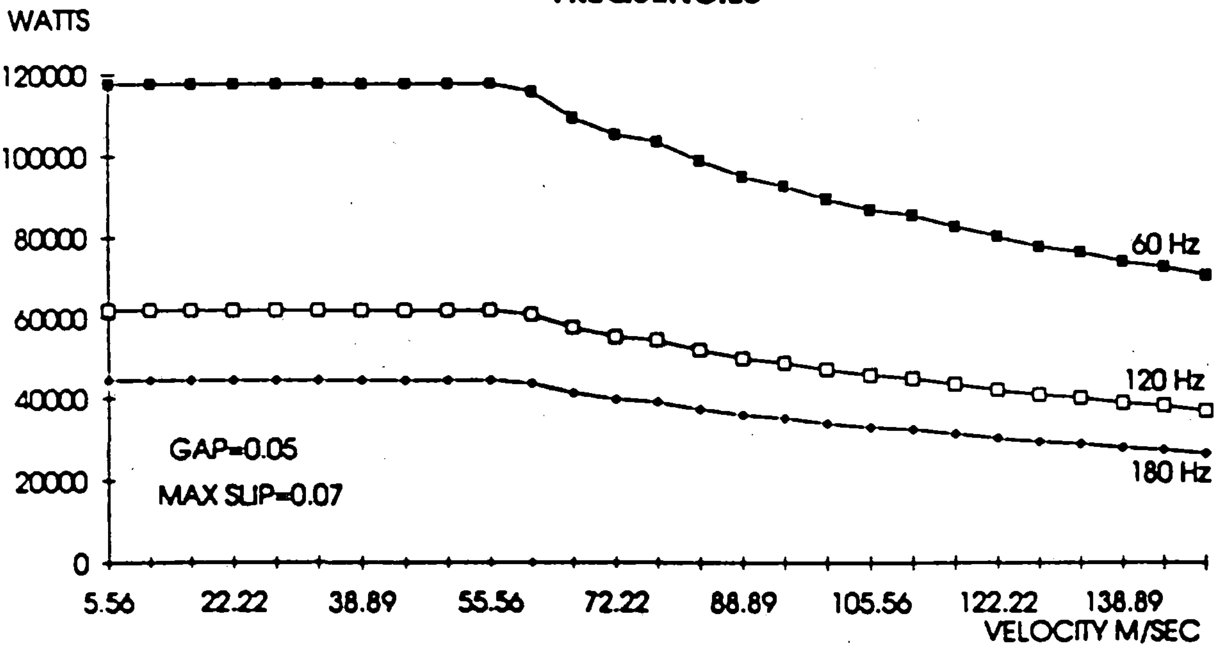


FIG V-9. I*I*R LOSSES VS VELOCITY AT 3 DIFFERENT MAX FREQUENCIES

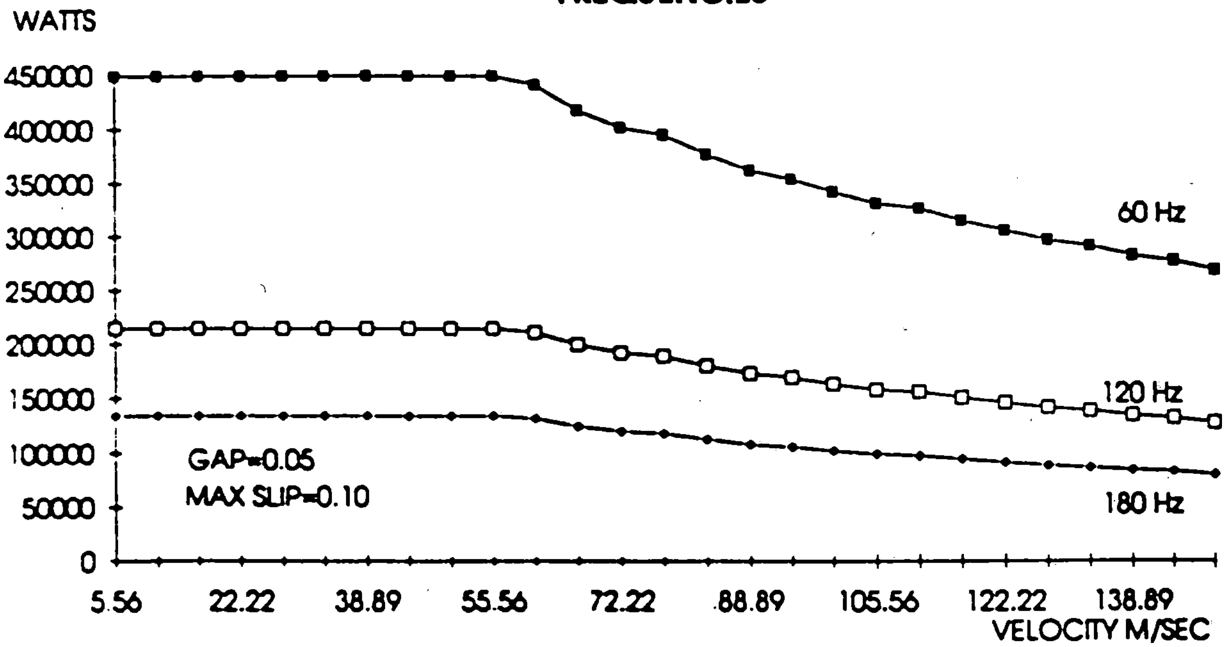


FIG V-10. I*I*R LOSSES VS VELOCITY AT 3 DIFFERENT MAX FREQUENCIES

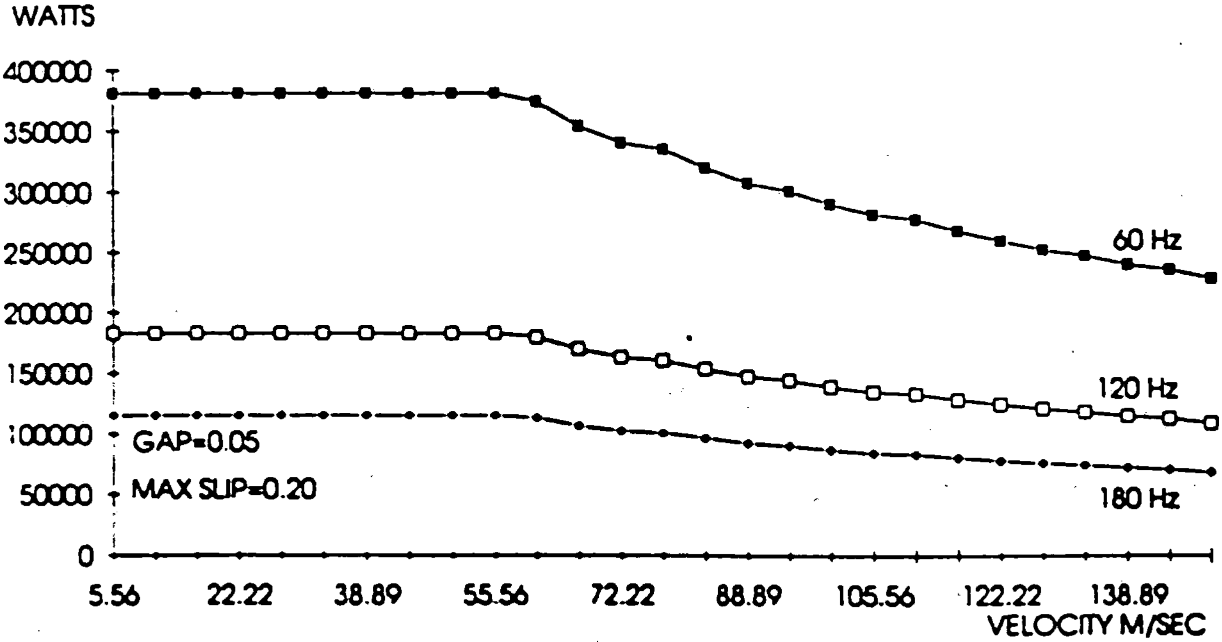


FIG V-11. I*I*R LOSSES VS VELOCITY AT 3 DIFFERENT MAX FREQUENCIES

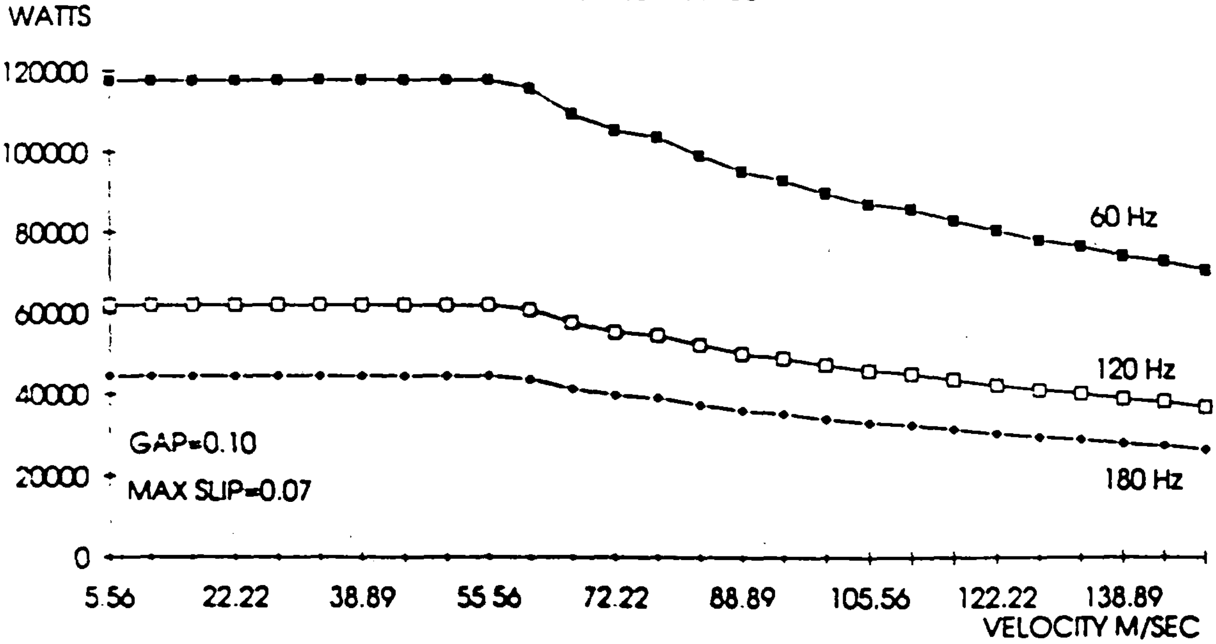


FIG V-12.I*I*R LOSSES VS VELOCITY AT 3 DIFFERENT MAX FREQUENCIES

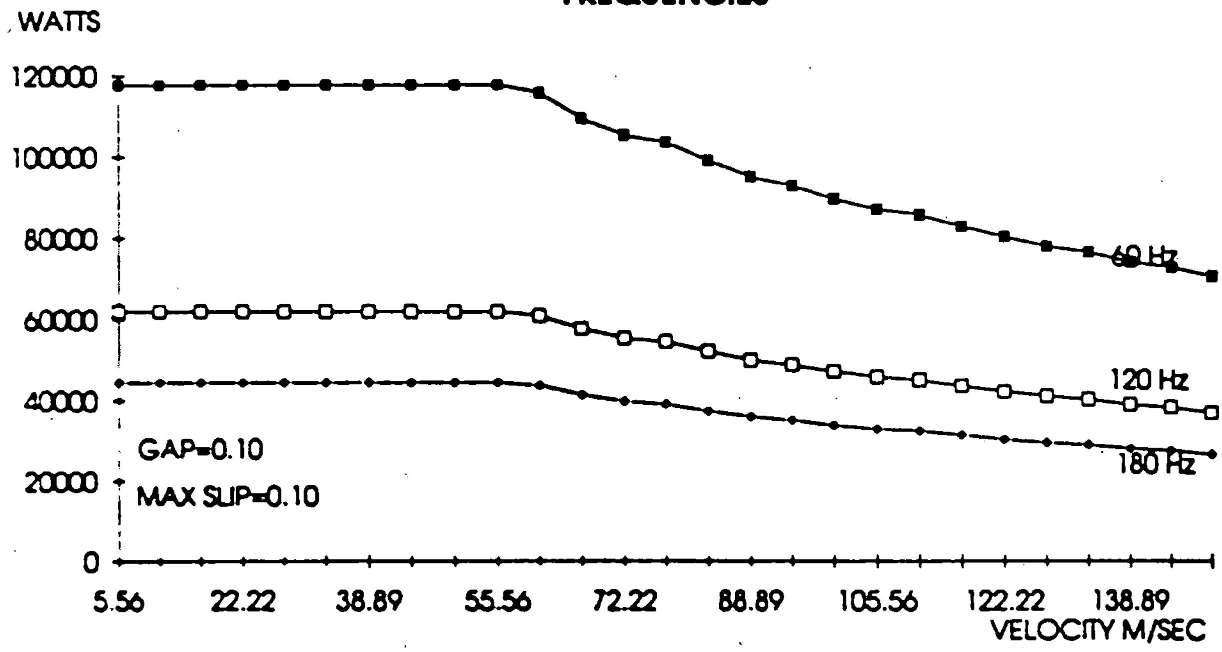


FIG V-13. I*I*R LOSSES VS VELOCITY AT 3 DIFFERENT MAX FREQUENCIES

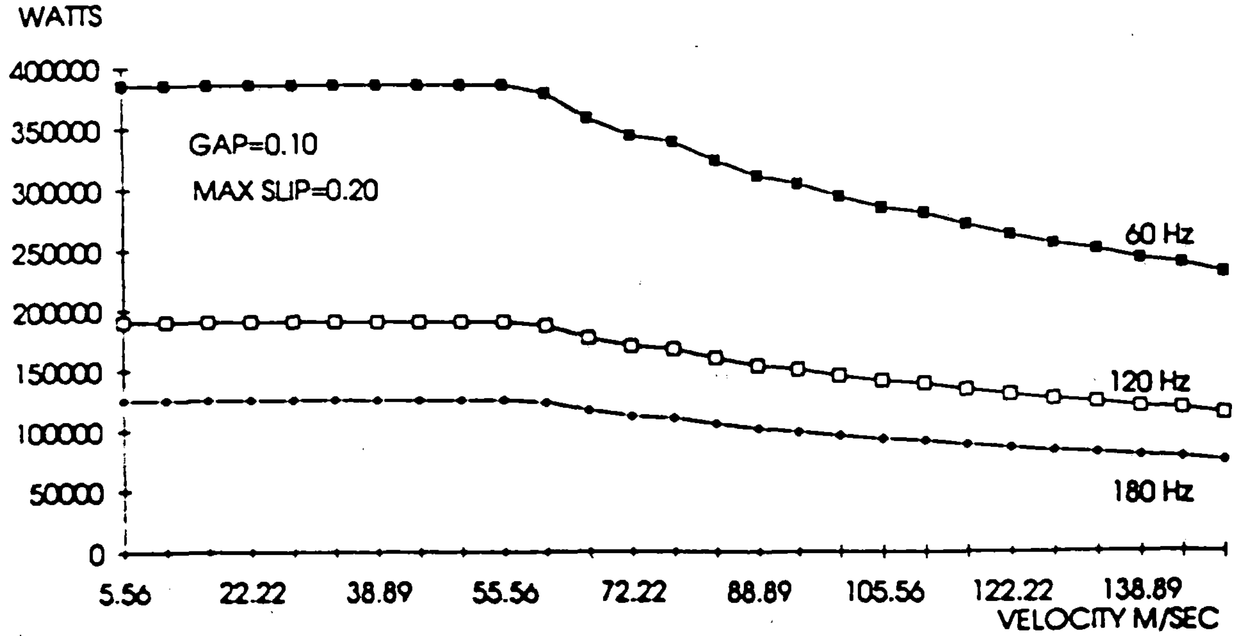


FIG V-14. AC LOSSES VS VELOCITY AT 3 DIFFERENT MAX FREQUENCIES

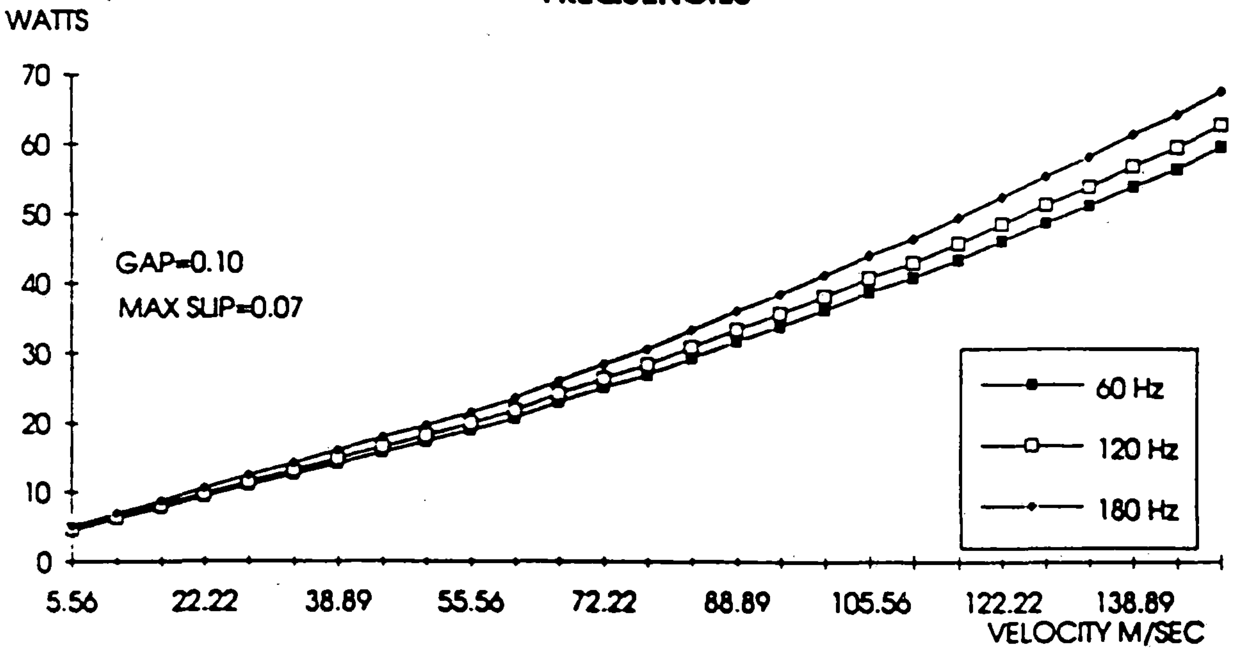


FIG V-15. AC LOSSES VS VELOCITY AT 3 DIFFERENT MAX FREQUENCIES

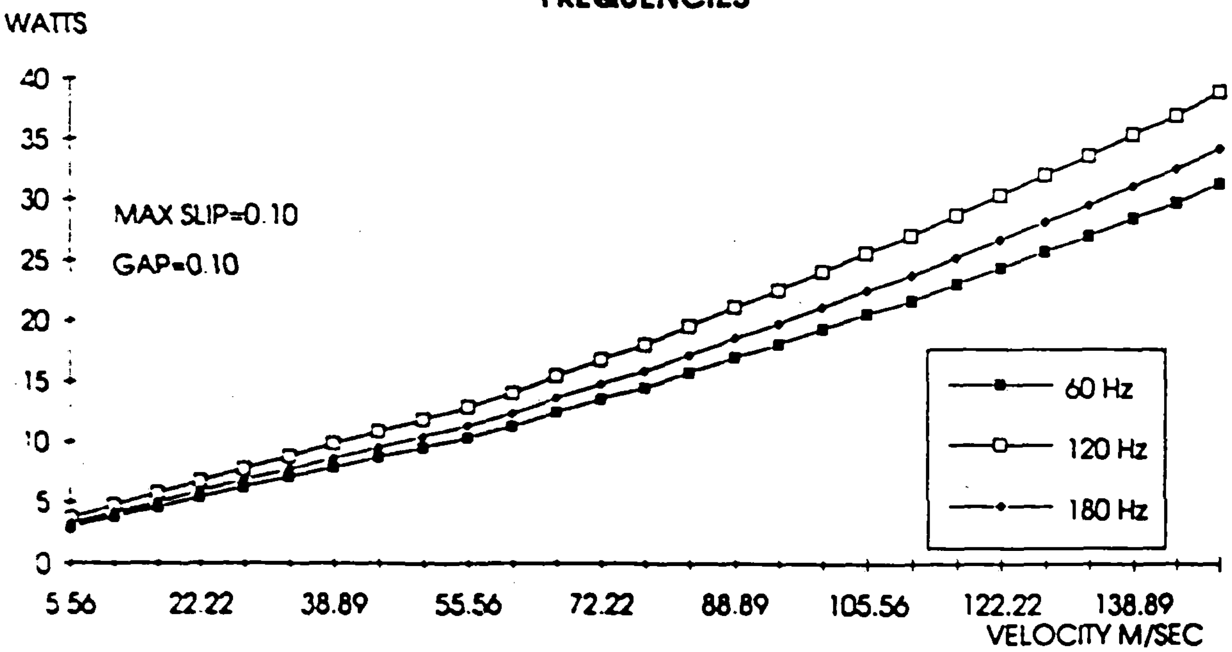


FIG V-16. AC LOSSES VS VELOCITY AT 3 DIFFERENT MAX FREQUENCIES

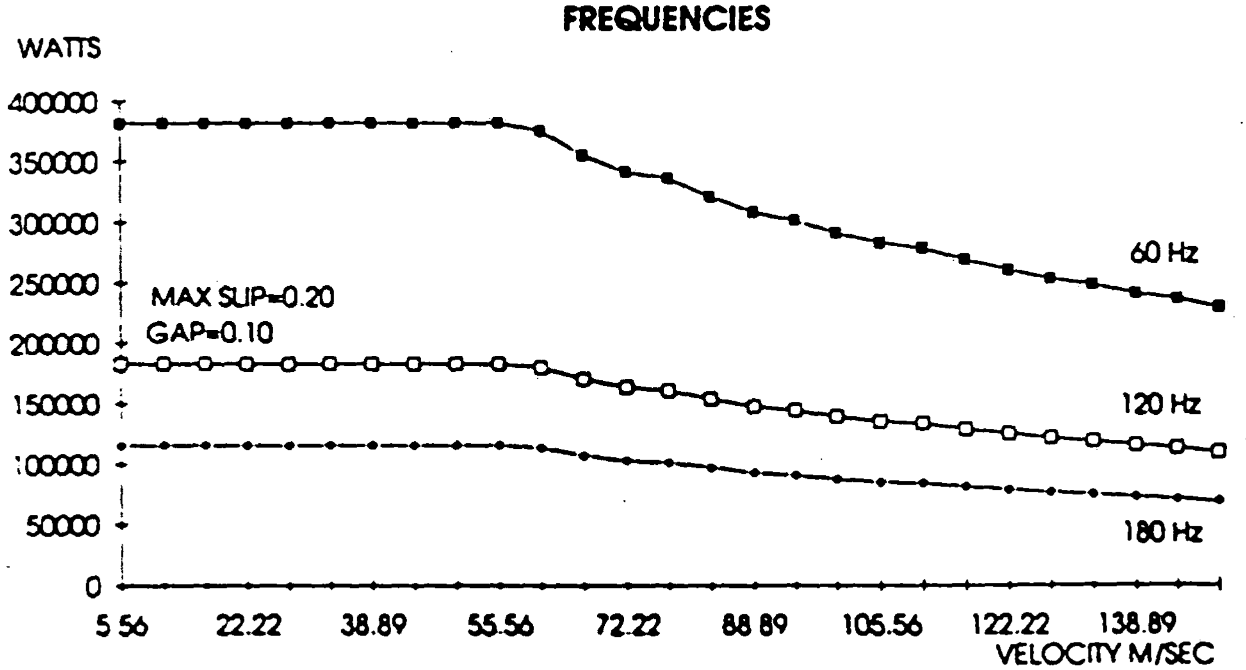


FIG V-17. AC LOSSES VS VELOCITY AT 3 DIFFERENT MAX FREQUENCIES

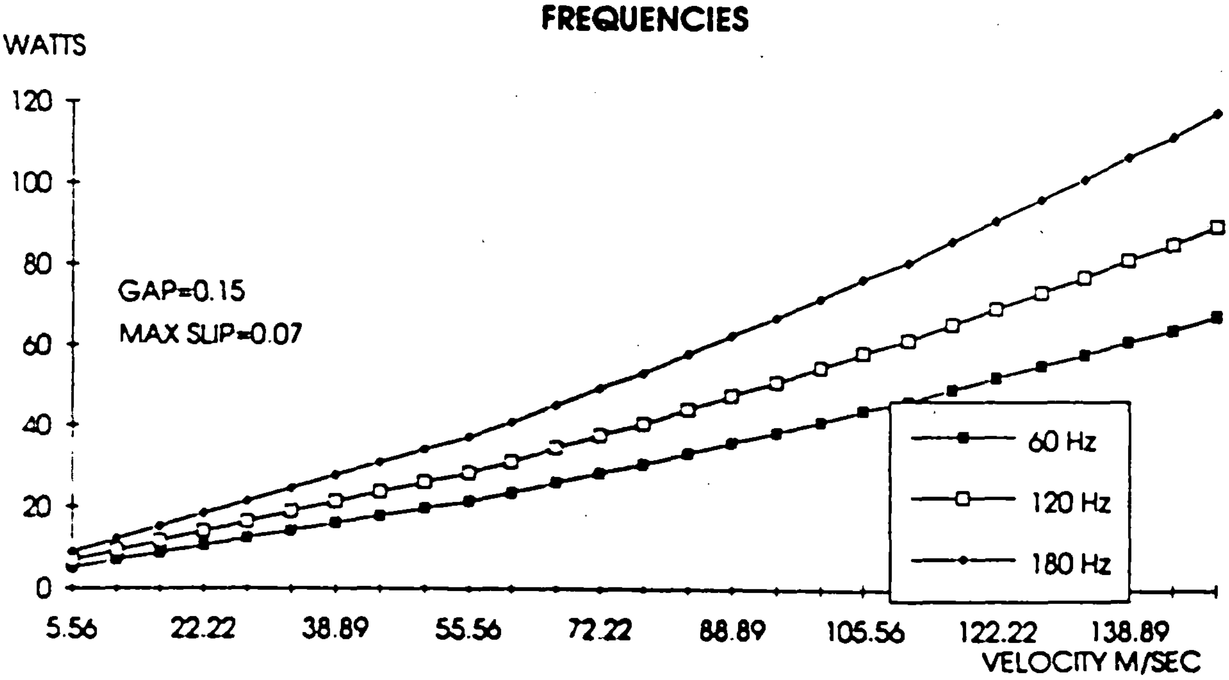


FIG V-18. AC LOSSES VS VELOCITY AT 3 DIFFERENT MAX FREQUENCIES

