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A COOPERATIVE RESEARCH PROGRAMME TO INVESTIGATE THE APPLICATION OF AIR-CORED LINEAR SYNCHRONOUS MACHINES TO ADVANCED GROUND TRANSPORT

1.0. Introduction

Railways throughout the world are beginning to rely more heavily on advances in technology to increase their effectiveness as a transport mode compared to the airplane and motorcar. In doing so the emphasis is usually placed on achieving higher average speeds to generate a commercial gain of reduced trip time, with the conflicting constraint of increase of cost usually providing the limiting factor.

Some areas where the impact of new technologies can be immediately felt are:

- Aerodynamic drag reduction
- Required energy reduction
- Tare weight per seat reduction
- More efficient use of track
- Better forms of traction and power conversion
- Higher average speeds through improved suspensions
- Increases in load factor
- Use of automation to reduce required manpower

Although some of these effects can be achieved by slight extensions to common practice, others represent distinct changes in philosophy for railway adminstrations. In particular, the trend has developed to produce fixed formation, articulated-rake trains with integral power for operation in the high speed 200-300 km/h (125-186 mph) range. Likewise, there is a growing interest in the development of novel techniques of propulsion, guidance and suspension for the very high speeds of 300-500 km/h (186-310 mph).

In all the proposed configurations, the method of trac tion chosen will heavily influence the other subsystems' design. For example, to meet the tractive power requirement at 500 km/h, either a wheel trainset with the best of conventional traction motors, or an attractive, magnetically-levitated vehicle with linear induction motor drive, would face severe problems in finding adequate remaining space for payloads.

The following proposal outlines the areas of existing work on AGT traction systems and suggests a possible line of research on one of the more promising of the linear drive systems, i.e. the air-cored, linear synchronous machine using superconducting magnets.

2.0. Existing Traction Methods

2.1. Conventional Vehicles

At present the majority of passenger vehicles are either diesel or electrically-powered. Although there was brief interest in the gas turbines which were built for the experimental versions of BR's APT and SNCF's TGV, the pre-production prototypes of these trains are electrically powered. It is to be expected that the expected increase in the price of oil and its adverse environmental effects will both eventually lead to the adoption of all-electric propulsion for ground transport in the foreseeable future.

Electric drives can be divided into three main classes, determined by the motor type

i) DC drives. The d.c. machine has for long been the most common drive motor because its full load torque capability at low speeds matches the traction requirement. As size and speed increase, however, commutation problems occur, and so the machines tend to be run at relatively slower rates. The recent use of semiconductor choppers for power regulation enables more efficient housekeeping of the energy used in accelerating and braking.

ii) Synchronous drives. If a synchronous machine is fed and controlled by a semiconductor inverter, its speed/torque characteristics can be made to match those of a d.c. machine. The rotor can be more robust than a d.c. machine's and requires slip-rings rather than a commutator, so higher peripheral speeds are possible producing a more efficient overall machine suited to large power ratings. However, with the exception of some Urban Transport applications, this motor has been relatively ignored for high power traction.

iii) Asynchronous drives. The induction motor with either a cage or cup secondary (rotor) can be used in two main modes. Using voltage control and secondary resistance insertion the torque/speed characteristic can be made to suit the traction need. An alternative approach is to use an inverter to match frequency with running speed so that the motor operates at similar slips as its speed increases. If the voltage/frequency ratio is kept constant then the load torque can be met with full pole flux implying the most efficient operation. A particular example of a modification of this concept is BR's Tubular axle induction motor (TAIM) where the motor is mounted directly on the axle shaft. Because of the extreme simplicity of the induction motor and the rapid advances made in power semiconductors, it is most likely to be the prime choice for conventional traction drives in the future.

2.2. Unconventional Vehicles

Magnetic Levitation (Maglev) research and development are proposed as a solution to the guidance, support, propulsion, maintenance and environmental problems inevitably created by attempting to run a contact wheel traction system at very high speeds. The main effort in this area is concentrated in Japan and Germany, with lesser effort in the USSR, Canada, America and the U.K. The sums of development money involved can be enormous - for example, Japan's Ministry of Transport plans to take over JNR's superconducting Maglev project and spend Y100,000m (> £250 million) over the next six years to have the system fully developed by 1985. In 1979 a plan to construct a 40 km test track will be financed by a Y10,000m (£25 million) grant to JNR. In addition the Ministry will also make available Y2,000m (£50 million) in 1979 to subsidise JAL's attractive Maglev scheme. Irregardless of whether magnetic suspension is necessary or not, the research has also established a core of technical knowledge about linear machines of different types. They can be briefly catagorised as follows:

i) Linear Induction Machines. Initially conceived as a double-sided machine, usually with a vertical reaction rail, the axial flux, linear induction machine (AFLIM) has now tended to superseded by the single-sided, linear induction machine (SSLIM), because of the unattractiveness of feeding a relatively weakly supported, vertically mounted reaction rail into a small air gap at high speeds. The LIM tends to have degradation of performance caused by lateral edge effects, as well as entry and exit edge effects which in the past have sometimes tended to escape analysis. Because of its induction effect only small clearances can be allowed in the air gap, otherwise the powerfactor-efficiency product becomes even more unreasonable. Some relief of entry and exit losses can be obtained by adopting a transverse-flux mode of construction, but the machine still relies on induction to establish currents in the secondary member.