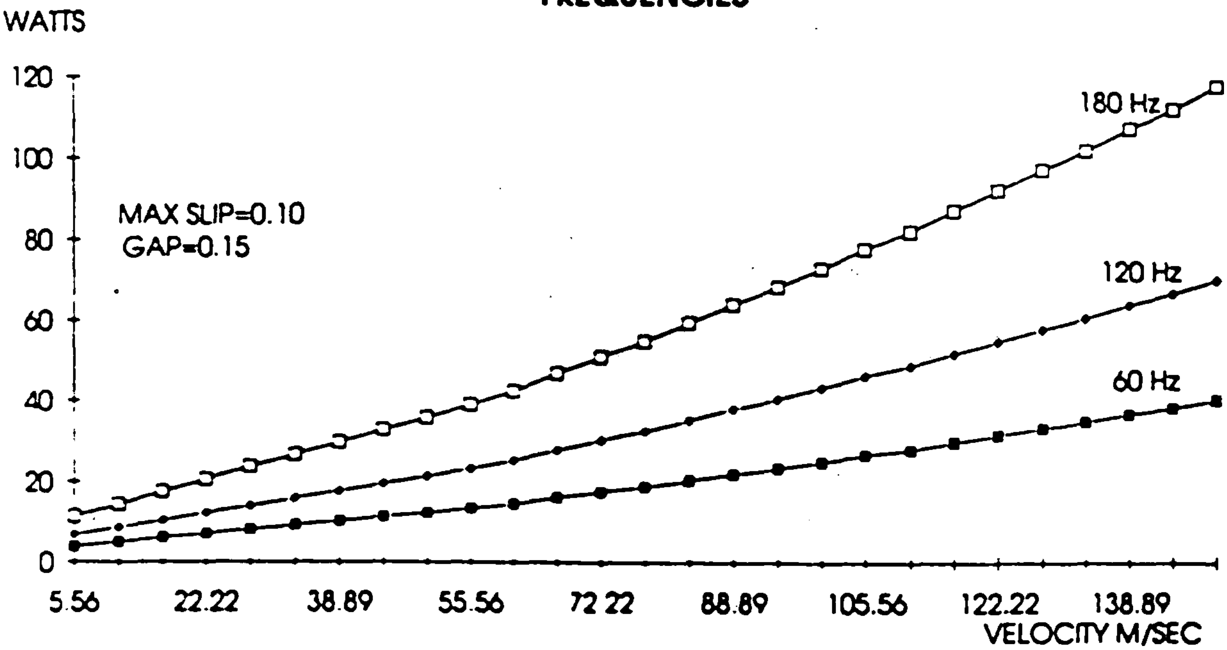


FIG V-19. AC LOSSES VS VELOCITY AT 3 DIFFERENT MAX FREQUENCIES

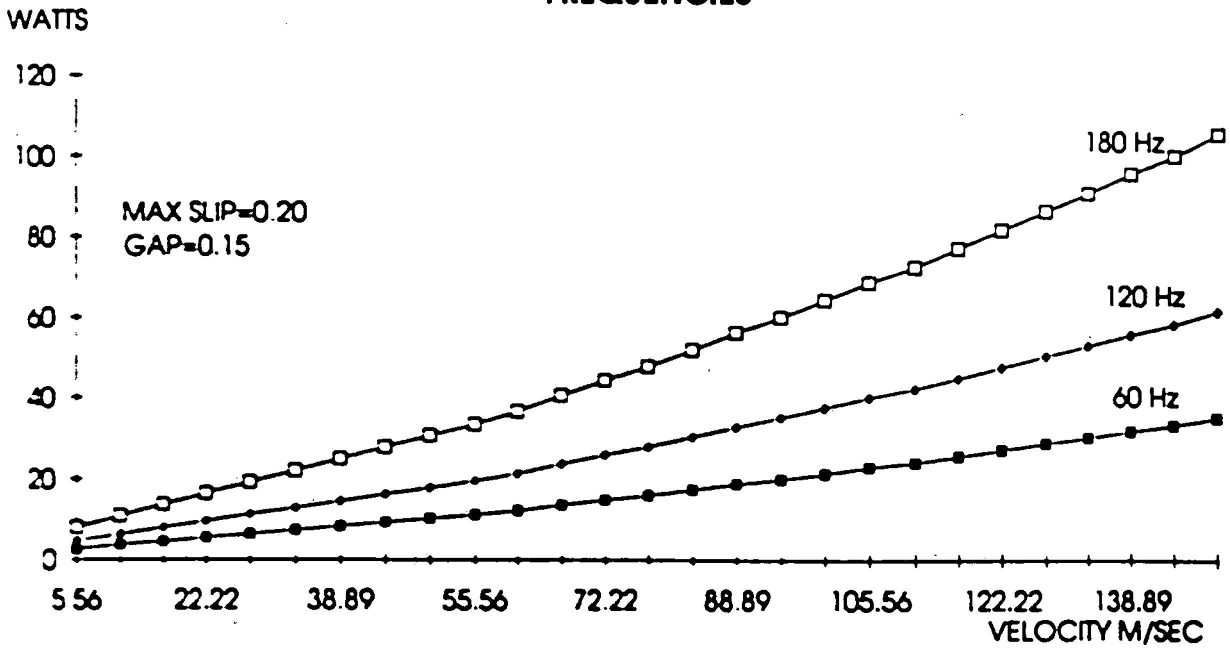


FIG V-20. AC LOSSES VS VELOCITY AT 3 DIFFERENT MAX FREQUENCIES

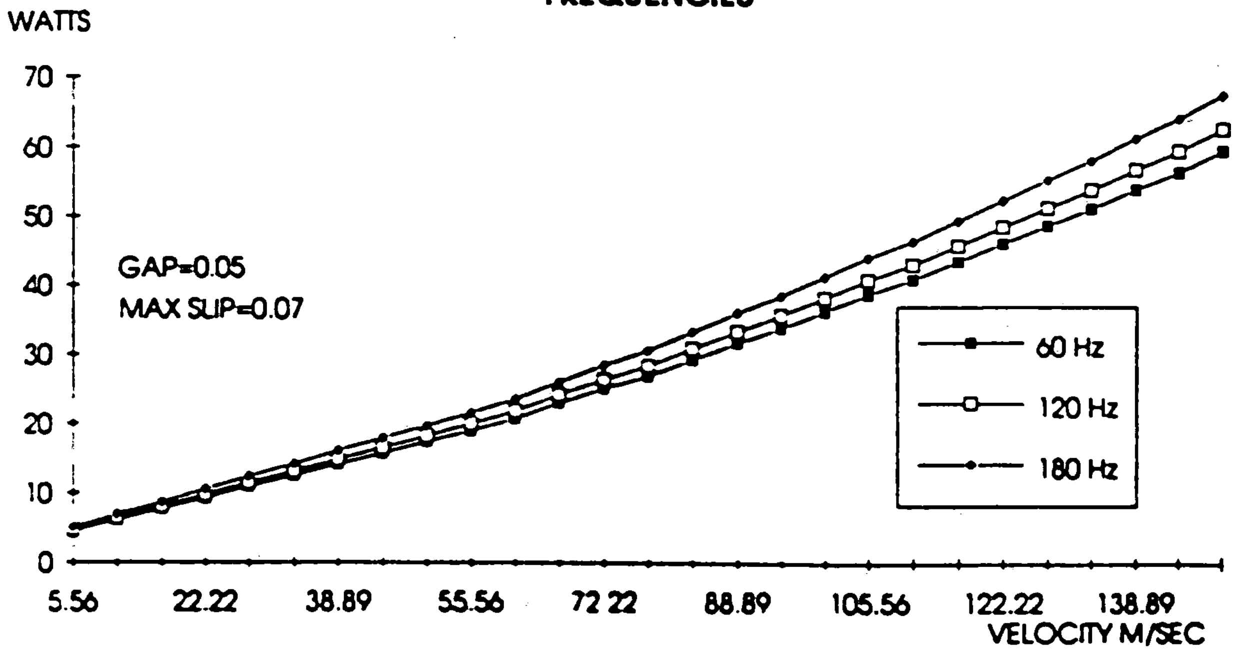


FIG V-21. AC LOSSES VS VELOCITY AT 3 DIFFERENT MAX FREQUENCIES

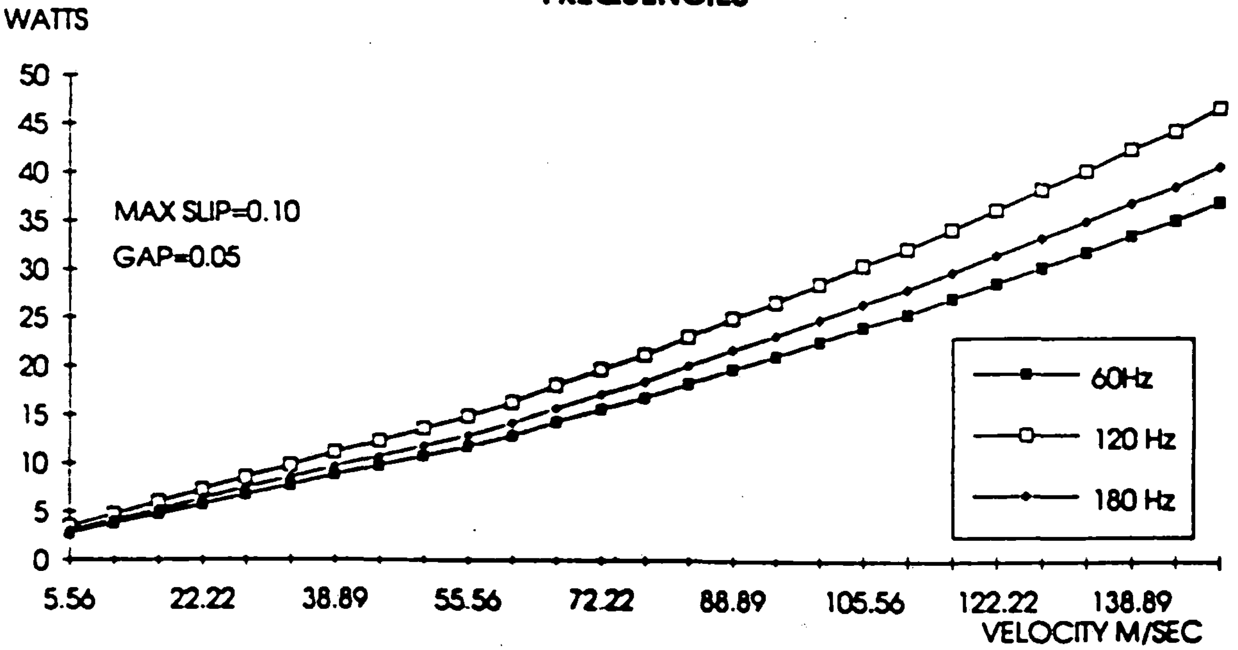


FIG V-22. AC LOSSES VS VELOCITY AT 3 DIFFERENT MAX FREQUENCIES

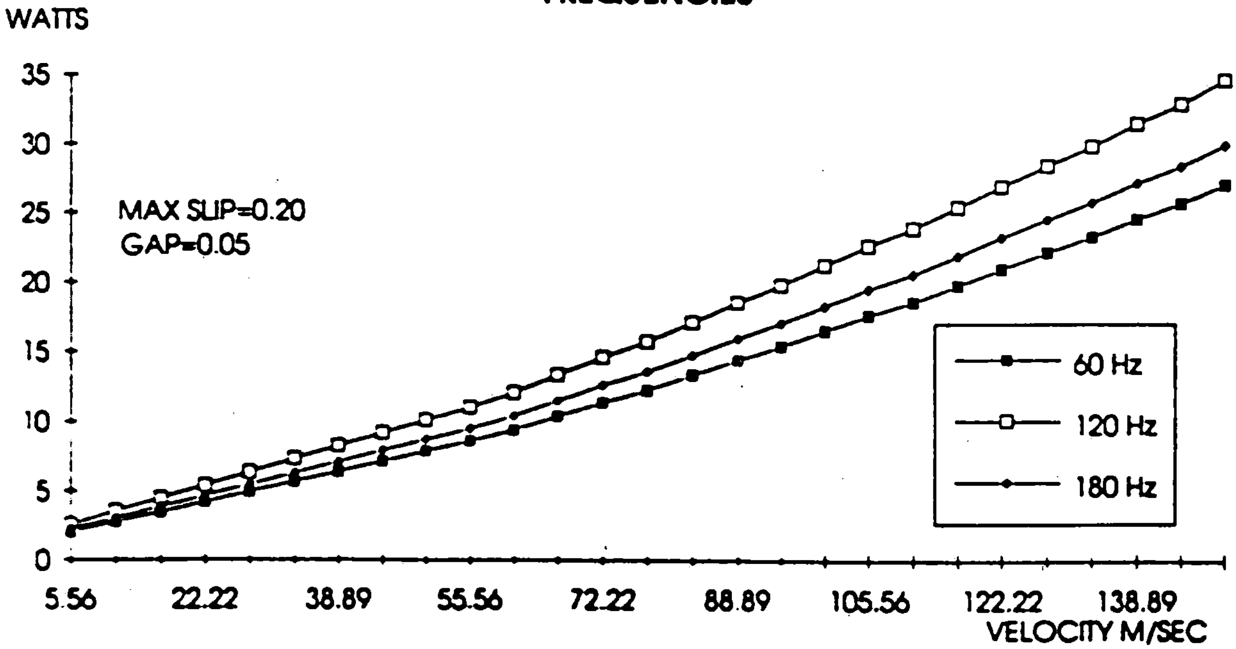


FIG V-23.POWER FACTOR VS VELOCITY AT DIFFERENT MAX FREQUENCIES

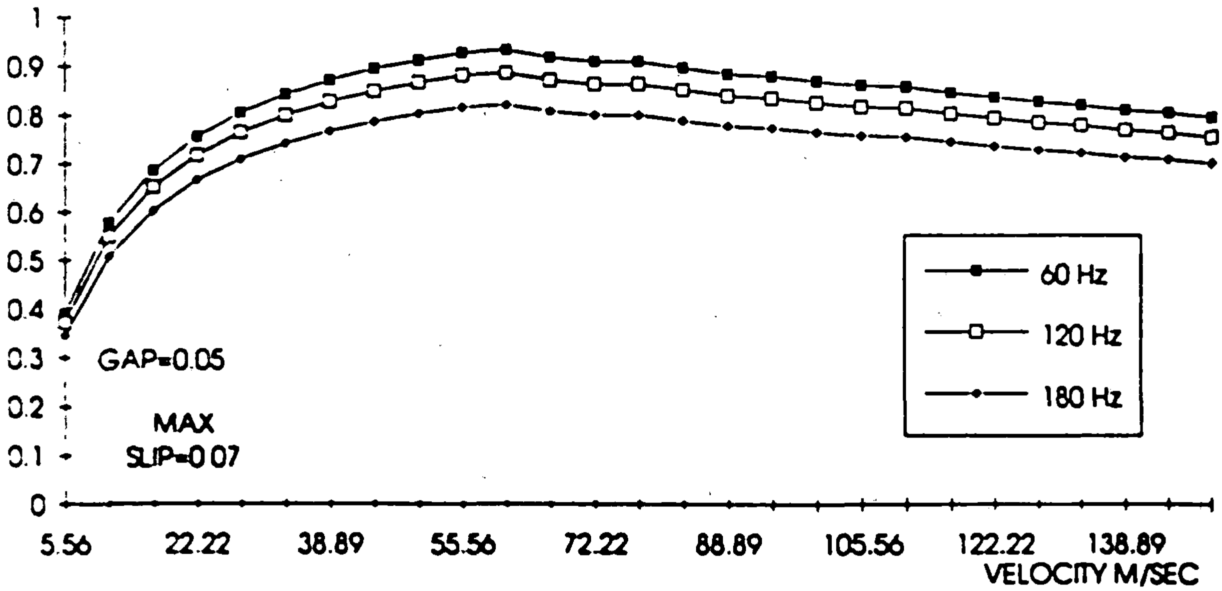


FIG V-24. POWER FACTOR VS VELOCITY AT DIFFERENT MAX SLIPS

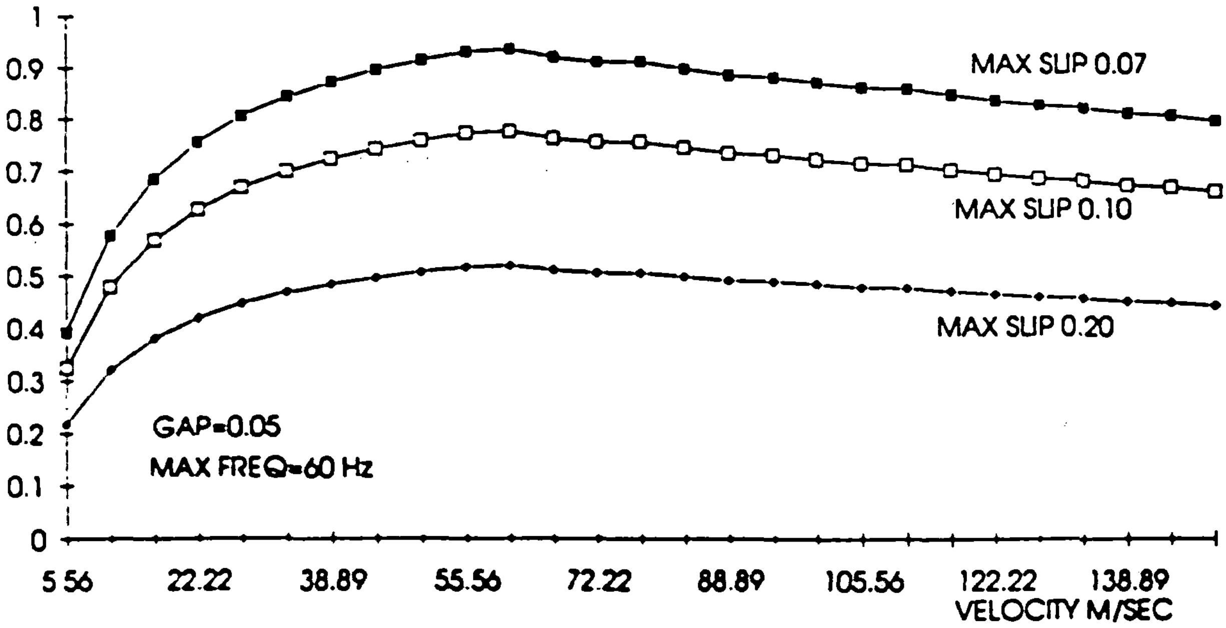


FIG V-25. GOODNESS FACTOR VS VELOCITY AT DIFFERENT MAX FREQUENCIES

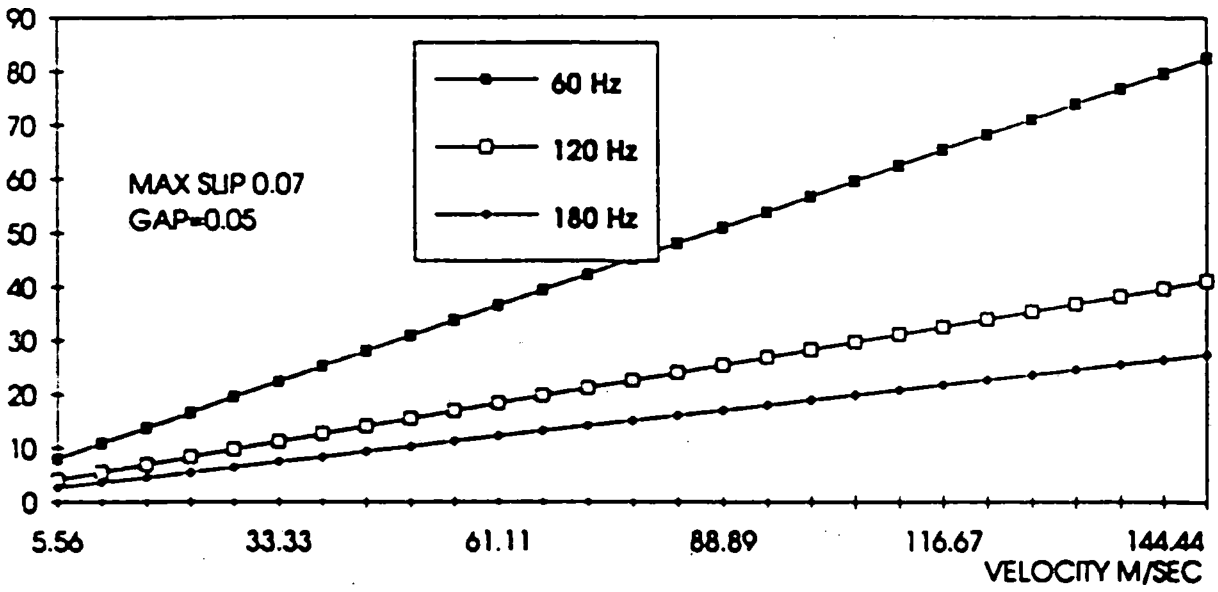


FIG V-26. GOODNESS FACTOR VS VELOCITY AT DIFFERENT MAX SLIPS AT MAX FREQ 60 Hz

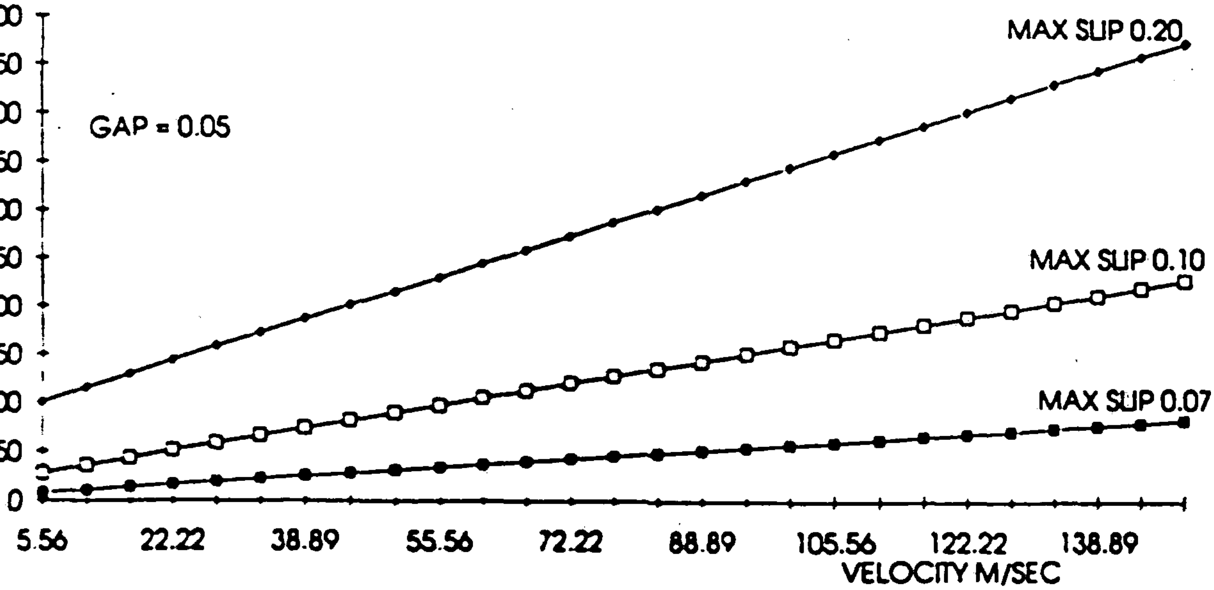


FIG V-27. CURRENT VS VELOCITY AT DIFFERENT TRACK THICKNESS

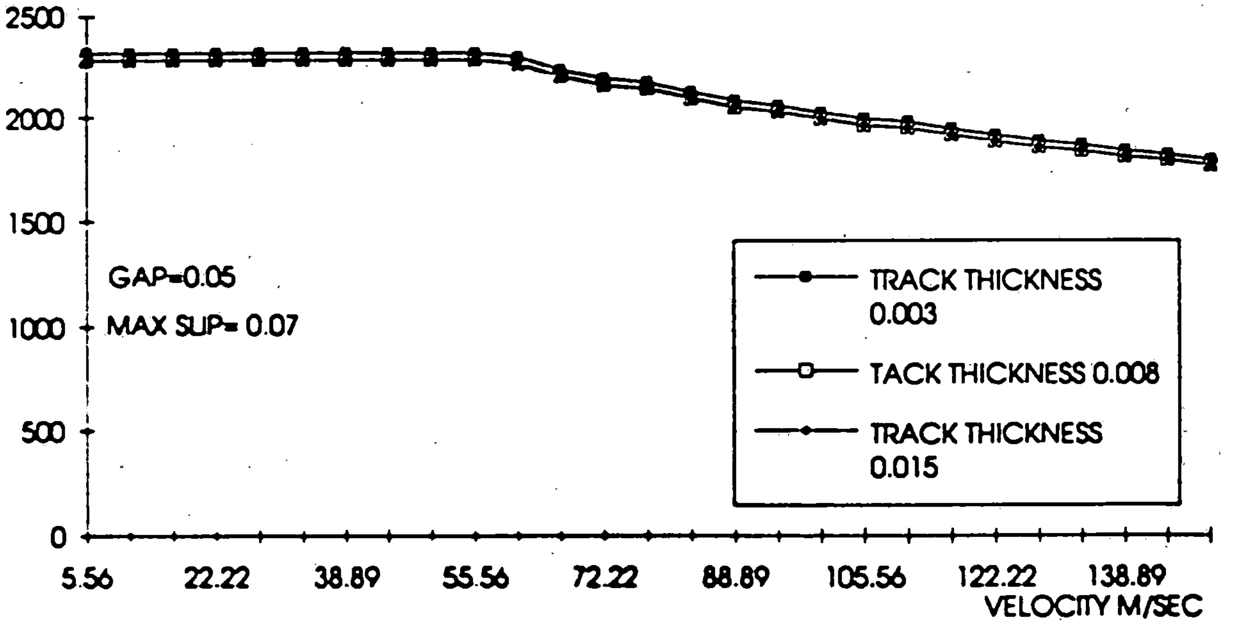


FIG 1. THRUST AND DRAG REQUIREMENTS FOR SCLIM

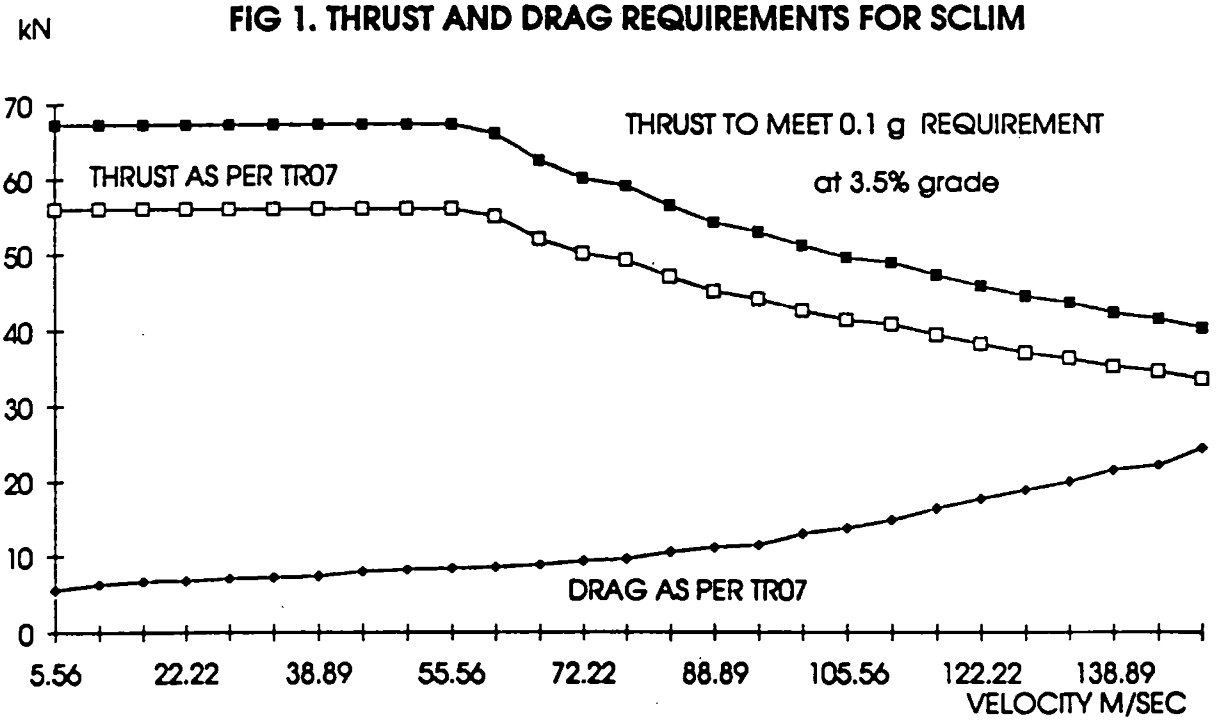
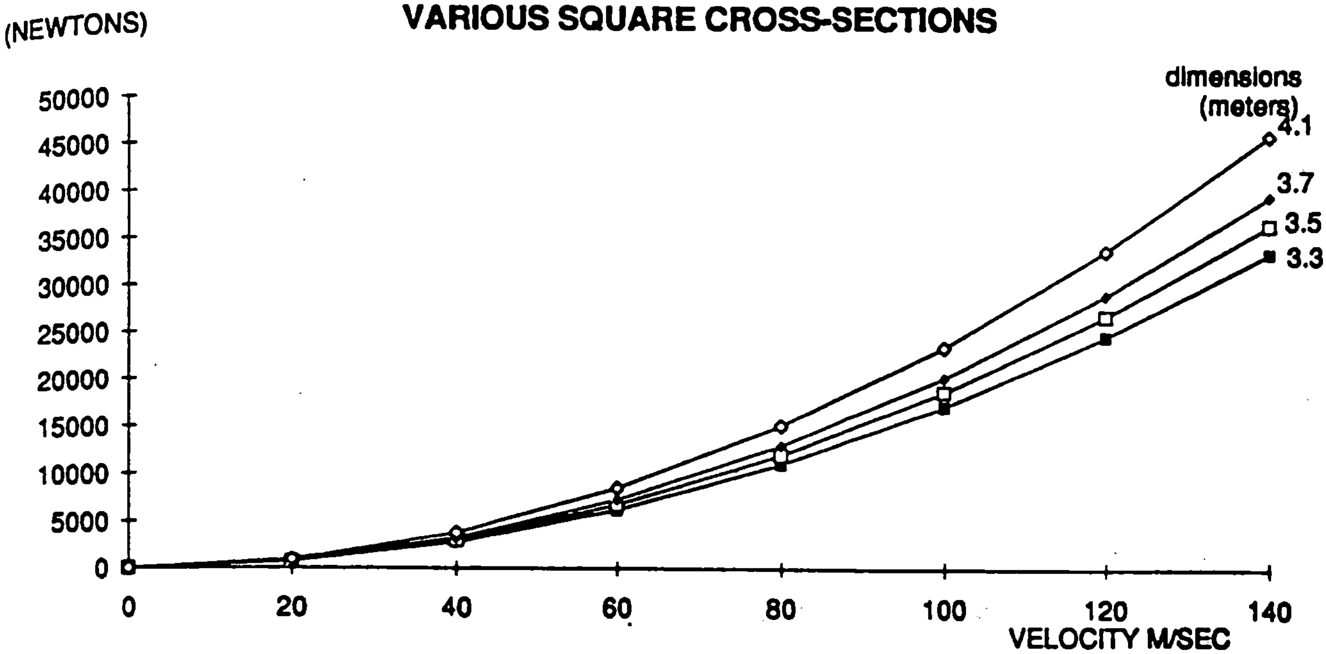
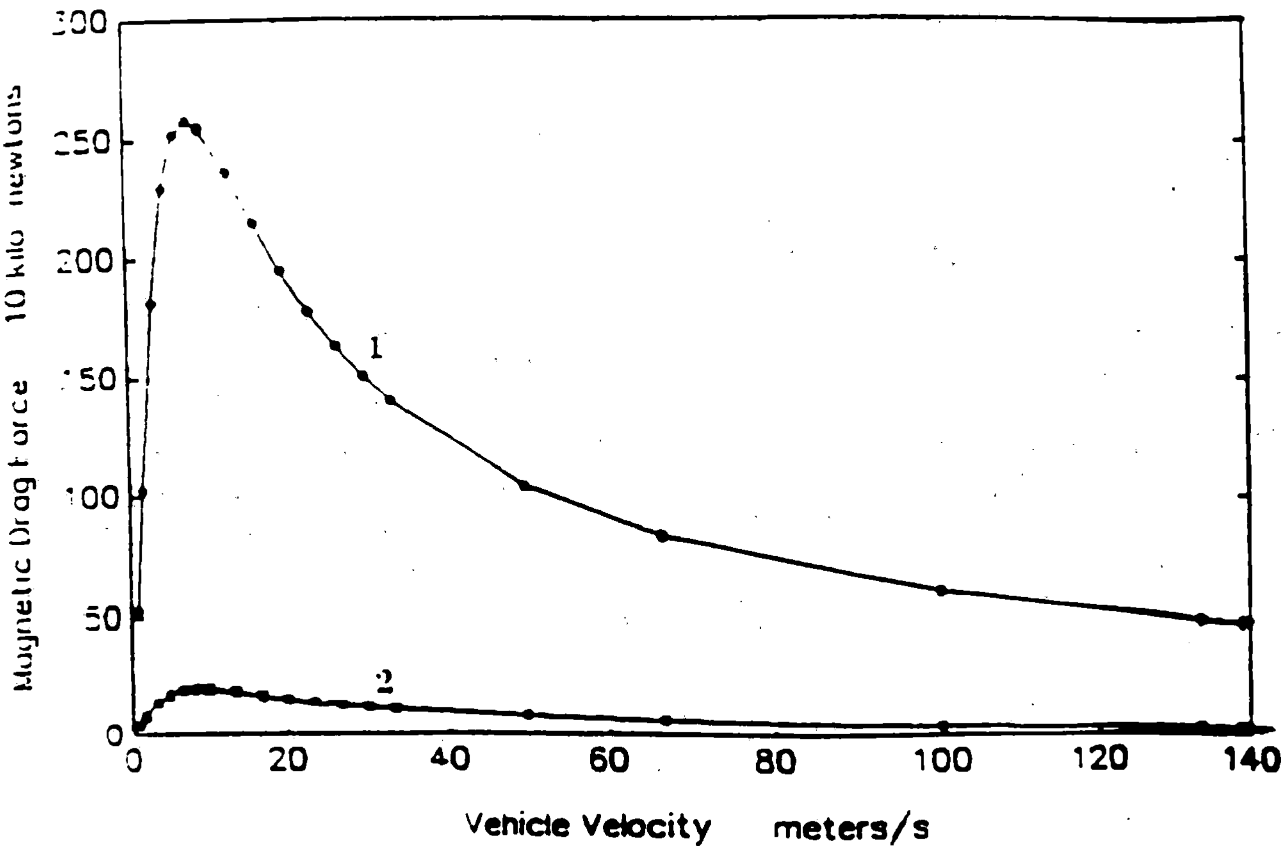


FIG 2. AERODYNAMIC PLOTS FOR MAGLEV VEHICLE WITH VARIOUS SQUARE CROSS-SECTIONS





Magnetic drag forces for CSAC levitation coils
with an air gap of 5cm and two different currents.

Curve 1 350kAT
Curve 2 100kAT

FIG 3. MAGNETIC DRAG FOR A CONTINUOUS EDS GUIDEWAY

FIG 4. NET FORCE REQUIREMENT FOR THE SCLIM VEHICLE

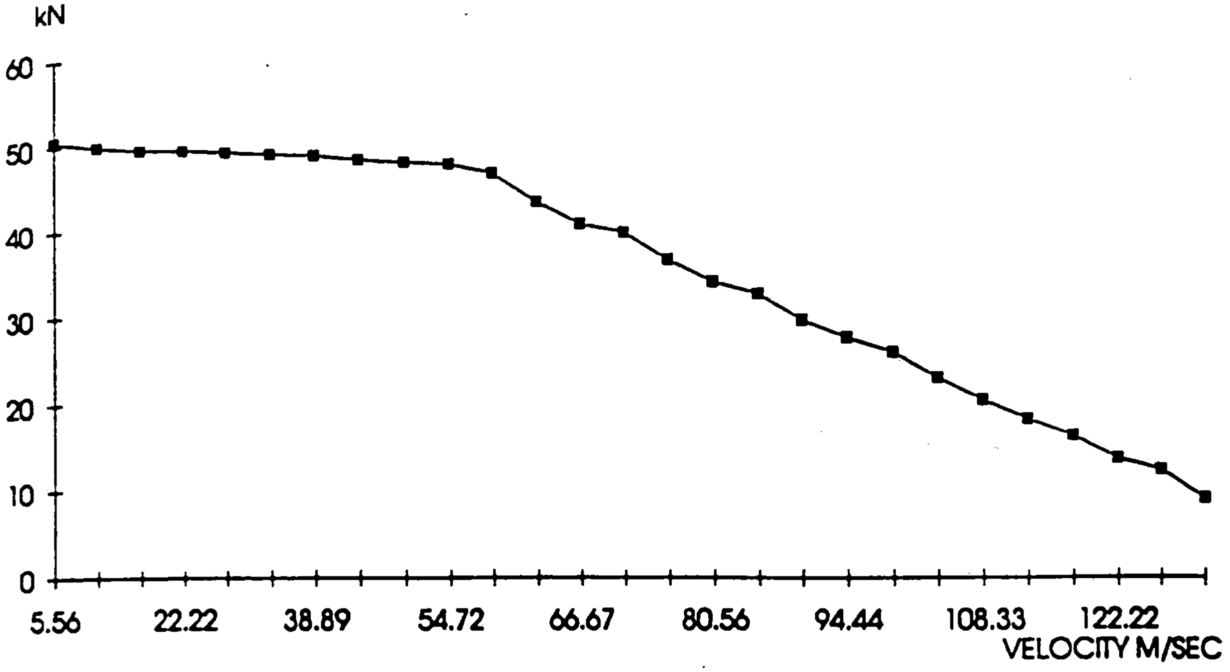
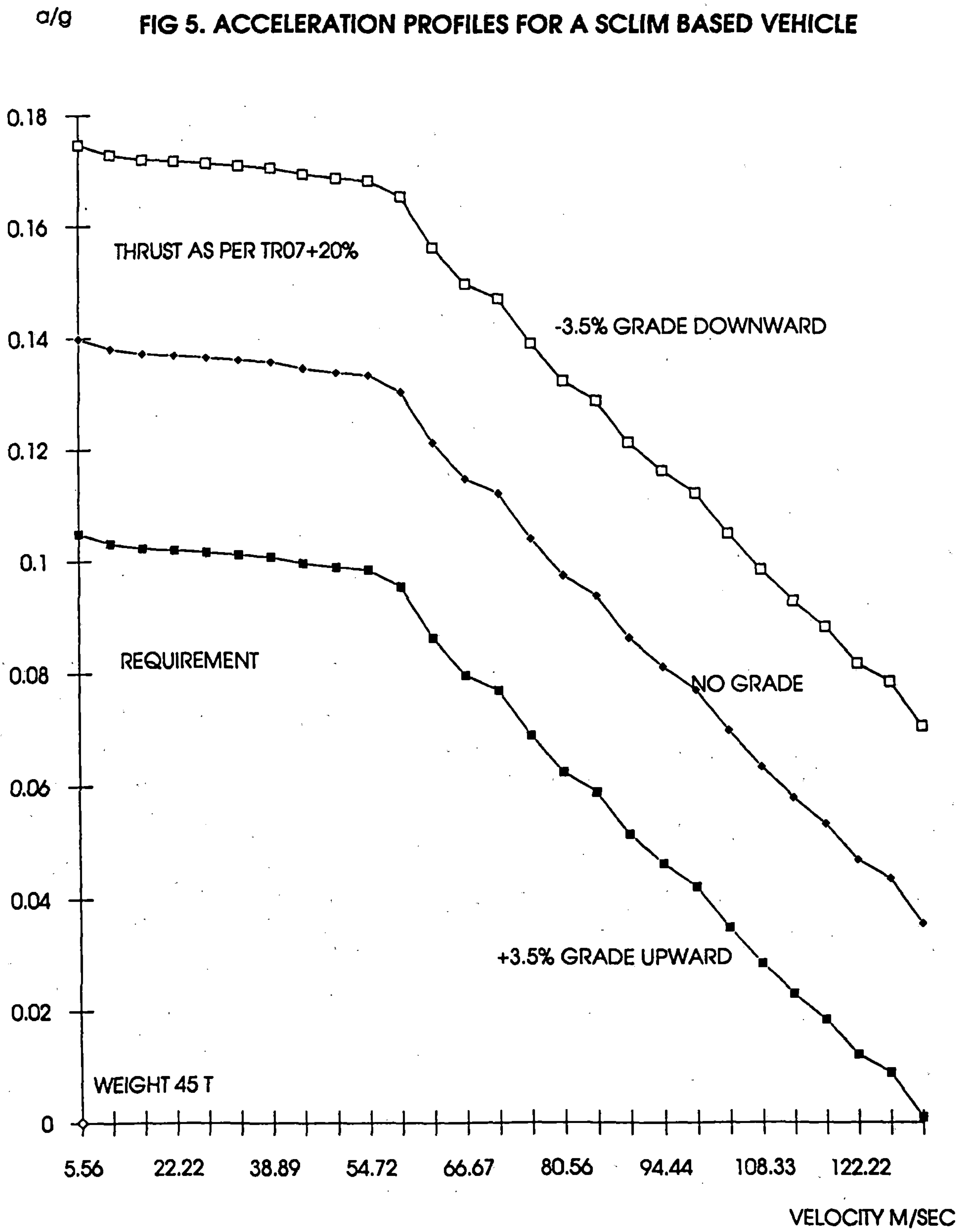


FIG 5. ACCELERATION PROFILES FOR A SCLIM BASED VEHICLE



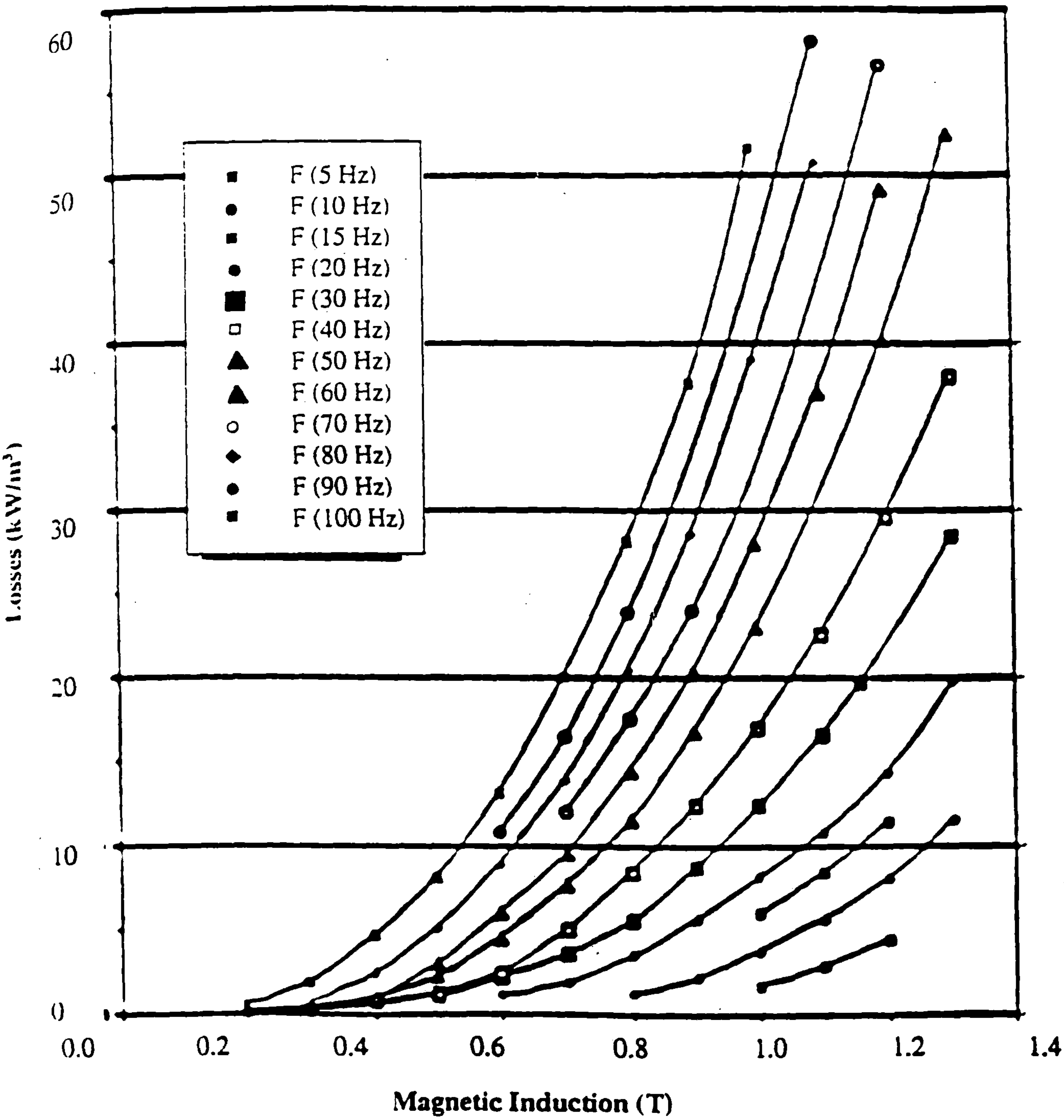
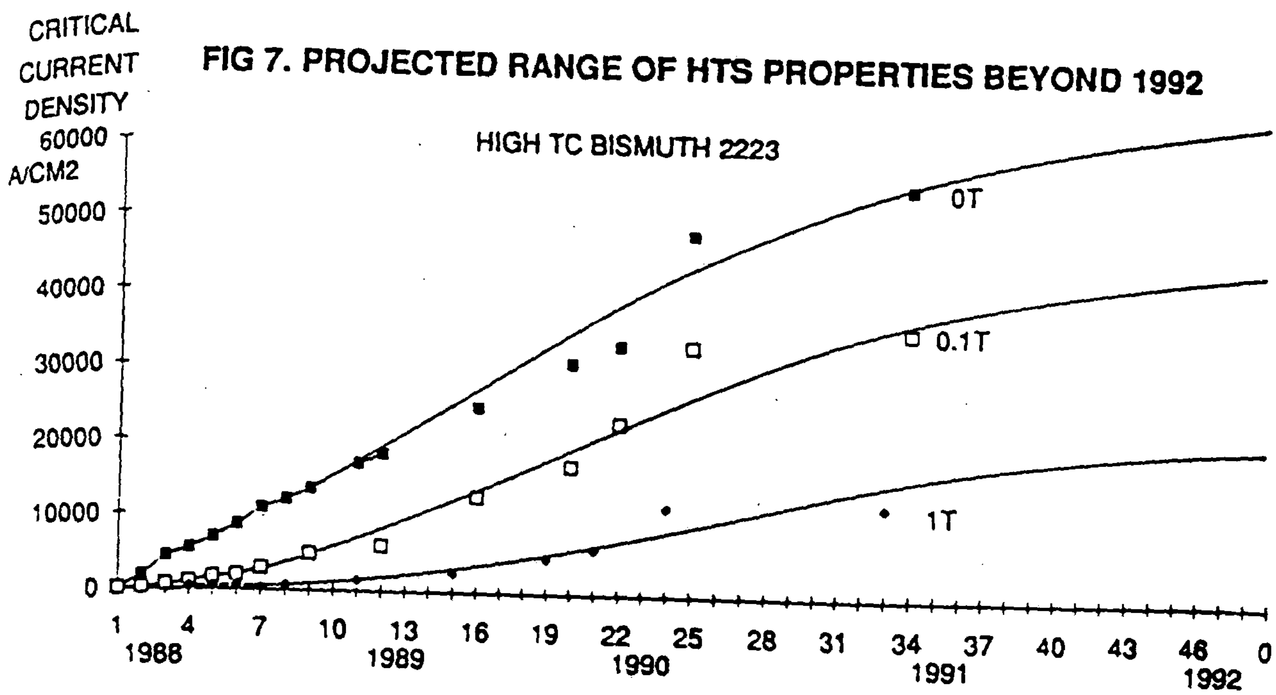


FIG 6. AC LOSSES FOR A HIGH PERFORMANCE, LOW TEMPERATURE SUPERCONDUCTOR MADE OF NBTI (SEE REFERENCE 6)

FIG 7. PROJECTED RANGE OF HTS PROPERTIES BEYOND 1992



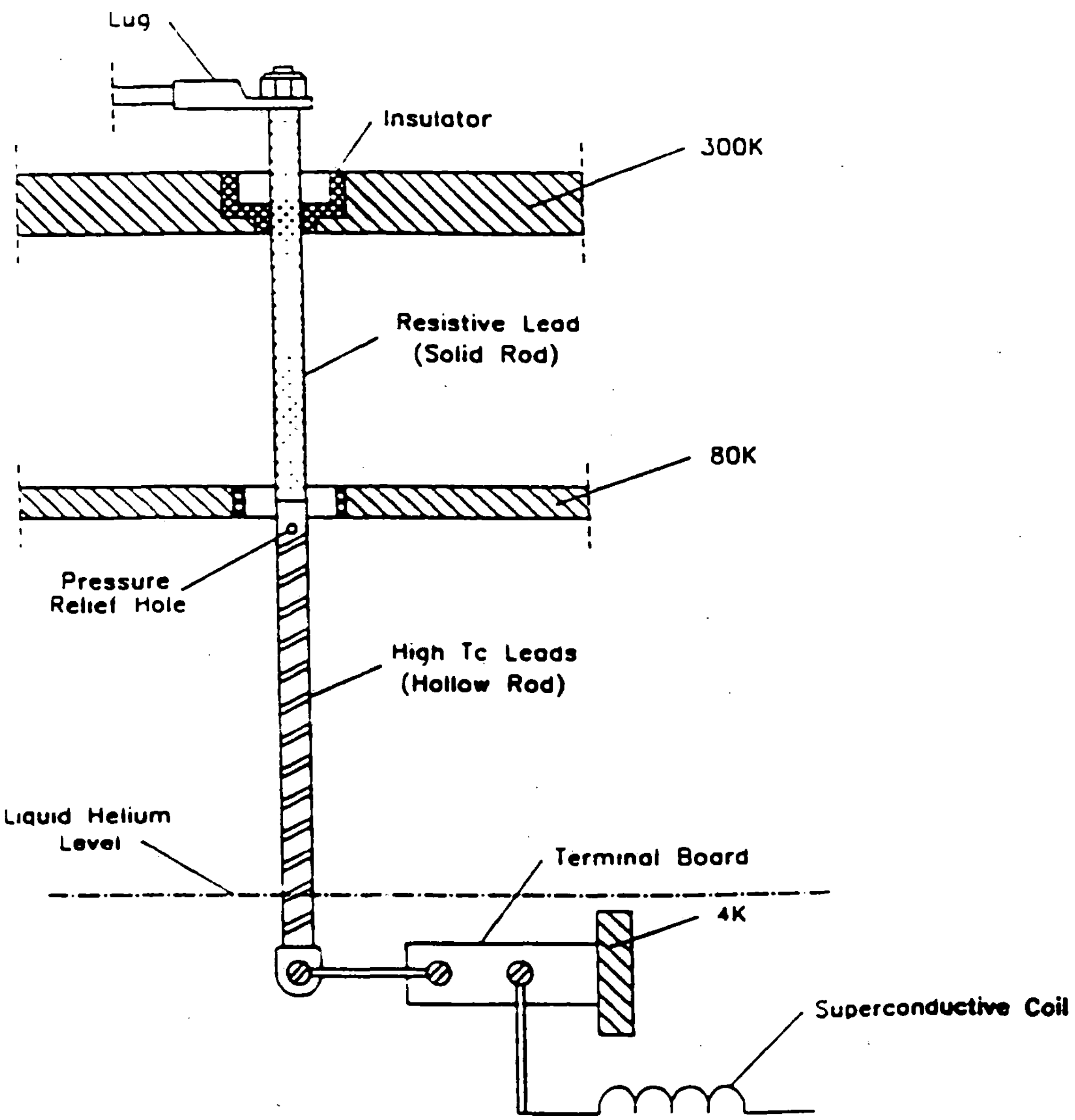


FIG 8A. HTS POWER LEAD SHOWING DETAIL FROM 4K TO 77K

IGC Ag-Sheathed BSCCO High Tc Leads

"BSCCO" : Bismuth-Lead-Strontium-Calcium-Copper-Oxide

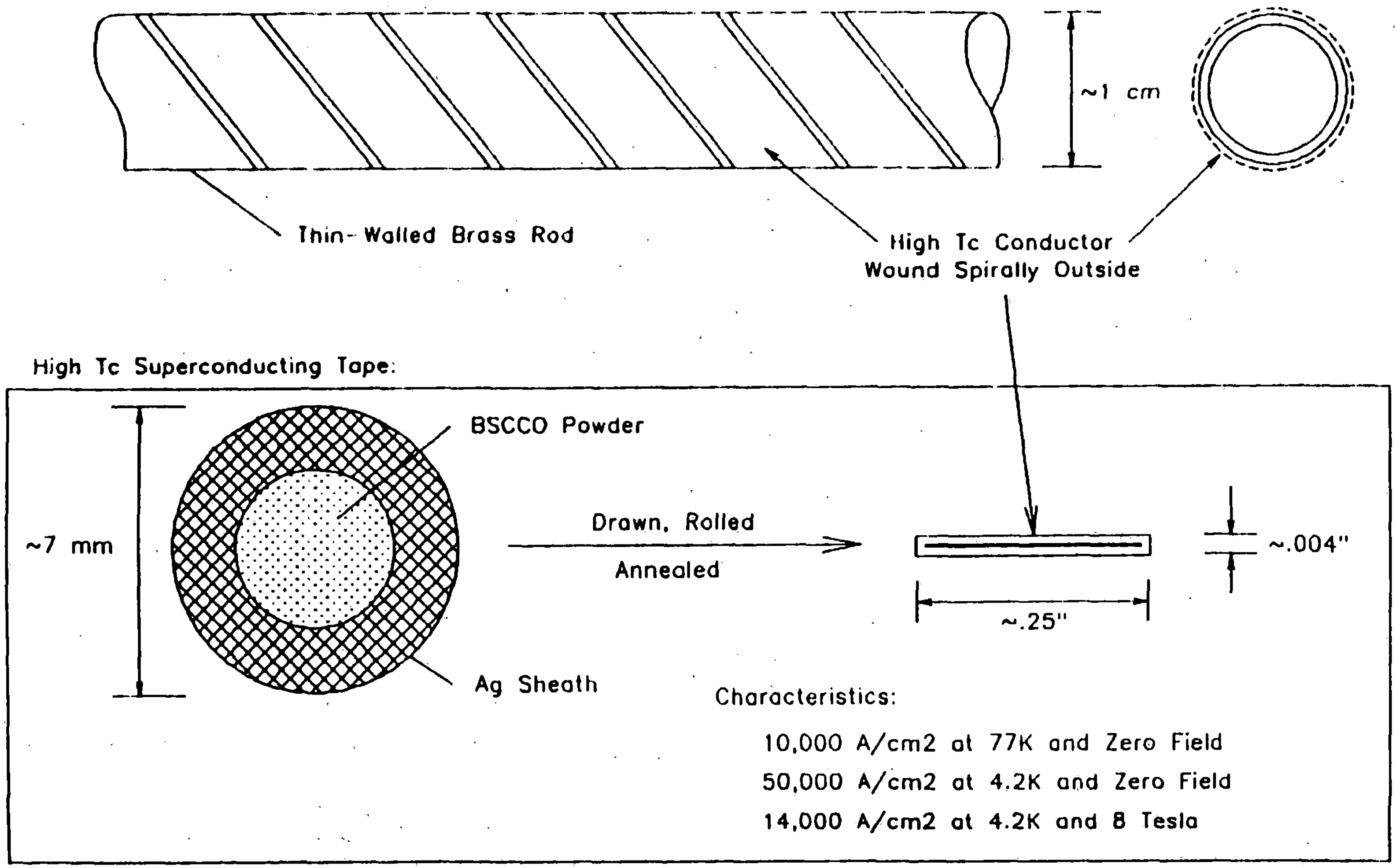


Fig. 8B HTS Power Lead showing 4K section only.

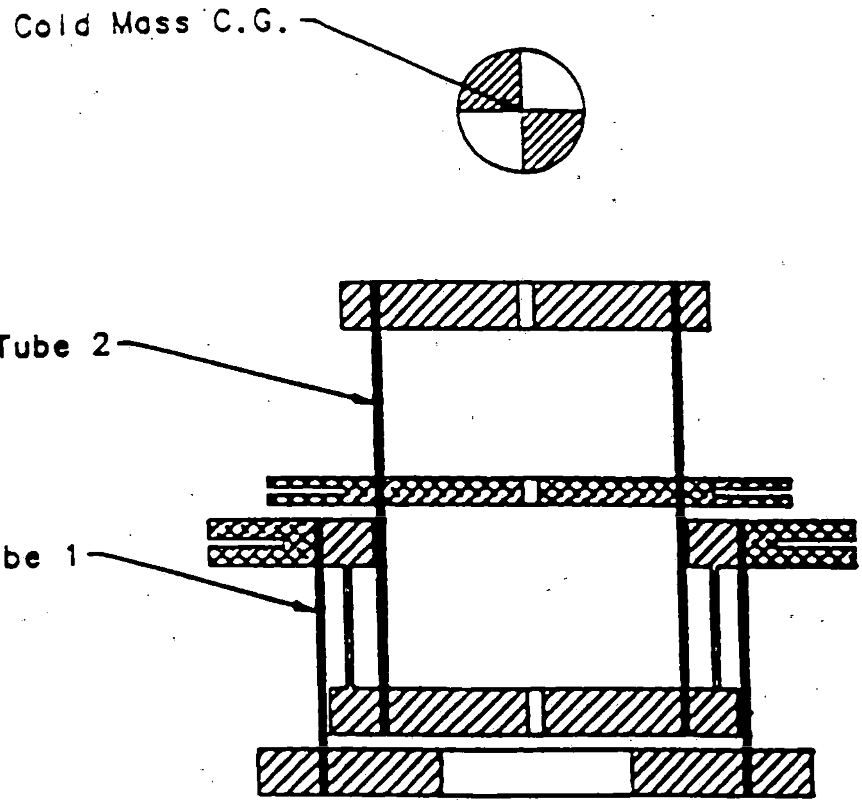


FIG 9. SSC CYLINDRICAL CRYOGENIC SUPPORT

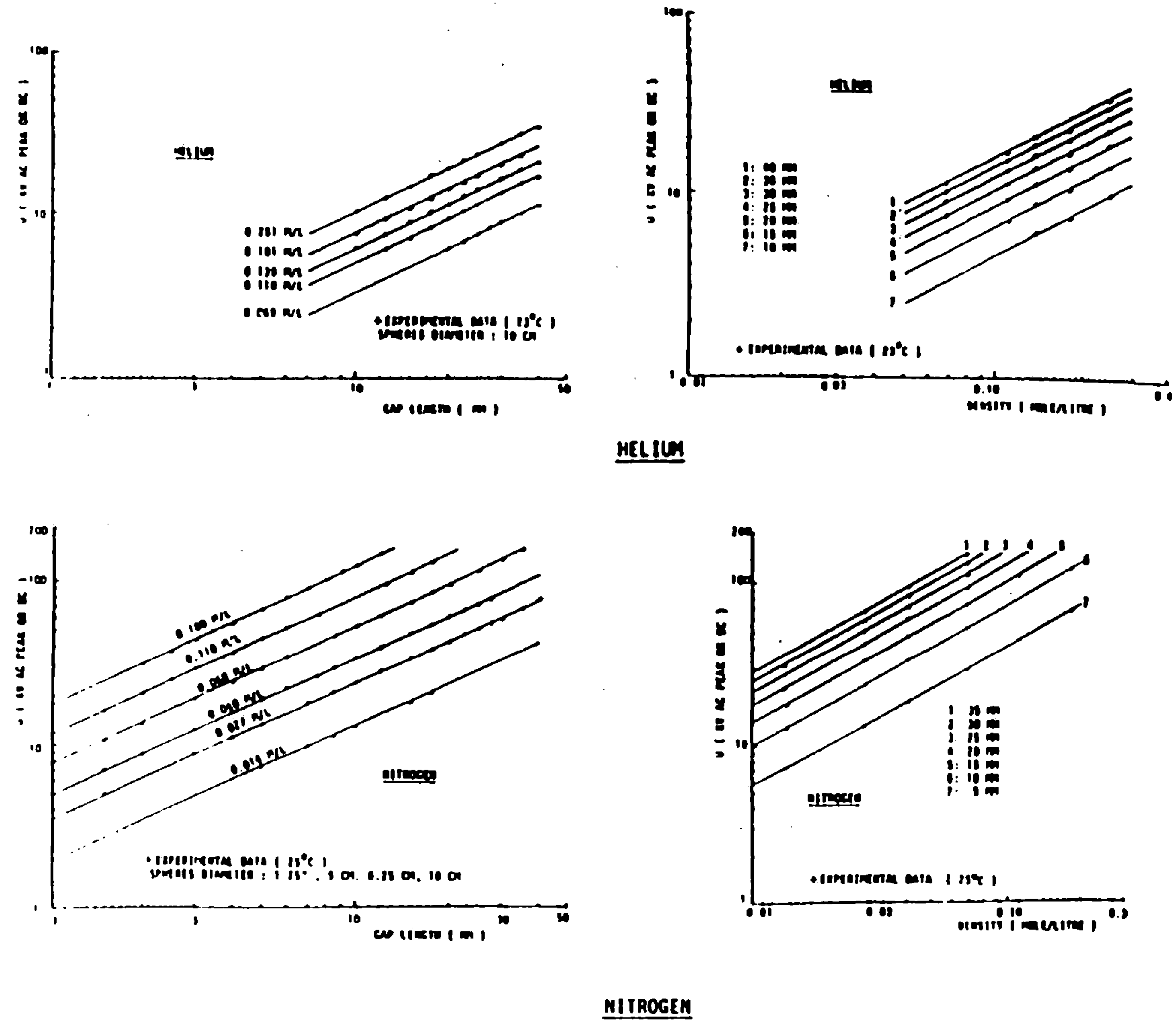


FIG 10. HELIUM AND NITROGEN VOLTAGE BREAKDOWN LIMITS

FIG 11. INPUT POWER VS VELOCITY AT DIFFERENT GAPS

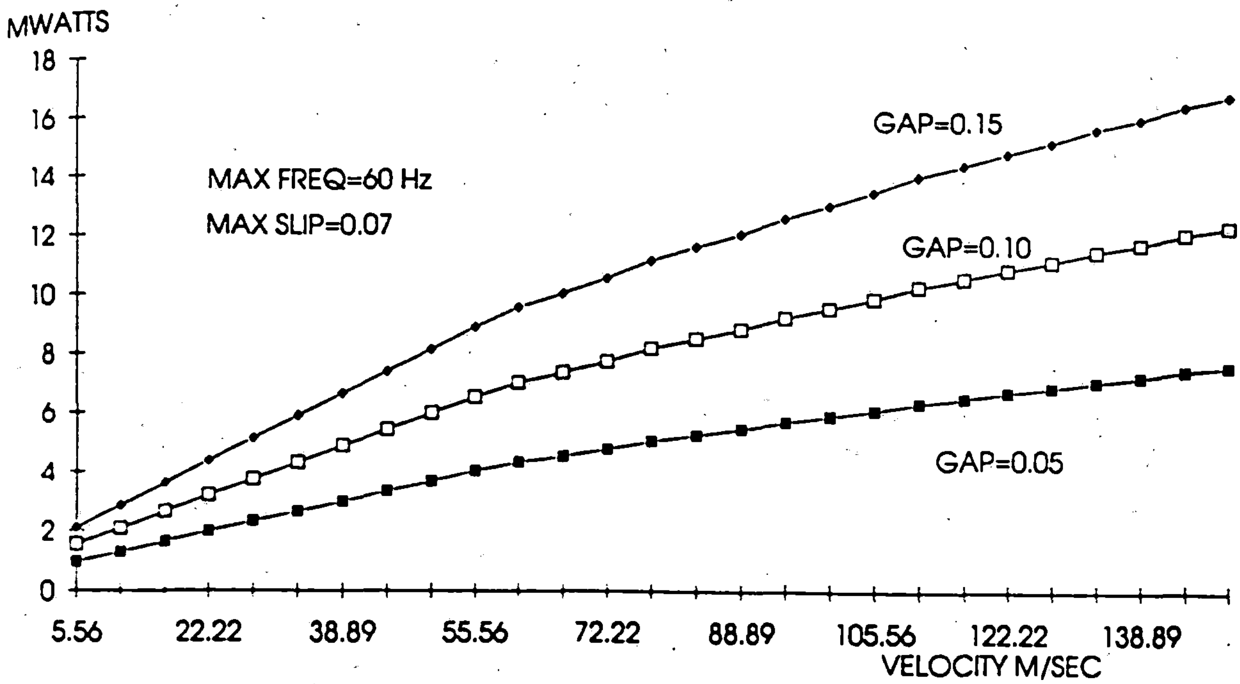


FIG 12. INPUT POWER VS VELOCITY AT DIFFERENT TRACK THICKNESS

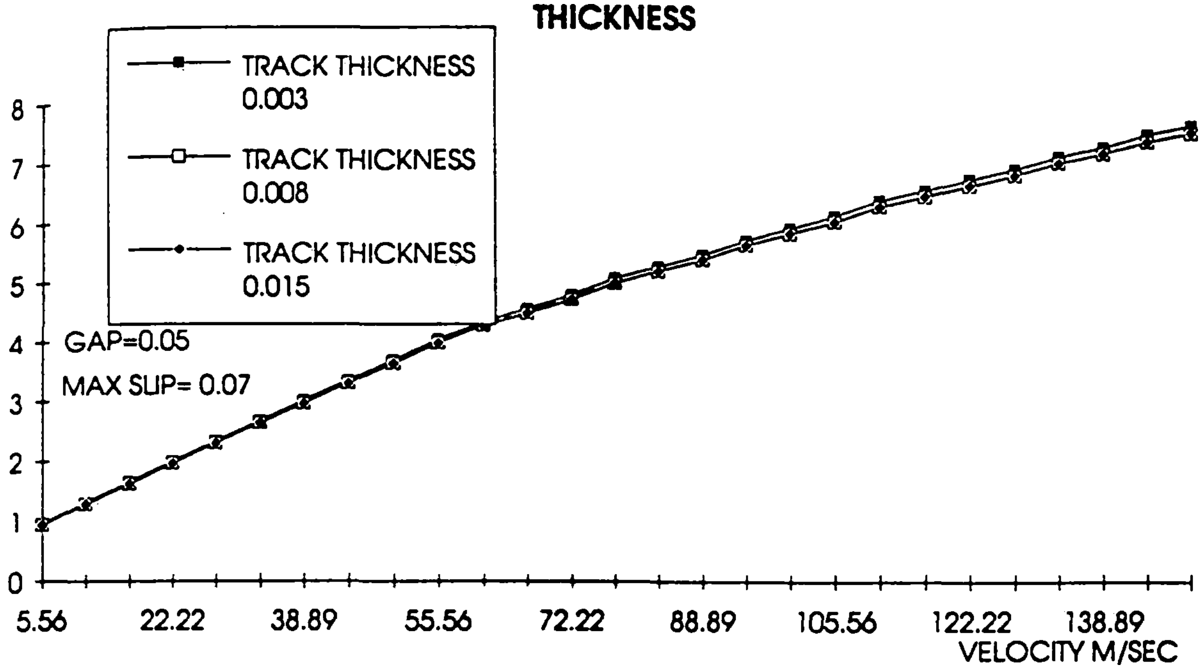
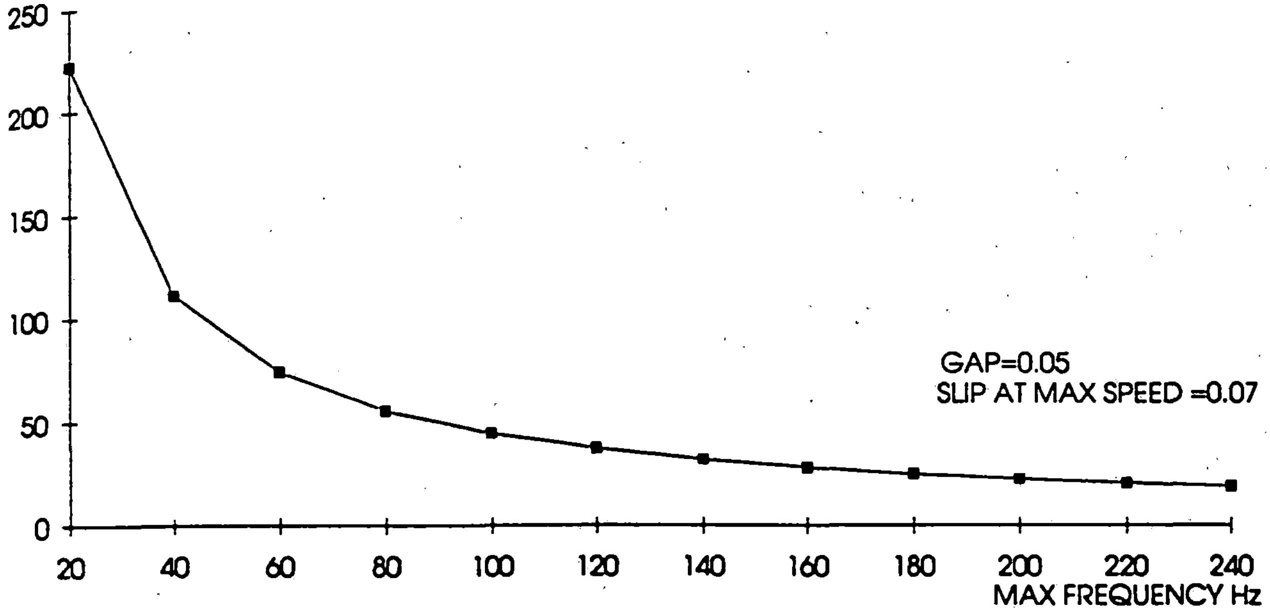


FIG 13. LIM GOODNESS VS. MAXIMUM DESIGN FREQUENCY (FM)



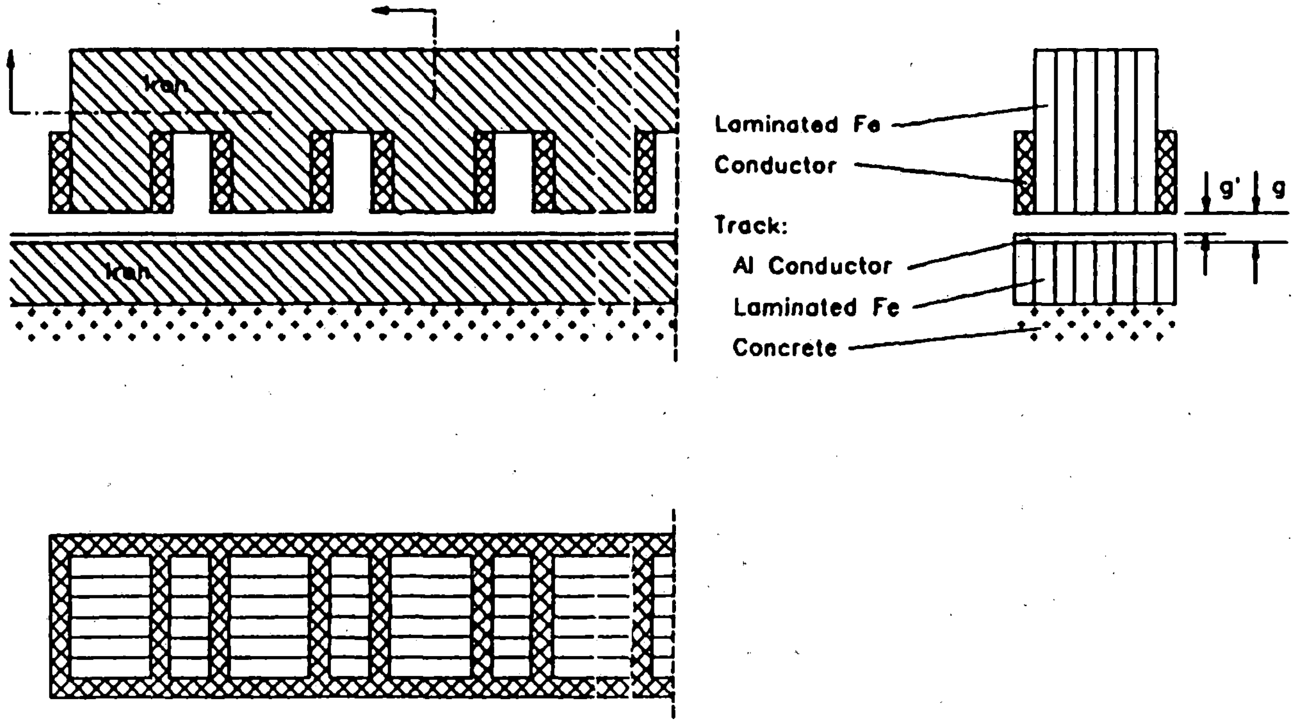


FIG 14. COPPER IRON CORE LIM

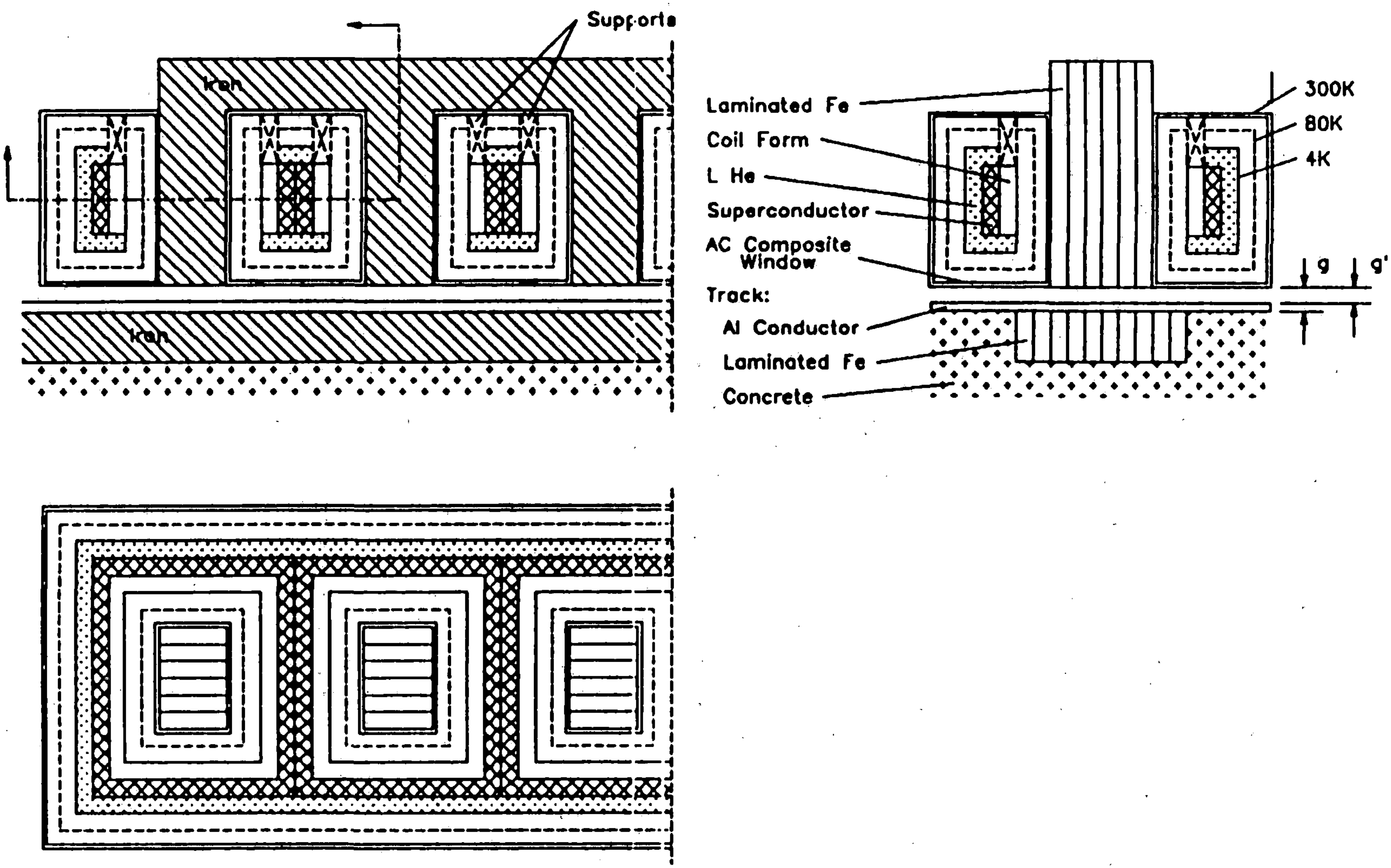
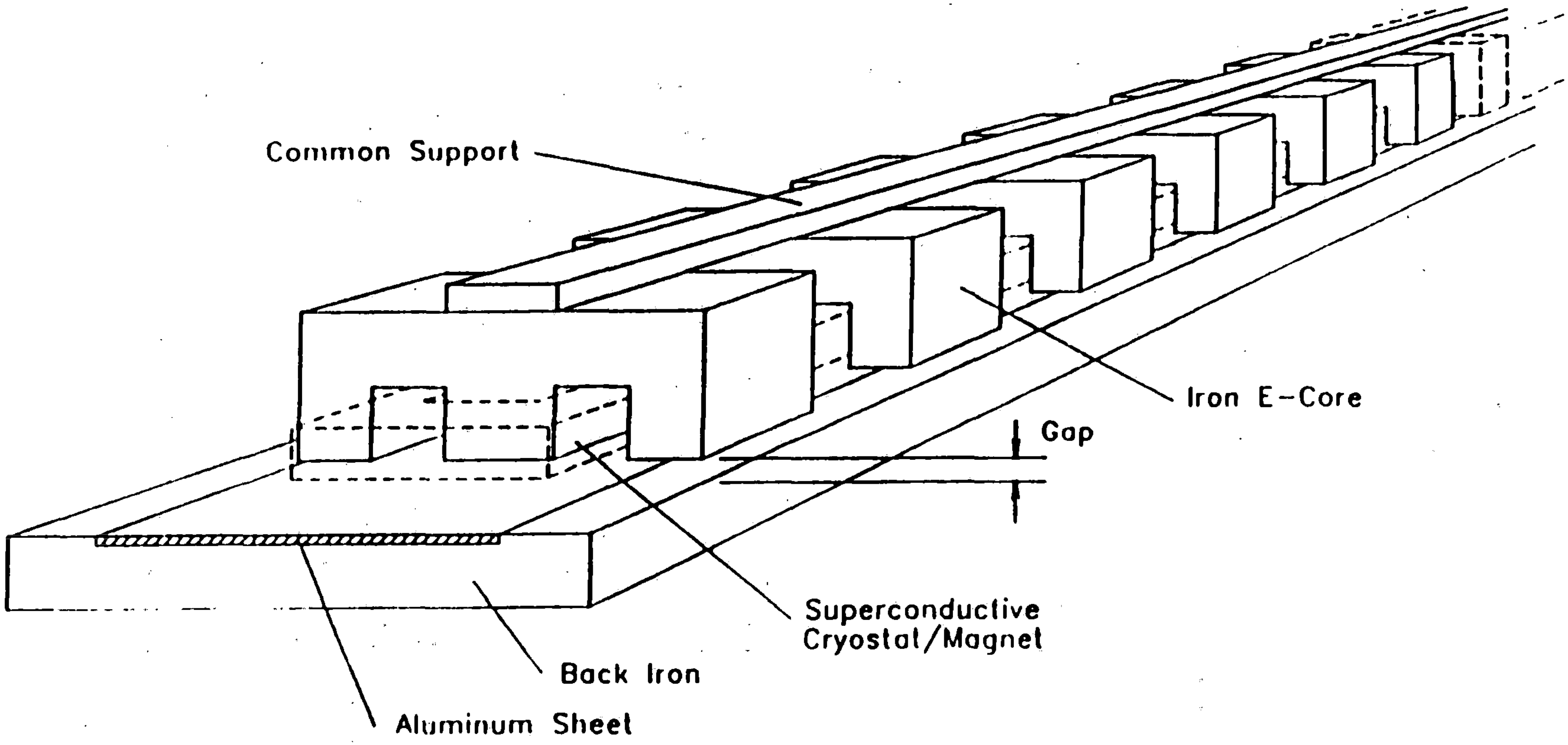


FIG 15. WARM IRON CORE SCLIM CONCEPTUAL DESIGN

FIG 16. WARM IRON CORE TRANSVERSE CONCEPTUAL DESIGN



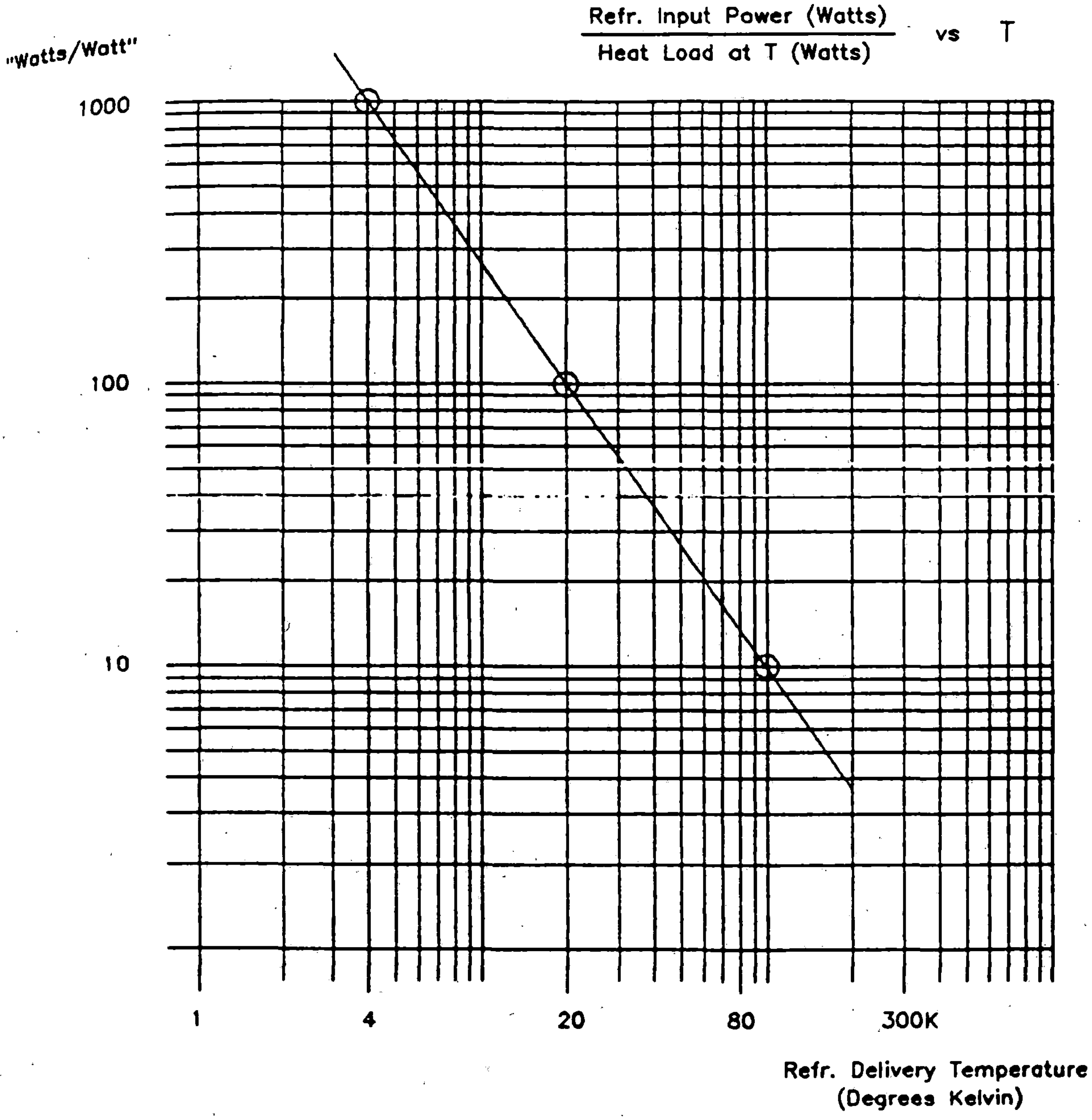


FIG 17. HELIUM REFRIGERATION INPUT POWER/HEATLOAD VS. TEMPERATURE

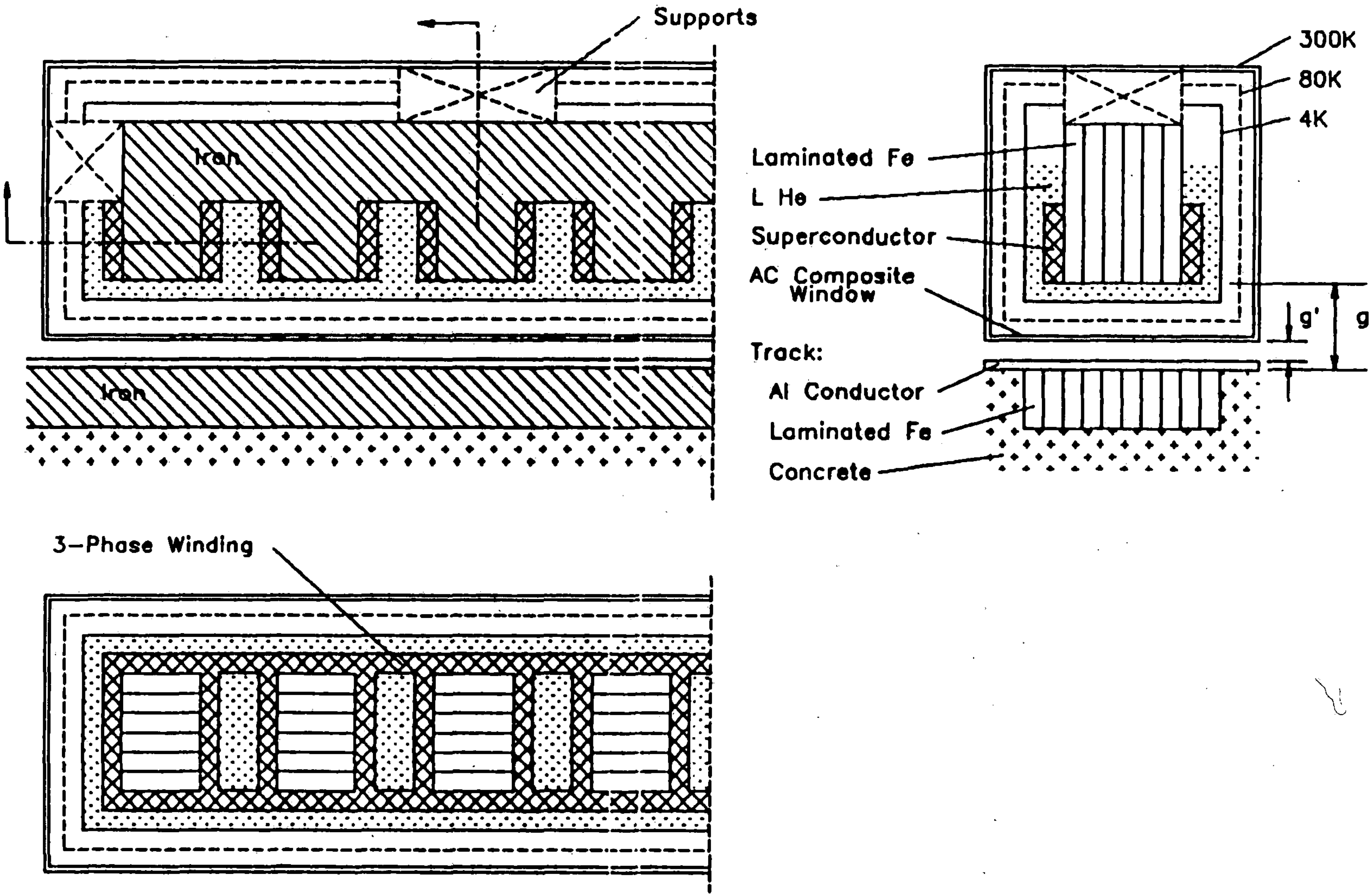


FIG 18. COLD IRON CORE SCLIM CONCEPTUAL DESIGN

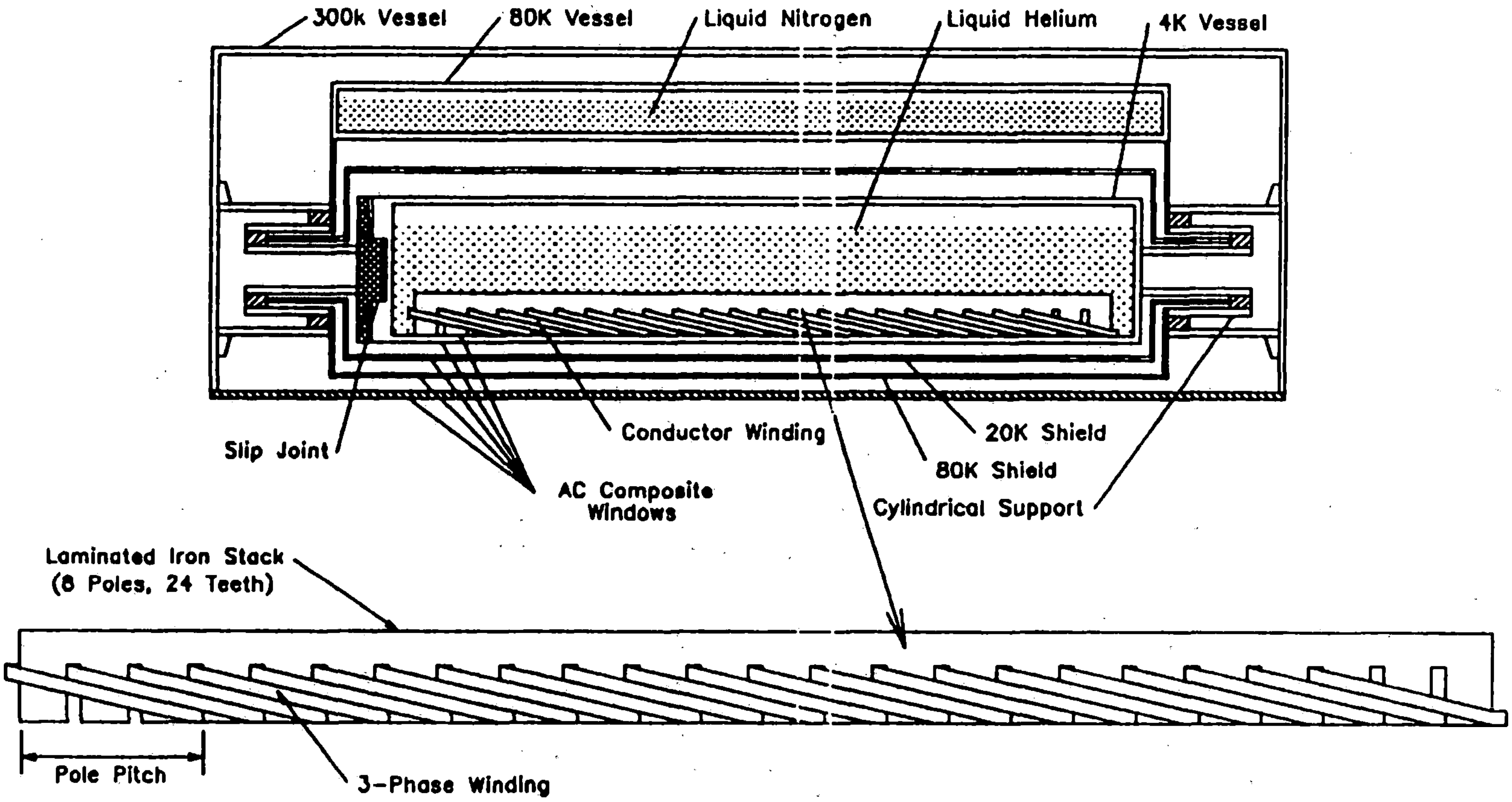
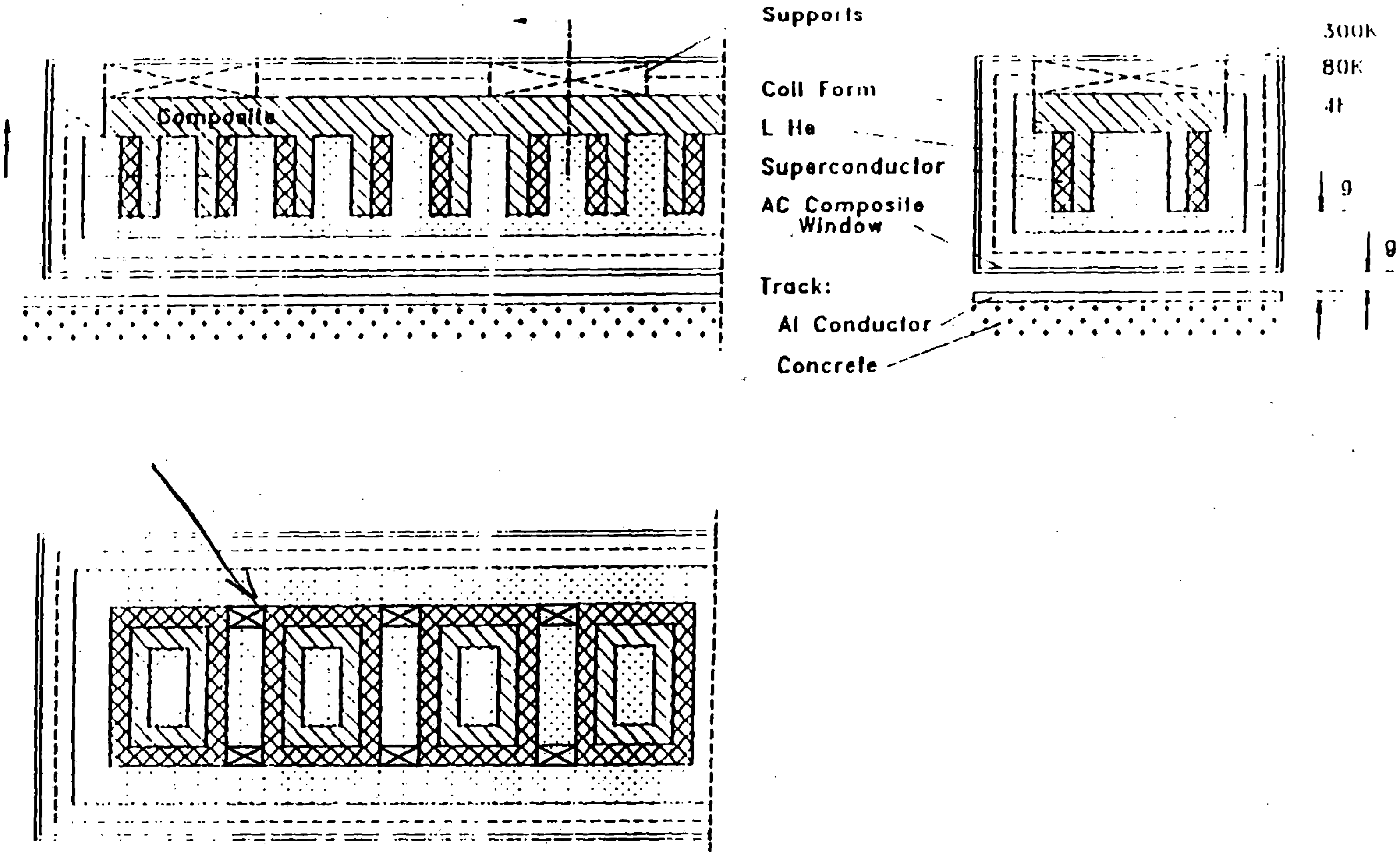


FIG 19. COLD IRON CORE SCLIM CONCEPTUAL DESIGN

(WITH HORIZONTAL SUPPORTS ONLY)

FIG 20. AIRCORE SCLIM CONCEPTUAL DESIGN



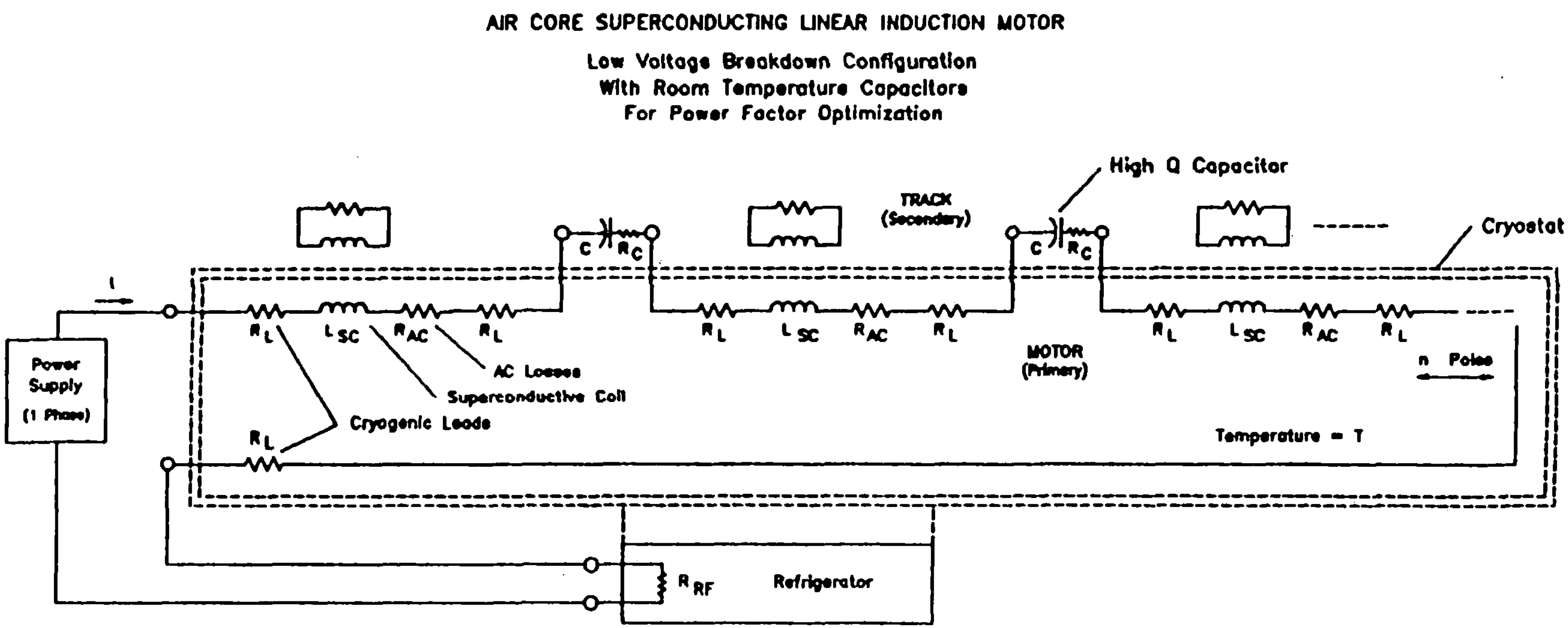


FIG 22. POWER FACTOR AND COMPENSATION EXTERNAL TO CRYOSTAT

TABLES

TABLE 1
CRYOGENIC DESIGN RULES

Radiation (300K to 77K)	0.75 W/m^2
Radiation (20K to 4K)	0.004 W/m^2
Cold Mass Support Conduction (300K to 77K)	1.12 W/1,000 kg
Cold Mass Support Conduction (20K to 4K)	0.018 W/1,000 kg

TABLE 2
COPPER IRON CORE LIM AT 10 CM GAP, 60 Hz AND 180 Hz COMPARISON

Gap = 10 cm	60 Hz	180 Hz	Units
Pole Pitch	1.2	0.4	meters
No. Poles	8	8	
Dimensions	0.11 x 1.48 x 9.64	0.13 x 0.53 x 3.25	meters
Voltage	2200	2200	volts (rms)
Current	2007	2863	kA (rms)
Input Power	7.65	10.9	MVA
Mechanical Output	5.97	5.97	MW
Power Factor	0.78	0.547	
Current Density	500	500	amp/cm^2
Cu I^2R Losses	80.3	38.2	kW
SC AC Losses	–	–	watts
Refrigeration	135	50	kW
Motor Weight	12.72	1.86	tonnes
System Weight	21.18	7.74	tonnes
Est. Cost	0.946	1.125	$ (millions)

TABLE 3
COPPER IRON CORE LIM AT 15 CM GAP, 60 Hz AND 180 Hz COMPARISON

Gap = 10 cm	60 Hz	180 Hz	Units
Pole Pitch	1.2	0.4	meters
No. Poles	8	8	
Voltage	2200	2200	volts (rms)
Current	2163	3750	kA (rms)
Input Power	8.24	14.3	MVA
Mechanical Output	5.97	5.97	MW
Power Factor	0.72	0.417	
Current Density	500	500	amp/cm^2
Cu I^2R Losses	86.6	50	kW

TABLE 4
COPPER IRON LIM AND WARM IRON SCLIM AT 60 Hz, 10 CM GAP

Gap = 10 cm	Copper Iron LIM	Warm Iron SCLIM	Units
Pole Pitch	1.2	0.4	meters
No. Poles	8	8	
Dimensions	0.11 x 1.48 x 9.64	0.11 x 1.58 x 9.74	meters
Voltage	2200	2200	volts (rms)
Current	2007	2007	kA (rms)
Input Power	7.65	7.65	MVA
Mechanical Output	5.97	5.97	MW
Power Factor	0.780	0.780	
Current Density	500	10,000	amp/cm^2
Cu I^2R Losses	80.3	–	kW
SC AC Losses	–	24.7	watts
Refrigeration	135	48	kW
Motor Weight	12.72	12.25	tonnes
System Weight	21.18	17.37	tonnes
Est. Cost	0.946	2.36	$ (millions)

TABLE 5
COPPER IRON CORE LIM AND COLD IRON SCLIM AT 60 Hz

60 Hz	Copper Iron LIM Gap = 10 cm	Cold Iron SCLIM Gap = 15 cm	Units
Pole Pitch	1.2	0.4	meters
No. Poles	8	8	
Dimensions	0.11 x 1.48 x 9.64	0.15 x 1.55 x 9.71	meters
Voltage	2200	2200	volts (rms)
Current	2007	2163	kA (rms)
Input Power	7.65	8.24	MVA
Mechanical Output	5.97	5.97	MW
Power Factor	0.78	0.72	
Current Density	500	10,000	amp/cm^2
Cu I^2R Losses	80.3	–	kW
SC AC Losses	–	26.7	watts
Refrigeration	135	excessive	kW
Motor Weight	12.72	8.63	tonnes
System Weight	21.18	349	tonnes
Est. Cost	0.946	excessive	$ (millions)

TABLE 6
WARM IRON CORE SCLIM AND COLD IRON SCLIM AT 60 Hz

60 Hz	Warm Iron SCLIM Gap = 10 cm	Cold Iron SCLIM Gap = 15 cm	Units
Pole Pitch	1.2	0.4	meters
No. Poles	8	8	
Dimensions	0.11 x 1.58 x 9.74	0.15 x 1.55 x 9.71	meters
Voltage	2200	2200	volts (rms)
Current	2007	2163	kA (rms)
Input Power	7.65	8.24	MVA
Mechanical Output	5.97	5.97	MW
Power Factor	0.78	0.72	
Current Density	10,000	10,000	amp/cm^2
Cu I^2R Losses	–	–	kW
SC AC Losses	24.7	26.7	watts
Refrigeration	48	excessive	kW
Motor Weight	12.25	8.63	tonnes
System Weight	21.18	349	tonnes
Est. Cost	2.36	excessive	$ (millions)

TABLE 7
AIR CORE SCLIM AT 60 Hz AND 180 Hz WITH GUIDEWAY BACK IRON

Gap = 15 cm	Air Core SCLIM 60 Hz	Air Core SCLIM 180 Hz	Units
Pole Pitch	1.2	0.4	meters
No. Poles	8	8	
Dimensions	0.13 x 1.56 x 9.72		meters
Voltage	1006	1976	volts (rms)
Current	5970	13,260	kA (rms)
Input Power	10.4	45.39	MVA
Mechanical Output	5.96	5.96	MW
Power Factor	0.57	0.131	
Current Density	500 10,000	500 10,000	amp/cm^2
Cu I^2R Losses	238	177	kW
SC AC Losses	106	353	watts
Refrigeration	132	381	kW
Motor Weight	4.09	0.682	tonnes
System Weight	16.95	39.95	tonnes
Est. Cost	3.23	8.48	$ (millions)

TABLE 8
AIR CORE SCLIM AT 60 Hz AND 180 Hz WITHOUT GUIDEWAY BACK IRON

Gap = 15 cm	Air Core SCLIM 60 Hz	Air Core SCLIM 180 Hz	Units
Pole Pitch	1.2	0.4	meters
No. Poles	8	8	
Voltage	1006	1976	volts (rms)
Current	1444	3279	kA (rms)
Input Power	26	130	MVA
Mechanical Output	5.96	5.96	MW
Power Factor	0.22	0.04	
Current Density	500 10,000	500 10,000	amp/cm^2
Cu I^2R Losses	416	307	kW
SC AC Losses	276	2683	watts

TABLE 9

COMPARISON TABLE OF VARIOUS SCLIM DESIGNS

Item	Copper Iron	Copper Iron	Warm Iron Supercon	Cold Iron Supercon	Air Core Supercon	Air Core Supercon	Units
Clearance		10	10	10	10	10	cm
Iron to Iron		10	10	15	15	15	cm
Guideway	Al+Fe	Al+Fe	Al+Fe	Al+Fe	Al+Fe	Al	
Iron Core		Yes	Yes	Yes	No	No	
Iron Losses		12.7	12.7	Impractical	None	None	kW
Cryostat		No	Yes	Yes	Yes	Yes	
Cryostat Type		N/A	Al	Al	Composite	Composite	
Frequency	60	180	60 Hz	60 Hz	60 Hz	60 Hz	Hz
Pitch	1.2	0.4	1.2	1.2	1.2	1.2	m
Forces on Winding		Low	Low	Low	High	High	
Cryogens		None	LN/LHe	LN/LHe	LN/LHe	LN/LHe	
Motor Bottom		Iron Yoke	Iron Yoke	AC Vacuum Window	AC Vacuum Window	AC Vacuum Window	
AC Shield		Minimal	Minimal	Minimal	Thick Aluminum	Thick Aluminum	
Motor Weight	12.72	1.86	12.25	8.63	4.09	–	kg
System Weight	21.18	7.74	17.37	Impractical	16.95	–	kg
Motor Power	7.65	10.91	7.65	8.24	10.4	26	MW
System Cost (millions)	0.946	1.125	2.36	Excessive	3.23	–	$

Appendix I

Typical AC Loss Extrapolation

Assumptions:

1. AC losses per cycle are linear at low fields.
2. AC losses per cycle are independent of frequency.

Notes:

1. These assumptions are valid at fields less than 0.5T.
2. These assumptions are linear approximations of the Bean Model and agree with data taken in typical superconductors [6].

Calculations:

From Figure 6 the AC loss per cycle at 50 Hz and 0.5T is 10 kW/m³.

The total power loss at any frequency scales with frequency and field and is given by:

$$P = P_o \cdot \frac{f}{f_o} \cdot \frac{B}{B_o}$$

where $P_o = 10 \text{ kW} / \text{m}^3$

$f_o = 50 \text{ Hz}$

$B_o = 0.5\text{T}$

Simplifying:

$P = 400\, B \cdot f \ (\text{W} / \text{m}^3)$, where B is in Tesla and f is in Hz.

Appendix II
Iron Core Motor Design

The design methods are based on the text by Nasar [1]. The design is incorporated in a spreadsheet and the formulas for each line of the spreadsheet are listed in the section marked Notes to Tables II-1 through II-9, pages II-11 through II-13.

The designs begin with the thrust requirements at maximum velocity, which is assumed to be 44.5 kN (somewhat higher than the requirement of 42.7 kN shown in Figure 1). The designs assume a maximum drive voltage of 2200 volts rms. From these assumptions, the number of turns of the motor, the motor impedance, and current are computed. The acceleration is controlled by the current in the winding and frequency.

Nine designs are presented as examples. All designs assume a slip of 7% at maximum speed. Both I^2R losses and superconducting losses are presented in each design. The tables are organized as follows:

Table II-1: LIM Design at 60 Hz, 5 cm gap

Table II-2: LIM Design at 60 Hz, 10 cm gap

Table II-3: LIM Design at 60 Hz, 15 cm gap

Table II-4: LIM Design at 120 Hz, 5 cm gap

Table II-5: LIM Design at 120 Hz, 10 cm gap

Table II-6: LIM Design at 120 Hz, 15 cm gap

Table II-8: LIM Design at 180 Hz, 5 cm gap

Table II-8: LIM Design at 180 Hz, 10 cm gap

Table II-9: LIM and SCLIM Designs at 180 Hz, 15 cm gap

Table II-1: LIM and SCLIM Design at 60 Hz, 5 cm Gap

Line	Type	Item	Value	Units
1				
2				
3	input	Maximum Thrust	44.5	kN
4	input	Train Velocity	134	m/sec
5				
6	input	Frequency	60	Hz
7	input	No. phases	3	
8	input	Voltage	2200	volts
9				
10	input	Slip @ Vmax	0.07	
11	input	Gap (iron-iron)	0.05	meters
12	input	Track Thickness	0.003	meters
13	formula	Gap to Cond.	0.097	meters
14	data	Al Track Res.	0.056	μohm-meter
15	formula	Skin Depth	0.015	meters
16				
17	formula	Sync Speed	144	m/sec
18	formula	Wavelength	2.40	meters
19	formula	Pitch	1.20	meters
20	rule	Ratio Core Width	1.2	
21	formula	Core Width	1.44	meters
22				
23	rule	Field at Pole	0.109	Tesla
24	f/rule	Flux	0.120	Webers
25				
26	rule	No. Poles	8	
27	formula	Pole Area	1.73	m^2
28	formula	Force/Area	0.32	$newtons/cm^2$
29				
30	rule	Winding Fac.	1.2	
31	formula	EMF/Turn	38.4	volts
32				
33	rule	Efficiency	0.52	
34	formula	No. of Turns	29.7	turns
35	formula	X_m	3.16	ohms
36	formula	R2 prime	0.042	ohms
37	formula	Goodness	74.14	
38	formula	AT/phase	14.16	kamp rms
39	formula	Current	1907	amps
40	formula	Mech. Power Out	5.97	Mwatt
41	formula	Input KVA	7.27	Mwatt
42	formula	Power Factor	0.82	
43				
44	Cu data	Current Density	500	$amps/cm^2$
45	formula	Wire Cross-Section	3.81	cm^2
46	formula	Conductor (L)	470.7	meters
47	formula	Wire Resistivity	0.017	μohm-meters
48	formula	Total R	0.02	ohms
49	formula	I^2R Losses	76.3	kwatts
50	formula	IR Drop/Phase	13.3	volts
51				
52	Sc data	Current Density	10,000	$amps/cm^2$
53	formula	Sc Cross Section	0.19	cm^2
54	formula	Sc volume	0.009	m^3
55	formula	Sc losses @ 4.2K	23.5	watts

Table II-2: LIM and SCLIM Design at 60 Hz, 10 cm Gap

Line	Type	Item	Value	Units
1				
2				
3	input	Maximum Thrust	44.5	kN
4	input	Train Velocity	134	m/sec
5				
6	input	Frequency	60	Hz
7	input	No. phases	3	
8	input	Voltage	2200	volts
9				
10	input	Slip @ Vmax	0.07	
11	input	Gap (iron-iron)	0.1	meters
12	input	Track Thickness	0.003	meters
13	formula	Gap to Cond.	0.097	meters
14	data	Al Track Res.	0.056	μohm-meter
15	formula	Skin Depth	0.015	meters
16				
17	formula	Sync Speed	144	m/sec
18	formula	Wavelength	2.40	meters
19	formula	Pitch	1.20	meters
20	rule	Ratio Core Width	1.2	
21	formula	Core Width	1.44	meters
22				
23	rule	Field at Pole	0.109	Tesla
24	f/rule	Flux	0.120	Webers
25				
26	rule	No. Poles	8	
27	formula	Pole Area	1.73	m^2
28	formula	Force/Area	0.32	$newtons/cm^2$
29				
30	rule	Winding Fac.	1.2	
31	formula	EMF/Turn	38.4	volts
32				
33	rule	Efficiency	0.52	
34	formula	No. of Turns	29.7	turns
35	formula	X_m	1.58	ohms
36	formula	R2 prime	0.042	ohms
37	formula	Goodness	37.1	
38	formula	AT/phase	14.9	kamp rms
39	formula	Current	2007	amps
40	formula	Mech. Power Out	5.97	Mwatt
41	formula	Input KVA	7.65	Mwatt
42	formula	Power Factor	0.780	
43				
44	Cu data	Current Density	500	$amps/cm^2$
45	formula	Wire Cross-Section	4.014	cm^2
46	formula	Conductor (L)	470.7	meters
47	formula	Wire Resistivity	0.020	μohm-meters
48	formula	Total R	0.004	ohms
49	formula	I^2R Losses	80.3	kwatts
50	formula	IR Drop/Phase	13.3	volts
51				
52	Sc data	Current Density	10,000	$amps/cm^2$
53	formula	Sc Cross Section	0.20	cm^2
54	formula	Sc volume	0.009	m^3
55	formula	Sc losses @ 4.2K	24.7	watts

Table II-3: LIM and SCLIM Design at 60 Hz, 15 cm Gap

Line	Type	Item	Value	Units
1				
2				
3	input	Maximum Thrust	44.5	kN
4	input	Train Velocity	134	m/sec
5				
6	input	Frequency	60	Hz
7	input	No. phases	3	
8	input	Voltage	2200	volts
9				
10	input	Slip @ Vmax	0.07	
11	input	Gap (iron-iron)	0.15	meters
12	input	Track Thickness	0.003	meters
13	formula	Gap to Cond.	0.147	meters
14	data	Al Track Res.	0.056	μohm-meter
15	formula	Skin Depth	0.015	meters
16				
17	formula	Sync Speed	144	m/sec
18	formula	Wavelength	2.40	meters
19	formula	Pitch	1.20	meters
20	rule	Ratio Core Width	1.2	
21	formula	Core Width	1.44	meters
22				
23	rule	Field at Pole	0.109	Tesla
24	f/rule	Flux	0.120	Webers
25				
26	rule	No. Poles	8	
27	formula	Pole Area	1.73	m^2
28	formula	Force/Area	0.32	$newtons/cm^2$
29				
30	rule	Winding Fac.	1.2	
31	formula	EMF/Turn	38.45	volts
32				
33	rule	Efficiency	0.52	
34	formula	No. of Turns	29.7	turns
35	formula	X_m	1.05	ohms
36	formula	R2 prime	0.042	ohms
37	formula	Goodness	24.7	
38	formula	AT/phase	16.1	kamp rms
39	formula	Current	2163	amps
40	formula	Mech. Power Out	5.97	Mwatt
41	formula	Input KVA	8.24	Mwatt
42	formula	Power Factor	0.72	
43				
44	Cu data	Current Density	500	$amps/cm^2$
45	formula	Wire Cross-Section	4.33	cm^2
46	formula	Conductor (L)	470.7	meters
47	formula	Wire Resistivity	0.017	μohm-meters
48	formula	Total R	0.018	ohms
49	formula	I^2R Losses	86.6	kwatts
50	formula	IR Drop/Phase	13.3	volts
51				
52	Sc data	Current Density	10,000	$amps/cm^2$
53	formula	Sc Cross Section	0.216	cm^2
54	formula	Sc volume	0.010	m^3
55	formula	Sc losses @ 4.2K	26.7	watts

Table II-4: LIM and SCLIM Design at 120 Hz, 5 cm Gap

Line	Type	Item	Value	Units
1				
2				
3	input	Maximum Thrust	44.5	kN
4	input	Train Velocity	134	m/sec
5				
6	input	Frequency	120	Hz
7	input	No. phases	3	
8	input	Voltage	2200	volts
9				
10	input	Slip @ Vmax	0.07	
11	input	Gap (iron-iron)	0.05	meters
12	input	Track Thickness	0.003	meters
13	formula	Gap to Cond.	0.097	meters
14	data	Al Track Res.	0.056	μohm-meter
15	formula	Skin Depth	0.011	meters
16				
17	formula	Sync Speed	144	m/sec
18	formula	Wavelength	1.20	meters
19	formula	Pitch	0.60	meters
20	rule	Ratio Core Width	1.2	
21	formula	Core Width	0.72	meters
22				
23	rule	Field at Pole	0.22	Tesla
24	f/rule	Flux	0.06	Webers
25				
26	rule	No. Poles	8	
27	formula	Pole Area	0.432	m^2
28	formula	Force/Area	1.28	newtons/cm^2
29				
30	rule	Winding Fac.	1.2	
31	formula	EMF/Turn	38.4	volts
32				
33	rule	Efficiency	0.52	
34	formula	No. of Turns	29.7	turns
35	formula	X_m	1.58	ohms
36	formula	R2 prime	0.04	ohms
37	formula	Goodness	37.0	
38	formula	AT/phase	14.9	kamp rms
39	formula	Current	2007	amps
40	formula	Mech. Power Out	5.97	Mwatt
41	formula	Input KVA	7.65	Mwatt
42	formula	Power Factor	0.78	
43				
44	Cu data	Current Density	500	amps/cm^2
45	formula	Wire Cross-Section	4.01	cm^2
46	formula	Conductor (L)	235	meters
47	formula	Wire Resistivity	0.017	μohm-meters
48	formula	Total R	0.01	ohms
49	formula	I^2R Losses	40.16	kwatts
50	formula	IR Drop/Phase	6.67	volts
51				
52	Sc data	Current Density	10,000	amps/cm^2
53	formula	Sc Cross Section	0.20	cm^2
54	formula	Sc volume	0.005	m^3
55	formula	Sc losses @ 4.2K	49.5	watts

Table II-5: LIM and SCLIM Design at 120 Hz, 10 cm Gap

Line	Type	Item	Value	Units
1				
2				
3	input	Maximum Thrust	44.5	kN
4	input	Train Velocity	134	m/sec
5				
6	input	Frequency	120	Hz
7	input	No. phases	3	
8	input	Voltage	2200	volts
9				
10	input	Slip @ Vmax	0.07	
11	input	Gap (iron-iron)	0.1	meters
12	input	Track Thickness	0.003	meters
13	formula	Gap to Cond.	0.097	meters
14	data	Al Track Res.	0.056	µohm-meter
15	formula	Skin Depth	0.011	meters
16				
17	formula	Sync Speed	144	m/sec
18	formula	Wavelength	1.20	meters
19	formula	Pitch	0.60	meters
20	rule	Ratio Core Width	1.2	
21	formula	Core Width	0.72	meters
22				
23	rule	Field at Pole	0.22	Tesla
24	f/rule	Flux	0.06	Webers
25				
26	rule	No. Poles	8	
27	formula	Pole Area	0.432	m^2
28	formula	Force/Area	1.28	$newtons/cm^2$
29				
30	rule	Winding Fac.	1.2	
31	formula	EMF/Turn	38.4	volts
32				
33	rule	Efficiency	0.52	
34	formula	No. of Turns	29.7	turns
35	formula	X_m	0.79	ohms
36	formula	R2 prime	0.04	ohms
37	formula	Goodness	18.5	
38	formula	AT/phase	17.56	kamp rms
39	formula	Current	2365	amps
40	formula	Mech. Power Out	5.97	Mwatt
41	formula	Input KVA	9.01	Mwatt
42	formula	Power Factor	0.66	
43				
44	Cu data	Current Density	500	$amps/cm^2$
45	formula	Wire Cross-Section	4.73	cm^2
46	formula	Conductor (L)	235	meters
47	formula	Wire Resistivity	0.017	µohm-meters
48	formula	Total R	0.008	ohms
49	formula	I^2R Losses	47.3	kwatts
50	formula	IR Drop/Phase	6.67	volts
51				
52	Sc data	Current Density	10,000	$amps/cm^2$
53	formula	Sc Cross Section	0.236	cm^2
54	formula	Sc volume	0.005	m^3
55	formula	Sc losses @ 4.2K	58.3	watts

Table II-6: LIM and SCLIM Design at 120 Hz, 15 cm Gap

Line	Type	Item	Value	Units
1				
2				
3	input	Maximum Thrust	44.5	kN
4	input	Train Velocity	134	m/sec
5				
6	input	Frequency	120	Hz
7	input	No. phases	3	
8	input	Voltage	2200	volts
9				
10	input	Slip @ Vmax	0.07	
11	input	Gap (iron-iron)	0.15	meters
12	input	Track Thickness	0.003	meters
13	formula	Gap to Cond.	0.147	meters
14	data	Al Track Res.	0.056	μohm-meter
15	formula	Skin Depth	0.011	meters
16				
17	formula	Sync Speed	144	m/sec
18	formula	Wavelength	1.20	meters
19	formula	Pitch	0.60	meters
20	rule	Ratio Core Width	1.2	
21	formula	Core Width	0.720	meters
22				
23	rule	Field at Pole	0.22	Tesla
24	f/rule	Flux	0.06	Webers
25				
26	rule	No. Poles	8	
27	formula	Pole Area	0.43	m^2
28	formula	Force/Area	1.29	newtons/cm^2
29				
30	rule	Winding Fac.	1.2	
31	formula	EMF/Turn	38.45	volts
32				
33	rule	Efficiency	0.52	
34	formula	No. of Turns	29.7	turns
35	formula	X_m	0.53	ohms
36	formula	R2 prime	0.04	ohms
37	formula	Goodness	12.3	
38	formula	AT/phase	21.3	kamp rms
39	formula	Current	2863	amps
40	formula	Mech. Power Out	5.97	Mwatt
41	formula	Input KVA	10.9	Mwatt
42	formula	Power Factor	0.54	
43				
44	Cu data	Current Density	500	amps/cm^2
45	formula	Wire Cross-Section	5.73	cm^2
46	formula	Conductor (L)	235	meters
47	formula	Wire Resistivity	0.017	μohm-meters
48	formula	Total R	0.007	ohms
49	formula	I^2R Losses	57.3	kwatts
50	formula	IR Drop/Phase	6.67	volts
51				
52	Sc data	Current Density	10,000	amps/cm^2
53	formula	Sc Cross Section	0.286	cm^2
54	formula	Sc volume	0.007	m^3
55	formula	Sc losses @ 4.2K	70.6	watts

Table II-7: LIM and SCLIM Design at 180 Hz, 5 cm Gap

Line	Type	Item	Value	Units
1				
2				
3	input	Maximum Thrust	44.5	kN
4	input	Train Velocity	134	m/sec
5				
6	input	Frequency	180	Hz
7	input	No. phases	3	
8	input	Voltage	2200	volts
9				
10	input	Slip @ Vmax	0.07	
11	input	Gap (iron-iron)	0.05	meters
12	input	Track Thickness	0.003	meters
13	formula	Gap to Cond.	0.047	meters
14	data	Al Track Res.	0.056	µohm-meter
15	formula	Skin Depth	0.009	meters
16				
17	formula	Sync Speed	144	m/sec
18	formula	Wavelength	0.800	meters
19	formula	Pitch	0.400	meters
20	rule	Ratio Core Width	1.2	
21	formula	Core Width	0.480	meters
22				
23	rule	Field at Pole	0.327	Tesla
24	f/rule	Flux	0.040	Webers
25				
26	rule	No. Poles	8	
27	formula	Pole Area	0.192	m^2
28	formula	Force/Area	2.90	$newtons/cm^2$
29				
30	rule	Winding Fac.	1.2	
31	formula	EMF/Turn	38.4	volts
32				
33	rule	Efficiency	0.52	
34	formula	No. of Turns	29.7	turns
35	formula	X_m	1.05	ohms
36	formula	R2 prime	0.042	ohms
37	formula	Goodness	24.7	
38	formula	AT/phase	16.1	kamp rms
39	formula	Current	2164	amps
40	formula	Mech. Power Out	5.97	Mwatt
41	formula	Input KVA	8.24	Mwatt
42	formula	Power Factor	0.72	
43				
44	Cu data	Current Density	500	$amps/cm^2$
45	formula	Wire Cross-Section	4.33	cm^2
46	formula	Conductor (L)	157	meters
47	formula	Wire Resistivity	0.017	µohm-meters
48	formula	Total R	0.006	ohms
49	formula	I^2R Losses	28.9	kwatts
50	formula	IR Drop/Phase	4.45	volts
51				
52	Sc data	Current Density	10,000	$amps/cm^2$
53	formula	Sc Cross Section	0.216	cm^2
54	formula	Sc volume	0.003	m^3
55	formula	Sc losses @ 4.2K	80.0	watts

Table II-8: LIM and SCLIM Design at 180 Hz, 10 cm Gap

Line	Type	Item	Value	Units
1				
2				
3	input	Maximum Thrust	44.5	kN
4	input	Train Velocity	134	m/sec
5				
6	input	Frequency	180	Hz
7	input	No. phases	3	
8	input	Voltage	2200	volts
9				
10	input	Slip @ Vmax	0.07	
11	input	Gap (iron-iron)	0.1	meters
12	input	Track Thickness	0.003	meters
13	formula	Gap to Cond.	0.097	meters
14	data	Al Track Res.	0.056	μohm-meter
15	formula	Skin Depth	0.009	meters
16				
17	formula	Sync Speed	144	m/sec
18	formula	Wavelength	0.800	meters
19	formula	Pitch	0.400	meters
20	rule	Ratio Core Width	1.2	
21	formula	Core Width	0.480	meters
22				
23	rule	Field at Pole	0.327	Tesla
24	f/rule	Flux	0.040	Webers
25				
26	rule	No. Poles	8	
27	formula	Pole Area	0.192	m^2
28	formula	Force/Area	2.90	$newtons/cm^2$
29				
30	rule	Winding Fac.	1.2	
31	formula	EMF/Turn	38.4	volts
32				
33	rule	Efficiency	0.52	
34	formula	No. of Turns	29.7	turns
35	formula	X_m	0.527	ohms
36	formula	R2 prime	0.042	ohms
37	formula	Goodness	12.4	
38	formula	AT/phase	21.26	kamp rms
39	formula	Current	2863	amps
40	formula	Mech. Power Out	5.97	Mwatt
41	formula	Input KVA	10.9	Mwatt
42	formula	Power Factor	0.547	
43				
44	Cu data	Current Density	500	$amps/cm^2$
45	formula	Wire Cross-Section	5.73	cm^2
46	formula	Conductor (L)	157	meters
47	formula	Wire Resistivity	0.017	μohm-meters
48	formula	Total R	0.005	ohms
49	formula	I^2R Losses	38.2	kwatts
50	formula	IR Drop/Phase	4.45	volts
51				
52	Sc data	Current Density	10,000	$amps/cm^2$
53	formula	Sc Cross Section	0.286	cm^2
54	formula	Sc volume	0.004	m^3
55	formula	Sc losses @ 4.2K	106	watts

Table II-9: LIM and SCLIM Design at 180 Hz, 15 cm Gap

Line	Type	Item	Value	Units
1				
2				
3	input	Maximum Thrust	44.5	kN
4	input	Train Velocity	134	m/sec
5				
6	input	Frequency	180	Hz
7	input	No. phases	3	
8	input	Voltage	2200	volts
9				
10	input	Slip @ Vmax	0.07	
11	input	Gap (iron-iron)	0.15	meters
12	input	Track Thickness	0.003	meters
13	formula	Gap to Cond.	0.147	meters
14	data	Al Track Res.	0.056	μohm-meter
15	formula	Skin Depth	0.009	meters
16				
17	formula	Sync Speed	144	m/sec
18	formula	Wavelength	0.800	meters
19	formula	Pitch	0.400	meters
20	rule	Ratio Core Width	1.2	
21	formula	Core Width	0.480	meters
22				
23	rule	Field at Pole	0.327	Tesla
24	f/rule	Flux	0.030	Webers
25				
26	rule	No. Poles	8	
27	formula	Pole Area	0.192	m^2
28	formula	Force/Area	2.89	newtons/cm^2
29				
30	rule	Winding Fac.	1.2	
31	formula	EMF/Turn	38.4	volts
32				
33	rule	Efficiency	0.52	
34	formula	No. of Turns	29.7	turns
35	formula	X_m	0.35	ohms
36	formula	R2 prime	0.042	ohms
37	formula	Goodness	8.24	
38	formula	AT/phase	27.8	kamp rms
39	formula	Current	3750	amps
40	formula	Mech. Power Out	5.97	Mwatt
41	formula	Input KVA	14.3	Mwatt
42	formula	Power Factor	0.417	
43				
44	Cu data	Current Density	500	amps/cm^2
45	formula	Wire Cross-Section	7.50	cm^2
46	formula	Conductor (L)	156.9	meters
47	formula	Wire Resistivity	0.017	μohm-meters
48	formula	Total R	0.003	ohms
49	formula	I^2R Losses	50.0	kwatts
50	formula	IR Drop/Phase	4.44	volts
51				
52	Sc data	Current Density	10,000	amps/cm^2
53	formula	Sc Cross Section	0.37	cm^2
54	formula	Sc volume	.0059	m^3
55	formula	Sc losses @ 4.2K	138.7	watts

Notes to Tables II-1 through II-9

Line	Item	Symbol/Formula
1		
2		
3	force = thrust requirement	F
4	velocity (300 mi/hr)	v
5		
6	frequency	f_0
7	no. phases	n_{ph}
8	drive voltage	V
9		
10	slip	s
11	magnetic air gap	g
12	track thickness	d
13	motor–track gap	$g' = g - d$
14	track resistivity	ρ_t
15	skin depth	$\delta = \sqrt{\frac{2\rho_t}{\mu_0(2\pi f)}}$
16		
17	synchronous speed	$v_s = \frac{v}{1-s}$
18	wavelength	$\lambda = \frac{v}{f}$
19	pitch	$\tau = \lambda / 2$
20	core width/pitch ratio good design uses 0.75 to 1.25	R_1
21	iron core width	$W_c = R_1 \tau$

Notes to Tables II-1 through II-9

Line	Item	Symbol/Formula
22		
23	air gap flux density at pole	$B_g = \sqrt{\dfrac{2 \cdot \mathcal{P} \cdot \rho_t}{s v_s \cdot d}}$
24	RMS flux at pole	$\phi = \frac{2}{\pi}\left(B_g\right)\tau W_c$
25		
26	no. of poles	n_p
27	pole area	$A_p = \tau \cdot W_c$
28	force/area good design ~ 1 Newton/cm²	$\mathcal{P} = F/A_p$
29		
30	winding factor	K_w
31	EMF/turn	$\xi = 2\sqrt{2} f B_g K_w \tau W_c$
32		
33	voltage fraction	$1 - \varepsilon_L$
34	no. of turns distributed over all poles	$W_1 = \dfrac{(1-\varepsilon_L)V}{\xi}$
35	reactance X_m	$X_m = \dfrac{\mu_0 (2\pi f) \cdot W_c \cdot \tau (K_w W_1)^2}{\pi^2 \left(\frac{n_{ph}}{2}\right) g}$
36	resistance R_2'	$R_2' = \dfrac{6 W_c (K_w W_1)^2 \rho_t}{d \cdot \tau \cdot \left(n_p / 2\right)}$

Notes to Tables II-1 through II-9

Line	Item	Symbol/Formula
37	goodness factor	$G = \frac{X_m}{R'_2}$
38	amp turns/slot	$AT = I \cdot W_1 \cdot 2 / n_p$
39	current	$I = \sqrt{\frac{F(s\lambda f)\left[(1/sG)^2 + 1\right]}{3R'_2}}$
40	mechanical power output	$P_o = F \cdot v$
41	input KVA	$P_I = \sqrt{3} \cdot V \cdot I$
42	power factor	$\cos\phi = \frac{P_o}{\sqrt{3} \cdot V \cdot I}$
43		
44	current density	J
45	wire cross section	$A_w = I / J$
46	conductor length	$L = 2\left[W_c + \tau\right] \cdot W_1 \cdot 3$
47	wire resistivity	ρ_w
48	total *R*	$R = \rho_w L / A_w$
49	I^2R	$P_L = I^2 R$
50	voltage drop per phase	$IR/3$
51		
52	superconductor current density	J_s
53	superconductor cross section	$A_s = I / J_s$
54	SC volume	$V_s = L \cdot A_s$
55	SC losses	$P = 400 \cdot f \cdot B_g$

Appendix III

Air Core Analysis

An exact solution of an infinitely long aircore linear motor is formulated based upon a Poynting vector approach. This approach allows for the calculation of all relevant motor parameters and equivalent circuit network elements. A similar solution/methodology can be worked out for the iron core motor. The model can be extended to include end effects.

The model starts by decomposing a typical three phase motor winding into forward and backward traveling waves. By proper phasing it is shown that the forward wave is dominant, especially if the winding is long and thin.

Motor parameters are found by analyzing the complex power which is formed by the Poynting vector. The inductances of the motor are proportional to the imaginary parts of the complex power, and the power consumption from the eddy current dissipation and mechanical work is proportional to the real part of the complex power. These powers are related to the current in the winding and to the motor impedance.

This approach is direct and accurate and does not require finite element analysis or field analysis. An example is worked out for the 60 Hz motor.

ɘ Harmonic Analysis

: Winding Representation

ıase linear motor has a spatial distribution of current shown below.

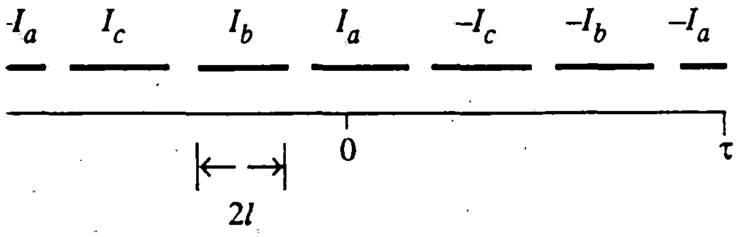


Figure III-1

le pitch, $2l$ is the length of the winding, and the current

s as follows:

$$= I_o e^{j(\omega t+\phi_b)}, \quad I_c = I_o e^{j(\omega t+\phi_c)},$$

$$\phi_b = \frac{\pi}{3}, \quad \phi_c = \frac{2\pi}{3}, \quad \text{and } j = \sqrt{-1}.$$

ꞇ density is defined over a wavelength (2τ) and is given by:

$$\begin{cases} -1 & -\tau < x < -\tau + l \\ e^{i\phi_c} & -\frac{2\tau}{3} - l < x < -\frac{2\tau}{3} + l \\ e^{i\phi_b} & -\frac{\tau}{3} - l < x < -\frac{\tau}{3} + l \\ +1 & -l < x < l \\ -e^{i\phi_c} & -\frac{\tau}{3} - l < x < -\frac{\tau}{3} + l \\ -e^{i\phi_b} & -\frac{2\tau}{3} - l < x < -\frac{2\tau}{3} + l \\ -1 & \tau - l < x < \tau \end{cases}$$

1.2 Fourier Expansion

If the current density is periodic and extends over all x space, then it can be expanded in a Fourier series of traveling waves such that

$$K(x,t) = \sum_{m=-\infty}^{m=\infty} K_m e^{j\left(\omega t - \frac{m\pi x}{\tau}\right)}$$

$$K_m = \frac{1}{2\tau}\int_{-\tau}^{\tau} K(x,t) e^{-j\left(\omega t - \frac{m\pi x}{\tau}\right)} d\tau$$

where K_m represents the amplitude of the harmonic at the spatial frequency $\frac{m\pi}{\tau}$. For a three phase winding of infinite extent which has a typical wavelength described by equation 1.1, the Fourier component becomes:

$$K_m = \begin{cases} 0 & m = 0 \\ \frac{K}{m\pi}\sin\frac{ml\pi}{\tau}\left[1-(-1)^m + 4\sin\frac{m\pi}{2}\cos\frac{(m-1)}{6}\pi\right] & m \neq 0 \end{cases}$$

For example, if $2l = \tau/3$, the harmonics are given in Table 1. In this example, the first harmonic dominates. The negative orders of m represent travelling waves of current density in the $(-x)$ direction. This analysis neglects end effects, which will be treated later.

m (order)	K_m/K
–89	0.0107
–77	0.0124
–65	0.0147
–53	0.0180
–41	0.0233
–29	0.0329
–17	0.0562
–5	0.1910
1	0.9549
13	0.0735
25	0.0382
37	0.0258
49	0.0195
61	0.0157
73	0.0131
85	0.0112
97	0.0098

2. Aircore SLIM Motor Analysis

2.1 Four Layer Model

Figure 2 shows a four layer air core SLIM having a secondary of finite thickness h.

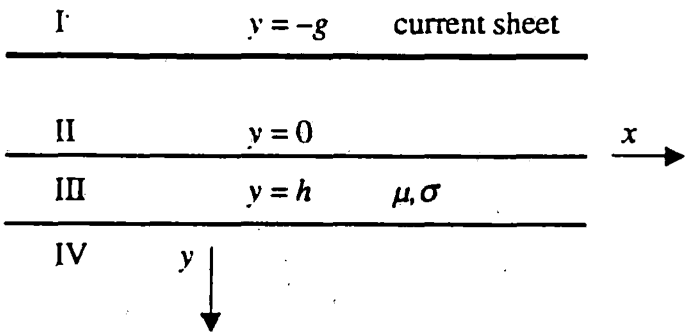


Figure III-2

The whole space is divided into four layers:
Layer I: Region above the current sheet
Layer II: The airgap betweeen the current sheet and secondary
Layer III: Conducting secondary
Layer IV: Region below the secondary

The interface between layer I and layer II is a current sheet of current density $K(x,t)$.

For the case where the first harmonic dominates,

$$\vec{K}(x,t) = K_1 e^{j(\omega t - \beta x)}\hat{z}. \tag{2.1}$$

where $\beta = \dfrac{\pi}{\tau}$ and $K_1 = \dfrac{6K}{\pi}\sin\dfrac{l\pi}{\tau}$.

To solve Maxwell's equation, we introduce a vector potential $\vec{A}_k$ for layer k, $k = 1,2,3,4$.

According to relativity, we assume that the secondary is moving in x direction with velocity

$$\vec{u} = u\hat{x} \tag{2.2}$$

The vector potential $\vec{A}_k$ is assumed to be z-directed

$$\vec{A} = A_{kz}\hat{z} \tag{2.3}$$

The equation for the k-th layer is

$$\nabla\vec{A}_k = \mu\sigma\left[\frac{\partial\vec{A}_k}{\partial t} - \vec{\mu}\times\nabla\times\vec{A}_k\right] \tag{2.4}$$

This can be rewritten as,

$$\frac{\partial^2 A_{kz}}{\partial x^2} + \frac{\partial^2 A_{kz}}{\partial y^2} = \mu\sigma\left(j\omega A_{kz} + \frac{\mu\partial A_{kz}}{\partial x}\right) \tag{2.5}$$

or

$$\frac{d^2 A_{kz}}{dy^2} - \lambda_k A_{zk} = 0, \quad k = 1,2,3,4 \tag{2.6}$$

where

$$\begin{aligned}
&\lambda_1 = \lambda_2 = \lambda_4 = \beta^2 \text{ and } \lambda_3 = \alpha^2, \text{ and} \\
&\alpha^2 = \beta^2\left(1 + \frac{j\mu\sigma s u_s}{\beta}\right), \\
&s u_s = u_s - u, \quad u_s = \frac{\omega}{\beta}
\end{aligned} \tag{2.7}$$

The solutions for (2.6) can be written as

$$\begin{aligned}
&A_{1z} = c_1 e^{\beta y} e^{j(\omega t - \beta x)}, \\
&A_{2z} = \left(c_3 e^{\beta y} + c_4 e^{-\beta y}\right) e^{j(\omega t - \beta x)}, \\
&A_{3z} = \left(c_5 e^{\alpha y} + c_6 e^{-\alpha y}\right) e^{j(\omega t - \beta x)}, \text{ and} \\
&A_{4z} = c_8 e^{-\beta y} e^{j(\omega t - \beta x)}.
\end{aligned} \tag{2.8}$$

By imposing the well-known boundary conditions for the transverse $\vec{H}$ and normal $\vec{B}$ fields, one can solve for the c coefficients, which are found to be:

$$
\begin{aligned}
c_1 &= \frac{\mu_o K_1}{2}\left\{\frac{\left(1-\gamma^2\right)\sinh(\alpha h)}{2\gamma\cosh(\alpha h)+\left(1+\gamma^2\right)\sinh(\alpha h)}e^{-\beta g} - e^{+\beta g}\right\}, \\
c_3 &= \left\{\frac{\left(1-\gamma^2\right)\mu_o K_1 \sinh(\alpha h)}{2\left[2\gamma\cosh(\alpha h)+\left(1+\gamma^2\right)\sinh(\alpha h)\right]}\right\}e^{-\beta g}, \\
c_4 &= -\frac{\mu_o K_1}{2}e^{-\beta g}, \\
c_5 &= -\frac{\gamma(1-\gamma)\mu_o K_1 e^{-(\alpha h+\beta g)}}{2\left[2\gamma\cosh(\alpha h)+\left(1+\gamma^2\right)\sinh(\alpha h)\right]}, \\
c_6 &= -\frac{\gamma(1+\gamma)\mu_o K_1 e^{\alpha h-\beta g}}{2\left[2\gamma\cosh(\alpha h)+\left(1+\gamma^2\right)\sinh(\alpha h)\right]}, \\
c_8 &= -\frac{\gamma\mu_o K_1 e^{\beta(h-g)}}{2\gamma\cosh(\alpha h)+\left(1+\gamma^2\right)\sinh(\alpha h)},
\end{aligned}
\tag{2.9}
$$

where

$$\gamma = \frac{\mu\beta}{\mu_o\alpha}$$

2.2 Poynting Vector

In order to characterize the aircore SLIM, we introduce the complex Poynting vector $\vec{E} \times \vec{H}*$ which is defined as the complex power per unit area flowing into various layers of the motor system.

The vector identity

$$\nabla \cdot \left(\vec{E} \times \vec{H}*\right) = \vec{H}* \cdot \nabla \times \vec{E} - \vec{E} \cdot \nabla \times \vec{H}* \tag{2.10}$$

and Ohm's Law for a moving conductor

$$\vec{J} = \sigma\left(\vec{E} + \vec{u} \times \vec{B}\right) \tag{2.11}$$

together with Ampere's Law will give

$$\nabla \cdot \left(\vec{E} \times \vec{H}*\right) = -\mu H * \frac{\partial \vec{H}}{\partial t} - \frac{1}{\sigma} \vec{J} \cdot \vec{J}* + \left(\vec{u} \times \vec{B}\right) \cdot \vec{J}* \tag{2.12}$$

Then the divergence theorem gives

$$\oiint_S \left(\vec{E} \times \vec{H}*\right) \cdot d\vec{s} = -\int_v \mu \vec{H}* \cdot \frac{\partial \vec{H}}{\partial t} dv - \frac{1}{\sigma} \int_v \vec{J} \cdot \vec{J}* dv + \int_v \vec{u} \times \vec{B} \cdot \vec{J}* dv \tag{2.13}$$

where the magnetic field is given by

$$\vec{B}_k = \nabla \times \vec{A}_k \tag{2.14}$$

and

$$\vec{H}_k = \vec{B}_k / \mu_k \tag{2.15}$$

Correspondingly, the electric field is given by

and

$$\vec{E}_k = -\frac{\partial \vec{A}_k}{\partial t} = -j\omega \vec{A}_k \tag{2.16}$$

and

$$\vec{J}_k = \sigma\left(-j\omega\vec{A}_k + uB_{ky}\hat{a}z\right)$$
$$= -\sigma\left(j\omega\vec{A}_k + u\frac{\partial\vec{A}_k}{\partial x}\right) \tag{2.17}$$

where $\vec{u} = \hat{u}$ is the velocity of the vehicle.

The power flowing into layer I is given by the integral of the Poynting vector, which is

$$P_1 = \oiint_s \left(\bar{E}_1 \times \bar{H}^*\right)\cdot d\bar{s} = -\frac{j\omega\beta\mu_o A K_1^2}{4}\left|\frac{\left(1-\gamma^2\right)\sinh(\alpha h)}{\Delta}e^{-2\beta g} - 1\right|^2 \tag{2.18}$$

where A is the area under one wavelength of the aircore and $\Delta = 2\gamma\cosh(\alpha h) + \left(1+\gamma^2\right)\sinh(\alpha h)$.

The power flowing into layer II is given by

$$P_2 = \oiint_{s_2} \left(\bar{E}_2 \times \bar{H}_2{}^*\right)\cdot d\bar{s} = -\frac{j\omega\beta\mu_o A K_1^2}{4}e^{-2\beta g}$$
$$\left[\left|\frac{\left(1-\gamma^2\right)\sinh(\alpha h)}{\Delta}\right|^2\left(1-e^{-2\beta g}\right) - 1 + e^{2\beta g}\right] \tag{2.19}$$

Similarly, the power flowing into layer III is given by

$$P_3 = \oiint_{s_3} \left(\bar{E}_3 \times \bar{H}_3{}^*\right)\cdot d\bar{s} - \frac{j\omega\mu_o^2 A|\gamma|^2 K_1^2}{\mu|\Delta|^2}e^{-2\beta g}\left(|\alpha|^2 D_1 + \beta^2 D_2\right)$$
$$-\frac{\sigma\mu_o^2\beta A|\gamma|^2 K_1^2}{|\Delta|^2}(u-u_s)^2 e^{-2\beta g} D_1$$
$$-\frac{\sigma\mu_o^2\beta A|\gamma|^2 K_1^2}{|\Delta|^2}u(u_s-u)e^{-2\beta g} D_1 \tag{2.20}$$

where

$$D_1 = \frac{1}{2}\left\{\frac{1+|\gamma|^2}{2M_1}\sinh(2M_1h) + \frac{1-|\gamma|^2}{2M_2}\sin(2M_2h) - \frac{\mu\beta}{\mu_o|\alpha|^2}\left[\cosh(2M_1h) - \cos(2M_2h)\right]\right\},$$

$$D_2 = \frac{1}{2}\left\{\frac{1+|\gamma|^2}{2M_1}\sinh(2M_1h) - \frac{1-|\gamma|^2}{2M_2}\sin(2M_2h) + \frac{\mu\beta}{\mu_o|\alpha|^2}\left[\cosh(2M_1h) + \cos(2M_2h) - 2\right]\right\}, \qquad (2.21)$$

and M_1 = real (α) and M_2 = imag (α).

Finally, the power flowing into layer IV is

$$P_4 = \oiint_{s_4}\left(\bar{E}_4 \times \bar{H}_4{}^*\right)\cdot d\bar{s} = -\frac{j\mu_o\beta\omega A|\gamma|^2 K_1^2}{|\Delta|^2}e^{-2\beta g} \qquad (2.22)$$

Using the Poynting vector integrals, one can form an equivalent circuit as shown in Figure 3, since

$$P_{TOTAL} = P_1 + P_2 + P_3 + P_4 \qquad (2.23)$$

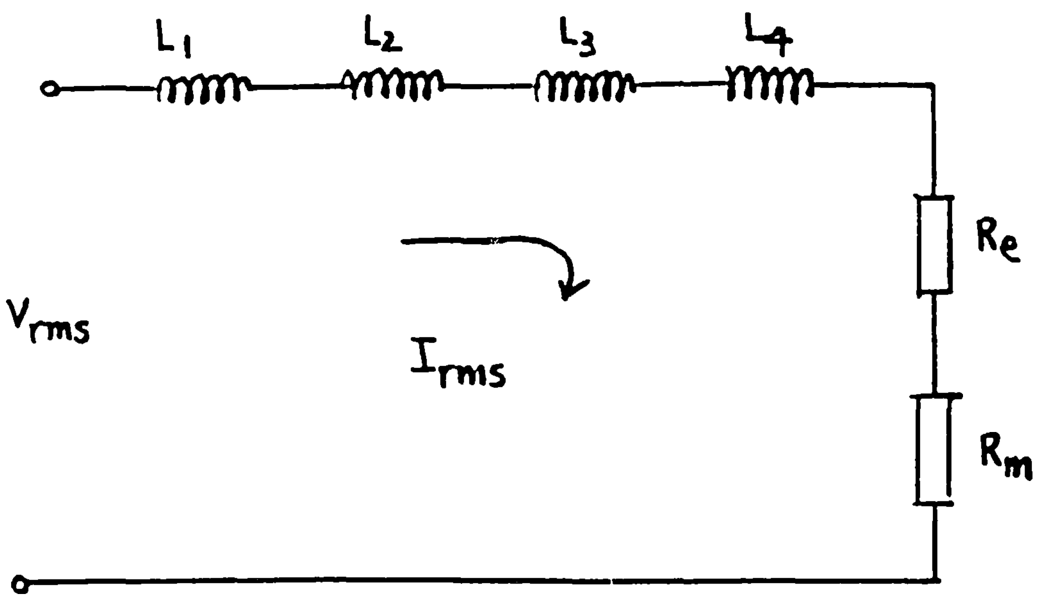


Figure 3

where $I_{rms} = \frac{1}{\sqrt{2}} 2lK.$ (2.24)

$$Z = R_{eddy} + R_{mech} + j\omega(L_1 + L_2 + L_3 + L_4), \quad (2.25)$$

$$V_{rms} = I_{rms}|Z|, \quad (2.26)$$

$$R_{eddy} = \frac{\sigma\mu_o^2\beta^2 A|\gamma|^2 (u-u_s)^2}{2|\Delta|^2 l^2} e^{-2\beta g} D_1, \quad (2.27)$$

$$R_{mech} = \frac{\sigma\mu_o\beta^2 A|\gamma|^2 u(u-u_s)^2}{2|\Delta|^2 l^2} e^{-2\beta g} D_1, \quad (2.28)$$

$$L_1 = \frac{\mu_o\beta A}{8l^2}\left|\frac{(1-\gamma^2)\sinh(\alpha h)}{\Delta} e^{-2\beta g} - 1\right|^2, \quad (2.29)$$

$$L_2 = \frac{\mu_o\beta A}{8l^2} e^{-2\beta g}\left[\left|\frac{(1-\gamma^2)\sinh(\alpha h)}{\Delta}\right|^2 \left(1 - e^{-2\beta g}\right) - 1 + e^{2\beta g}\right], \quad (2.30)$$

$$L_3 = \frac{\mu_o A|\gamma|^2}{2\mu|\Delta|^2 l^2} e^{-2\beta g}\left(|\alpha|^2 D_1 + \beta^2 D_2\right), \text{ and} \quad (2.31)$$

$$L_4 = \frac{\mu_o\beta A|\gamma|^2}{2|\Delta|^2 l^2} e^{-2\beta g} \quad (2.32)$$

Then

$$P_{eddy} = R_{eddy} I_{rms}^2 \tag{2.33}$$

is the power from eddy current dissipation, and

$$P_{mech} = R_{mech} I_{rms}^2 \tag{2.34}$$

is the power associated with mechanical work.

A similar analysis has been done for all harmonics. The powers become a sum over harmonics, and the corresponding impedances are computed on the basis of a sum of harmonics. For the conceptual design, we have restricted our work to the first harmonic. The expressions given are for the equivalent circuit components and power for one wavelength. As a consequence, the parameters scale with the length of the motor.

The analysis presented represents the total loads of the motor. To accurately represent each phase of a three-phase motor, the expressions and equations must be divided by three, assuming the motor is a balanced three-phase load.

3. Air Core Motor Design Design

To demonstrate the methodology, several motor designs are shown in Tables III-1 through III-18. The designs assume the width of the winding is given by $l = \tau / 6$. The motor is assumed to have eight poles and the same number of total turns as the iron core system (29.7). (The non-integer turns are indicative of a conceptual design. In the detailed designs the turns would be adjusted to 32, or 4 turns per pole.)

Motor designs were developed for guideways with and without backing iron. As expected, motors that work with guideways having iron backing were more efficient than those without iron.

Table III-1
SLIM Winding Design with Iron Under the Guideway at 60 Hz, 5 cm Gap

Type	Item	Value	Units
formula	Force	44.5	kN
input	Train velocity	134	m/sec
input	Frequency	60	Hz
input	No. phases	3	
input	Slip @ Vmax	0.07	
input	Gap (iron-iron)	0.05	meter
input	Track thickness	0.003	meter
formula	Gap to cond	0.047	meter
data	Al track res	0.056	µohm-meter
formula	Skin depth	0.015	meters
formula	Sync speed	144	m/sec
formula	Wavelength	2.40	meters
formula	Pitch	1.20	meters
rule	Ratio core width	1.2	
formula	Core width	1.44	meters
rule	No. poles	8	
formula	Pole area	1.73	m^2
formula	Force/area	0.32	newtons/cm^2
rule	Winding fac	1	
rule	Efficiency	1	
formula	No. of turns	29.7	turns
input	Field at gap	0.133	Tesla
formula	Field at winding	0.153	Tesla
formula	EMF/turn	121	volts
formula	AT/phase	34.08	kamp rms
input	Voltage (rms)	968	volts rms
formula	Current (rms)	4590	amps
formula	Mech power out	5.963	MW
formula	Input MVA	7.70	MW
formula	Power factor	0.77	
Cu data	Current density	500	amps/cm^2
formula	Wire cross section	9.18	cm^2
formula	Conductor (L)	470.7	meters
formula	Wire resistivity	0.017	µohm-meters
formula	Total R	0.0087	ohms
formula	I^2R losses	183.65	kW
formula	IR drop/phase	13.34	volts
Sc data	Current density	10,000	amps/cm^2
formula	Sc cross section	0.459	cm^2
formula	Sc volume	0.022	m^3
formula	SC losses @ 4.2K	79.31	watts

Table III-2
SLIM Winding Design with Iron Under the Guideway at 60 Hz, 10 cm Gap

Type	Item	Value	Units
formula	Force	44.5	kN
input	Train velocity	134	m/sec
input	Frequency	60	Hz
input	No. phases	3	
input	Slip @ Vmax	0.07	
input	Gap (iron-iron)	0.1	meter
input	Track thickness	0.003	meter
formula	Gap to cond	0.097	meter
data	Al track res	0.056	μohm-meter
formula	Skin depth	0.015	meters
formula	Sync speed	144	m/sec
formula	Wavelength	2.40	meters
formula	Pitch	1.20	meters
rule	Ratio core width	1.2	
formula	Core width	1.44	meters
rule	No. poles	8	
formula	Pole area	1.73	m^2
formula	Force/area	0.32	newtons/cm^2
rule	Winding fac	1	
rule	Efficiency	1	
formula	No. of turns	29.7	turns
input	Field at gap	0.134	Tesla
formula	Field at winding	0.154	Tesla
formula	EMF/turn	125	volts
formula	AT/phase	38.9	kamp rms
input	Voltage (rms)	1004.6	volts rms
formula	Current (rms)	5240	amps
formula	Mech power out	5.963	MW
formula	Input MVA	9.12	MW
formula	Power factor	0.65	
Cu data	Current density	500	amps/cm^2
formula	Wire cross section	10.48	cm^2
formula	Conductor (L)	470.7	meters
formula	Wire resistivity	0.017	μohm-meters
formula	Total R	0.0076	ohms
formula	I^2R losses	209.67	kW
formula	IR drop/phase	13.34	volts
Sc data	Current density	10,000	amps/cm^2
formula	Sc cross section	0.524	cm^2
formula	Sc volume	0.025	m^3
formula	SC losses @ 4.2K	91.22	watts

Table III-3
SLIM Winding Design with Iron Under the Guideway at 60 Hz, 15 cm Gap

Type	Item	Value	Units
formula	Force	44.5	kN
input	Train velocity	134	m/sec
input	Frequency	60	Hz
input	No. phases	3	
input	Slip @ Vmax	0.07	
input	Gap (iron-iron)	0.15	meter
input	Track thickness	0.003	meter
formula	Gap to cond	0.147	meter
data	Al track res	0.056	µohm-meter
formula	Skin depth	0.015	meters
formula	Sync speed	144	m/sec
formula	Wavelength	2.40	meters
formula	Pitch	1.20	meters
rule	Ratio core width	1.2	
formula	Core width	1.44	meters
rule	No. poles	8	
formula	Pole area	1.73	m^2
formula	Force/area	0.32	newtons/cm^2
rule	Winding fac	1	
rule	Efficiency	1	
formula	No. of turns	29.7	turns
input	Field at gap	0.137	Tesla
formula	Field at winding	0.158	Tesla
formula	EMF/turn	125.8	volts
formula	AT/phase	44.33	kamp rms
input	Voltage (rms)	1006.4	volts rms
formula	Current (rms)	5970	amps
formula	Mech power out	5.963	MW
formula	Input MVA	10.41	MW
formula	Power factor	0.57	
Cu data	Current density	500	amps/cm^2
formula	Wire cross section	11.94	cm^2
formula	Conductor (L)	470.7	meters
formula	Wire resistivity	0.017	µohm-meters
formula	Total R	0.0067	ohms
formula	I^2R losses	238.87	kW
formula	IR drop/phase	13.34	volts
Sc data	Current density	10,000	amps/cm^2
formula	Sc cross section	0.597	cm^2
formula	Sc volume	0.028	m^3
formula	SC losses @ 4.2K	106.26	watts

Table III-4
SLIM Winding Design with Iron Under the Guideway at 120 Hz, 5 cm Gap

Type	Item	Value	Units
formula	Force	44.5	kN
input	Train velocity	134	m/sec
input	Frequency	120	Hz
input	No. phases	3	
input	Slip @ Vmax	0.07	
input	Gap (iron-iron)	0.05	meter
input	Track thickness	0.003	meter
formula	Gap to cond	0.047	meter
data	Al track res	0.056	μohm-meter
formula	Skin depth	0.011	meters
formula	Sync speed	144	m/sec
formula	Wavelength	1.20	meters
formula	Pitch	0.60	meters
rule	Ratio core width	1.2	
formula	Core width	0.72	meters
rule	No. poles	8	
formula	Pole area	0.43	m^2
formula	Force/area	1.29	newtons/cm^2
rule	Winding fac	1	
rule	Efficiency	1	
formula	No. of turns	29.7	turns
input	Field at gap	0.269	Tesla
formula	Field at winding	0.309	Tesla
formula	EMF/turn	125.85	volts
formula	AT/phase	39.13	kamp rms
input	Voltage (rms)	1006.8	volts rms
formula	Current (rms)	5270	amps
formula	Mech power out	5.963	MW
formula	Input MVA	9.19	MW
formula	Power factor	0.65	
Cu data	Current density	500	amps/cm^2
formula	Wire cross section	10.54	cm^2
formula	Conductor (L)	235.3	meters
formula	Wire resistivity	0.017	μohm-meters
formula	Total R	0.0038	ohms
formula	I^2R losses	105.43	kW
formula	IR drop/phase	6.67	volts
Sc data	Current density	10,000	amps/cm^2
formula	Sc cross section	0.527	cm^2
formula	Sc volume	0.012	m^3
formula	SC losses @ 4.2K	184.18	watts

Table III-5
SLIM Winding Design with Iron Under the Guideway at 120 Hz, 10 cm Gap

Type	Item	Value	Units
formula	Force	44.5	kN
input	Train velocity	134	m/sec
input	Frequency	120	Hz
input	No. phases	3	
input	Slip @ Vmax	0.07	
input	Gap (iron-iron)	0.1	meter
input	Track thickness	0.003	meter
formula	Gap to cond	0.097	meter
data	Al track res	0.056	μohm-meter
formula	Skin depth	0.011	meters
formula	Sync speed	144	m/sec
formula	Wavelength	2.40	meters
formula	Pitch	0.6	meters
rule	Ratio core width	1.2	
formula	Core width	0.72	meters
rule	No. poles	8	
formula	Pole area	0.43	m^2
formula	Force/area	1.29	newtons/cm^2
rule	Winding fac	1	
rule	Efficiency	1	
formula	No. of turns	29.7	turns
input	Field at gap	0.284	Tesla
formula	Field at winding	0.327	Tesla
formula	EMF/turn	144.2	volts
formula	AT/phase	50.86	kamp rms
input	Voltage (rms)	1153.8	volts rms
formula	Current (rms)	6850	amps
formula	Mech power out	5.963	MW
formula	Input MVA	13.69	MW
formula	Power factor	0.436	
Cu data	Current density	500	amps/cm^2
formula	Wire cross section	13.7	cm^2
formula	Conductor (L)	235.36	meters
formula	Wire resistivity	0.017	μohm-meters
formula	Total R	0.0029	ohms
formula	I^2R losses	137.04	kW
formula	IR drop/phase	6.67	volts
Sc data	Current density	10,000	amps/cm^2
formula	Sc cross section	0.685	cm^2
formula	Sc volume	0.161	m^3
formula	SC losses @ 4.2K	252.7	watts

Table III-6
SLIM Winding Design with Iron Under the Guideway at 120 Hz, 15 cm Gap

Type	Item	Value	Units
formula	Force	44.5	kN
input	Train velocity	134	m/sec
input	Frequency	120	Hz
input	No. phases	3	
input	Slip @ Vmax	0.07	
input	Gap (iron-iron)	0.15	meter
input	Track thickness	0.003	meter
formula	Gap to cond	0.147	meter
data	Al track res	0.056	µohm-meter
formula	Skin depth	0.011	meters
formula	Sync speed	144	m/sec
formula	Wavelength	2.40	meters
formula	Pitch	0.60	meters
rule	Ratio core width	1.2	
formula	Core width	0.72	meters
rule	No. poles	8	
formula	Pole area	0.43	m^2
formula	Force/area	1.29	newtons/cm^2
rule	Winding fac	1	
rule	Efficiency	1	
formula	No. of turns	29.7	turns
input	Field at gap	0.306	Tesla
formula	Field at winding	0.352	Tesla
formula	EMF/turn	174.6	volts
formula	AT/phase	66.08	kamp rms
input	Voltage (rms)	1396.6	volts rms
formula	Current (rms)	8900	amps
formula	Mech power out	5.963	MW
formula	Input MVA	21.5	MW
formula	Power factor	0.277	
Cu data	Current density	500	amps/cm^2
formula	Wire cross section	17.8	cm^2
formula	Conductor (L)	235.4	meters
formula	Wire resistivity	0.017	µohm-meters
formula	Total R	0.0022	ohms
formula	I^2R losses	178.05	kW
formula	IR drop/phase	6.67	volts
Sc data	Current density	10,000	amps/cm^2
formula	Sc cross section	0.89	cm^2
formula	Sc volume	0.021	m^3
formula	SC losses @ 4.2K	353.82	watts

Table III-7
SLIM Winding Design with Iron Under the Guideway at 180 Hz, 5 cm Gap

Type	Item	Value	Units
formula	Force	44.5	kN
input	Train velocity	134	m/sec
input	Frequency	180	Hz
input	No. phases	3	
input	Slip @ Vmax	0.07	
input	Gap (iron-iron)	0.05	meter
input	Track thickness	0.003	meter
formula	Gap to cond	0.047	meter
data	Al track res	0.056	μohm-meter
formula	Skin depth	0.009	meters
formula	Sync speed	144	m/sec
formula	Wavelength	0.8	meters
formula	Pitch	0.4	meters
rule	Ratio core width	1.2	
formula	Core width	0.48	meters
rule	No. poles	8	
formula	Pole area	0.19	m^2
formula	Force/area	2.89	newtons/cm^2
rule	Winding fac	1	
rule	Efficiency	1	
formula	No. of turns	29.7	turns
input	Field at gap	0.414	Tesla
formula	Field at winding	0.476	Tesla
formula	EMF/turn	134	volts
formula	AT/phase	44.8	kamp rms
input	Voltage (rms)	1072	volts rms
formula	Current (rms)	6040	amps
formula	Mech power out	5.963	MW
formula	Input MVA	11.22	MW
formula	Power factor	0.53	
Cu data	Current density	500	amps/cm^2
formula	Wire cross section	12.1	cm^2
formula	Conductor (L)	156.9	meters
formula	Wire resistivity	0.017	μohm-meters
formula	Total R	0.002	ohms
formula	I^2R losses	80.56	kW
formula	IR drop/phase	4.45	volts
Sc data	Current density	10,000	amps/cm^2
formula	Sc cross section	0.604	cm^2
formula	Sc volume	0.009	m^3
formula	SC losses @ 4.2K	324.9	watts

Table III-8
SLIM Winding Design with Iron Under the Guideway at 180 Hz, 10 cm Gap

Type	Item	Value	Units
formula	Force	44.5	kN
input	Train velocity	134	m/sec
input	Frequency	180	Hz
input	No. phases	3	
input	Slip @ Vmax	0.07	
input	Gap (iron-iron)	0.10	meter
input	Track thickness	0.003	meter
formula	Gap to cond	0.097	meter
data	Al track res	0.056	μohm-meter
formula	Skin depth	0.009	meters
formula	Sync speed	144	m/sec
formula	Wavelength	0.8	meters
formula	Pitch	0.4	meters
rule	Ratio core width	1.2	
formula	Core width	0.48	meters
rule	No. poles	8	
formula	Pole area	0.19	m^2
formula	Force/area	2.89	newtons/cm^2
rule	Winding fac	1	
rule	Efficiency	1	
formula	No. of turns	29.7	turns
input	Field at gap	0.556	Tesla
formula	Field at winding	0.639	Tesla
formula	EMF/turn	175	volts
formula	AT/phase	66.5	kamp rms
input	Voltage (rms)	1403	volts rms
formula	Current (rms)	8950	amps
formula	Mech power out	5.963	MW
formula	Input MVA	21.75	MW
formula	Power factor	0.27	
Cu data	Current density	500	amps/cm^2
formula	Wire cross section	17.9	cm^2
formula	Conductor (L)	156.9	meters
formula	Wire resistivity	0.017	μohm-meters
formula	Total R	0.0015	ohms
formula	I^2R losses	119.37	kW
formula	IR drop/phase	4.46	volts
Sc data	Current density	10,000	amps/cm^2
formula	Sc cross section	0.895	cm^2
formula	Sc volume	0.014	m^3
formula	SC losses @ 4.2K	646.51	watts

Table III-9
SLIM Winding Design with Iron Under the Guideway at 180 Hz, 15 cm Gap

Type	Item	Value	Units
formula	Force	44.5	kN
input	Train velocity	134	m/sec
input	Frequency	180	Hz
input	No. phases	3	
input	Slip @ Vmax	0.07	
input	Gap (iron-iron)	0.15	meter
input	Track thickness	0.003	meter
formula	Gap to cond	0.147	meter
data	Al track res	0.056	µohm-meter
formula	Skin depth	0.009	meters
formula	Sync speed	144	m/sec
formula	Wavelength	0.8	meters
formula	Pitch	0.4	meters
rule	Ratio core width	1.2	
formula	Core width	0.48	meters
rule	No. poles	8	
formula	Pole area	0.19	m^2
formula	Force/area	2.89	newtons/cm^2
rule	Winding fac	1	
rule	Efficiency	1	
formula	No. of turns	29.7	turns
input	Field at gap	0.567	Tesla
formula	Field at winding	0.652	Tesla
formula	EMF/turn	247	volts
formula	AT/phase	98.46	kamp rms
input	Voltage (rms)	1976.5	volts rms
formula	Current (rms)	13260	amps
formula	Mech power out	5.963	MW
formula	Input MVA	45.39	MW
formula	Power factor	0.13	
Cu data	Current density	500	amps/cm^2
formula	Wire cross section	26.52	cm^2
formula	Conductor (L)	156.9	meters
formula	Wire resistivity	0.017	µohm-meters
formula	Total R	0.001	ohms
formula	I^2R losses	176.86	kW
formula	IR drop/phase	4.45	volts
Sc data	Current density	10,000	amps/cm^2
formula	Sc cross section	1.326	cm^2
formula	Sc volume	0.021	m^3
formula	SC losses @ 4.2K	976.8	watts

Table III-10
SLIM Winding Design With No Iron Under the Guideway at 60 Hz, 5 cm Gap

Type	Item	Value	Units
formula	Force	44.5	kN
input	Train velocity	134	m/sec
input	Frequency	60	Hz
input	No. phases	3	
input	Slip @ Vmax	0.07	
input	Gap (iron-iron)	0.05	meter
input	Track thickness	0.003	meter
formula	Gap to cond	0.047	meter
data	Al track res	0.056	μohm-meter
formula	Skin depth	0.015	meters
formula	Sync speed	144	m/sec
formula	Wavelength	2.4	meters
formula	Pitch	1.2	meters
rule	Ratio core width	1.2	
formula	Core width	1.44	meters
rule	No. poles	8	
formula	Pole area	1.73	m^2
formula	Force/area	0.32	newtons/cm^2
rule	Winding fac	1	
rule	Efficiency	1	
formula	No. of turns	29.7	turns
input	Field at gap	0.181	Tesla
formula	Field at winding	0.208	Tesla
formula	EMF/turn	137	volts
formula	AT/phase	59.5	kamp rms
input	Voltage (rms)	1905.9	volts rms
formula	Current (rms)	8020	amps
formula	Mech power out	5.963	MW
formula	Input MVA	15.22	MW
formula	Power factor	0.391	
Cu data	Current density	500	amps/cm^2
formula	Wire cross section	16.04	cm^2
formula	Conductor (L)	470.7	meters
formula	Wire resistivity	0.017	μohm-meters
formula	Total R	0.005	ohms
formula	I^2R losses	320.9	kW
formula	IR drop/phase	13.3	volts
Sc data	Current density	10,000	amps/cm^2
formula	Sc cross section	1.802	cm^2
formula	Sc volume	0.038	m^3
formula	SC losses @ 4.2K	188.6	watts

Table III-11
SLIM Winding Design With No Iron Under the Guideway at 60 Hz, 10 cm Gap

Type	Item	Value	Units
formula	Force	44.5	kN
input	Train velocity	134	m/sec
input	Frequency	60	Hz
input	No. phases	3	
input	Slip @ Vmax	0.07	
input	Gap (iron-iron)	0.10	meter
input	Track thickness	0.003	meter
formula	Gap to cond	0.097	meter
data	Al track res	0.056	µohm-meter
formula	Skin depth	0.015	meters
formula	Sync speed	144	m/sec
formula	Wavelength	2.4	meters
formula	Pitch	1.2	meters
rule	Ratio core width	1.2	
formula	Core width	1.44	meters
rule	No. poles	8	
formula	Pole area	1.73	m^2
formula	Force/area	0.321	newtons/cm^2
rule	Winding fac	1	
rule	Efficiency	1	
formula	No. of turns	29.7	turns
input	Field at gap	0.192	Tesla
formula	Field at winding	0.221	Tesla
formula	EMF/turn	157.1	volts
formula	AT/phase	67.86	kamp rms
input	Voltage (rms)	1257.1	volts rms
formula	Current (rms)	9140	amps
formula	Mech power out	5.963	MW
formula	Input MVA	19.9	MW
formula	Power factor	0.3	
Cu data	Current density	500	amps/cm^2
formula	Wire cross section	18.28	cm^2
formula	Conductor (L)	470.7	meters
formula	Wire resistivity	0.017	µohm-meters
formula	Total R	0.004	ohms
formula	I^2R losses	365.7	kW
formula	IR drop/phase	13.34	volts
Sc data	Current density	10,000	amps/cm^2
formula	Sc cross section	0.914	cm^2
formula	Sc volume	0.043	m^3
formula	SC losses @ 4.2K	228	watts

Table III-12
SLIM Winding Design With No Iron Under the Guideway at 60 Hz, 15 cm Gap

Type	Item	Value	Units
formula	Force	44.5	kN
input	Train velocity	134	m/sec
input	Frequency	60	Hz
input	No. phases	3	
input	Slip @ Vmax	0.07	
input	Gap (iron-iron)	0.15	meter
input	Track thickness	0.003	meter
formula	Gap to cond	0.147	meter
data	Al track res	0.056	µohm-meter
formula	Skin depth	0.015	meters
formula	Sync speed	144	m/sec
formula	Wavelength	2.4	meters
formula	Pitch	1.2	meters
rule	Ratio core width	1.2	
formula	Core width	1.44	meters
rule	No. poles	8	
formula	Pole area	1.73	m^2
formula	Force/area	0.321	newtons/cm^2
rule	Winding fac	1	
rule	Efficiency	1	
formula	No. of turns	29.7	turns
input	Field at gap	0.204	Tesla
formula	Field at winding	0.235	Tesla
formula	EMF/turn	180.4	volts
formula	AT/phase	77.37	kamp rms
input	Voltage (rms)	1443.5	volts rms
formula	Current (rms)	10420	amps
formula	Mech power out	5.963	MW
formula	Input MVA	26.05	MW
formula	Power factor	0.229	
Cu data	Current density	500	amps/cm^2
formula	Wire cross section	20.84	cm^2
formula	Conductor (L)	470.7	meters
formula	Wire resistivity	0.017	µohm-meters
formula	Total R	0.004	ohms
formula	I^2R losses	416.9	kW
formula	IR drop/phase	13.34	volts
Sc data	Current density	10,000	amps/cm^2
formula	Sc cross section	1.042	cm^2
formula	Sc volume	0.049	m^3
formula	SC losses @ 4.2K	276	watts

Table III-13
SLIM Winding Design With No Iron Under the Guideway at 120 Hz, 5 cm Gap

Type	Item	Value	Units
formula	Force	44.5	kN
input	Train velocity	134	m/sec
input	Frequency	120	Hz
input	No. phases	3	
input	Slip @ Vmax	0.07	
input	Gap (iron-iron)	0.05	meter
input	Track thickness	0.003	meter
formula	Gap to cond	0.047	meter
data	Al track res	0.056	μohm-meter
formula	Skin depth	0.011	meters
formula	Sync speed	144	m/sec
formula	Wavelength	1.2	meters
formula	Pitch	0.6	meters
rule	Ratio core width	1.2	
formula	Core width	0.72	meters
rule	No. poles	8	
formula	Pole area	0.43	m^2
formula	Force/area	1.29	newtons/cm^2
rule	Winding fac	1	
rule	Efficiency	1	
formula	No. of turns	29.7	turns
input	Field at gap	0.386	Tesla
formula	Field at winding	0.44	Tesla
formula	EMF/turn	157.8	volts
formula	AT/phase	68.09	kamp rms
input	Voltage (rms)	1262.3	volts rms
formula	Current (rms)	9170	amps
formula	Mech power out	5.963	MW
formula	Input MVA	20.0	MW
formula	Power factor	0.3	
Cu data	Current density	500	amps/cm^2
formula	Wire cross section	18.34	cm^2
formula	Conductor (L)	235.36	meters
formula	Wire resistivity	0.017	μohm-meters
formula	Total R	0.002	ohms
formula	I^2R losses	183.5	kW
formula	IR drop/phase	6.67	volts
Sc data	Current density	10,000	amps/cm^2
formula	Sc cross section	0.917	cm^2
formula	Sc volume	0.022	m^3
formula	SC losses @ 4.2K	459.9	watts

Table III-14
SLIM Winding Design With No Iron Under the Guideway at 120 Hz, 10 cm Gap

Type	Item	Value	Units
formula	Force	44.5	kN
input	Train velocity	134	m/sec
input	Frequency	120	Hz
input	No. phases	3	
input	Slip @ Vmax	0.07	
input	Gap (iron-iron)	0.10	meter
input	Track thickness	0.003	meter
formula	Gap to cond	0.097	meter
data	Al track res	0.056	µohm-meter
formula	Skin depth	0.011	meters
formula	Sync speed	144	m/sec
formula	Wavelength	1.2	meters
formula	Pitch	0.6	meters
rule	Ratio core width	1.2	
formula	Core width	0.72	meters
rule	No. poles	8	
formula	Pole area	0.43	m^2
formula	Force/area	1.286	newtons/cm^2
rule	Winding fac	1	
rule	Efficiency	1	
formula	No. of turns	29.7	turns
input	Field at gap	0.435	Tesla
formula	Field at winding	0.500	Tesla
formula	EMF/turn	207.8	volts
formula	AT/phase	88.5	kamp rms
input	Voltage (rms)	1662.5	volts rms
formula	Current (rms)	11920	amps
formula	Mech power out	5.963	MW
formula	Input MVA	34.32	MW
formula	Power factor	0.17	
Cu data	Current density	500	amps/cm^2
formula	Wire cross section	23.84	cm^2
formula	Conductor (L)	235.36	meters
formula	Wire resistivity	0.017	µohm-meters
formula	Total R	0.002	ohms
formula	I^2R losses	238.47	kW
formula	IR drop/phase	6.67	volts
Sc data	Current density	10,000	amps/cm^2
formula	Sc cross section	1.192	cm^2
formula	Sc volume	0.028	m^3
formula	SC losses @ 4.2K	673.7	watts

Table III-15
SLIM Winding Design With No Iron Under the Guideway at 120 Hz, 15 cm Gap

Type	Item	Value	Units
formula	Force	44.5	kN
input	Train velocity	134	m/sec
input	Frequency	120	Hz
input	No. phases	3	
input	Slip @ Vmax	0.07	
input	Gap (iron-iron)	0.15	meter
input	Track thickness	0.003	meter
formula	Gap to cond	0.147	meter
data	Al track res	0.056	μohm-meter
formula	Skin depth	0.011	meters
formula	Sync speed	144	m/sec
formula	Wavelength	1.2	meters
formula	Pitch	0.6	meters
rule	Ratio core width	1.2	
formula	Core width	0.72	meters
rule	No. poles	8	
formula	Pole area	0.43	m^2
formula	Force/area	1.286	newtons/cm^2
rule	Winding fac	1	
rule	Efficiency	1	
formula	No. of turns	29.7	turns
input	Field at gap	0.606	Tesla
formula	Field at winding	0.6969	Tesla
formula	EMF/turn	273.05	volts
formula	AT/phase	115.01	kamp rms
input	Voltage (rms)	2184.4	volts rms
formula	Current (rms)	15490	amps
formula	Mech power out	5.963	MW
formula	Input MVA	58.6	MW
formula	Power factor	0.10	
Cu data	Current density	500	amps/cm^2
formula	Wire cross section	30.98	cm^2
formula	Conductor (L)	235.4	meters
formula	Wire resistivity	0.017	μohm-meters
formula	Total R	0.001	ohms
formula	I^2R losses	309.89	kW
formula	IR drop/phase	6.67	volts
Sc data	Current density	10,000	amps/cm^2
formula	Sc cross section	1.549	cm^2
formula	Sc volume	0.036	m^3
formula	SC losses @ 4.2K	1219.6	watts

Table III-16
SLIM Winding Design With No Iron Under the Guideway at 180 Hz, 5 cm Gap

Type	Item	Value	Units
formula	Force	44.5	kN
input	Train velocity	134	m/sec
input	Frequency	180	Hz
input	No. phases	3	
input	Slip @ Vmax	0.07	
input	Gap (iron-iron)	0.05	meter
input	Track thickness	0.003	meter
formula	Gap to cond	0.047	meter
data	Al track res	0.056	μohm-meter
formula	Skin depth	0.009	meters
formula	Sync speed	0.8	m/sec
formula	Wavelength	0.4	meters
formula	Pitch	1.2	meters
rule	Ratio core width	0.48	
formula	Core width	1.44	meters
rule	No. poles	8	
formula	Pole area	0.192	m^2
formula	Force/area	2.89	newtons/cm^2
rule	Winding fac	1	
rule	Efficiency	1	
formula	No. of turns	29.7	turns
input	Field at gap	0.616	Tesla
formula	Field at winding	0.708	Tesla
formula	EMF/turn	181.8	volts
formula	AT/phase	77.96	kamp rms
input	Voltage (rms)	1454.6	volts rms
formula	Current (rms)	10500	amps
formula	Mech power out	5.963	MW
formula	Input MVA	26.45	MW
formula	Power factor	0.225	
Cu data	Current density	500	amps/cm^2
formula	Wire cross section	21	cm^2
formula	Conductor (L)	156.9	meters
formula	Wire resistivity	0.017	μohm-meters
formula	Total R	0.001	ohms
formula	I^2R losses	140.0	kW
formula	IR drop/phase	4.45	volts
Sc data	Current density	10,000	amps/cm^2
formula	Sc cross section	1.05	cm^2
formula	Sc volume	0.016	m^3
formula	SC losses @ 4.2K	840.3	watts

Table III-17
SLIM Winding Design With No Iron Under the Guideway at 180 Hz,10 cm Gap

Type	Item	Value	Units
formula	Force	44.5	kN
input	Train velocity	134	m/sec
input	Frequency	180	Hz
input	No. phases	3	
input	Slip @ Vmax	0.07	
input	Gap (iron-iron)	0.10	meter
input	Track thickness	0.003	meter
formula	Gap to cond	0.097	meter
data	Al track res	0.056	μohm-meter
formula	Skin depth	0.009	meters
formula	Sync speed	144	m/sec
formula	Wavelength	0.8	meters
formula	Pitch	0.4	meters
rule	Ratio core width	1.2	
formula	Core width	0.48	meters
rule	No. poles	8	
formula	Pole area	0.192	m^2
formula	Force/area	2.89	newtons/cm^2
rule	Winding fac	1	
rule	Efficiency	1	
formula	No. of turns	29.7	turns
input	Field at gap	0.742	Tesla
formula	Field at winding	0.853	Tesla
formula	EMF/turn	274.09	volts
formula	AT/phase	115.46	kamp rms
input	Voltage (rms)	2192.7	volts rms
formula	Current (rms)	15550	amps
formula	Mech power out	5.963	MW
formula	Input MVA	59.06	MW
formula	Power factor	0.10	
Cu data	Current density	500	amps/cm^2
formula	Wire cross section	31.1	cm^2
formula	Conductor (L)	156.9	meters
formula	Wire resistivity	0.017	μohm-meters
formula	Total R	0.001	ohms
formula	I^2R losses	207.4	kW
formula	IR drop/phase	4.45	volts
Sc data	Current density	10,000	amps/cm^2
formula	Sc cross section	1.555	cm^2
formula	Sc volume	0.024	m^3
formula	SC losses @ 4.2K	1449.0	watts

Table III-18
SLIM Winding Design With No Iron Under the Guideway at 180 Hz, 15 cm Gap

Type	Item	Value	Units
formula	Force	44.5	kN
input	Train velocity	134	m/sec
input	Frequency	180	Hz
input	No. phases	3	
input	Slip @ Vmax	0.07	
input	Gap (iron-iron)	0.15	meter
input	Track thickness	0.003	meter
formula	Gap to cond	0.147	meter
data	Al track res	0.056	μohm-meter
formula	Skin depth	0.009	meters
formula	Sync speed	144	m/sec
formula	Wavelength	0.8	meters
formula	Pitch	0.4	meters
rule	Ratio core width	1.2	
formula	Core width	0.48	meters
rule	No. poles	8	
formula	Pole area	0.19	m^2
formula	Force/area	2.89	$newtons/cm^2$
rule	Winding fac	1	
rule	Efficiency	1	
formula	No. of turns	29.7	turns
input	Field at gap	0.897	Tesla
formula	Field at winding	1.03	Tesla
formula	EMF/turn	409.9	volts
formula	AT/phase	171	kamp rms
input	Voltage (rms)	3278.9	volts rms
formula	Current (rms)	23030	amps
formula	Mech power out	5.963	MW
formula	Input MVA	130.8	MW
formula	Power factor	0.046	
Cu data	Current density	500	$amps/cm^2$
formula	Wire cross section	46.06	cm^2
formula	Conductor (L)	156.9	meters
formula	Wire resistivity	0.017	μohm-meters
formula	Total R	0.001	ohms
formula	I^2R losses	307.16	kW
formula	IR drop/phase	4.45	volts
Sc data	Current density	10,000	$amps/cm^2$
formula	Sc cross section	2.303	cm^2
formula	Sc volume	0.036	m^3
formula	SC losses @ 4.2K	2683.9	watts