ii) Homo-and Heteropolar machines. These belong to a class of iron-cored machines which have an a.c. and a d.c. winding on one member and rely on track saliency to produce a working thrust. Only small scale testing (< 100 kW) has been performed on linear and arch motors of this type, which do seem to have a slight advantage over LIM's.

iii) Iron-Cored LSM. This alternative, developed mainly by Prof. Weh at T.U. Braunschweig in West Germany has been adopted by the Transrapid-EMS group to power the demonstration vehicle being built for IVA-79 at Hamburg. Although a small gap device, with an extended iron-cored track armature i.e. a long stator, the degradation of eddy current distortion occurring in the LIM is absent, and the machine is therefore claimed to be much more efficient and have virtually no degradation with increases in speed. The short stator LIM has therefore been effectively dropped in Germany as a propulsion device.

iv) DC Linear Motor. Developed by JNR this machine consists of an iron-cored field array on the vehicle interacting with track-bound, normal conducting, air-cored coils. The track coils are switched using a flip-flop inverter with superforced commutation to provide correct progression of the armature field The motor has been designed to be used for levitation as well as propulsion, and does not require superconducting technology for implementation. The air gap for a 300 km/h system is 157 mm including a 97 mm coil.

v) Air-cored Linear Synchronous Superconducting Machine, LSM. This LSM design uses high-field superconducting magnets on-board the vehicle to produce a field variation at the track surface which will interact with the armature, travelling magnetic wave, generated by a trackbound distribution of an air-cored winding. The major advantage of this machine over the induction, d.c. or reluctance machines, is that the majority of air-gap flux is provided by no expense of reactive power at trackside substations. In fact, the armature reaction of the machine is relatively small, its amount being determined by the traction requirement. In this respect, the machine differs from an a.c. superconducting generator, where the stator armature is designed to link as much flux as possible and hence, this results in a large number of turns per pole per phase. Typical LSM designs go from 1 to 6 full pitch turns per pole per phase, amounting to perhaps 5 - 30 kg per meter of track length.

All the research so far on these machines has been to develop the long stator LSM for propelling magnetically levitated vehicles, and so relatively large gaps (< 0.3 m) have been chosen. Likewise emphasis has been placed on very lightweight cryostats to house the superconducting coils. This has led to problems in cryostat design and coil stressing, some of which would be relieved if a slight weight penalty could be allowed.

3.0. The Intermediate Speed Gap

3.1. Technologies Involved

As mentioned previously the Electromagnetic system of levitation (EMS) is at the stage of development where passenger-carrying prototypes are about to be tested. For medium to high speeds the technologies required are not expected to be overstretched, but for very high speeds reliance must be placed on tight track tolerances and adequate margins of safety built into levitation power control systems. With the possible exception of Japan, the Electrodynamic system of levitation (EDS) lags behind EMS because of the lead time of the latter, and also because the technologies involved in large-scale applications of superconductivity are still in their infancy.

3.2. Hybrid Vehicles

It would appear, therefore, that an important step could be made to advance both the LSM and advanced transport vehicles, such as APT, by introducing the concept of a hybrid vehicle. The suspension and guidance modes of the steel wheel on steel rail would be retained, but the propulsion would be by the long stator LSM with superconducting magnets on the vehicle. Conventional railway vehicles would obtain a thrust unit which would not depend on wheel adhesion for traction and braking and it would require only minor modifications to track surface. It would remove the need for pantographs and overhead systems, and it would have an electrical performance as good as, if not superior, to existing systems. Higher average speeds could be easily obtained with maximum speeds approaching 350 km/h, although now the limiting factor would be deceleration rates for passenger comfort rather than onset of wheel slip. A further advantage would be that a complete automated train control system is possible from a central computer without the need to transmit information to and from the train.

4.0. Research Aims and Means of Obtaining Them

4.1. Facilities at Warwick University

Two main test facilities exist at Warwick University and are suitable for the type of research envisaged, i.e.

- A 550 m straight track, 1.3 m wide, timber construction on concrete pillars. This facility incorporates a wheeled trolley on which test vehicles can be mounted and which can be forced down the track at speeds up to 45 m/s. The track has been designed to take a deadweight of $\sim$ 1 tonne and its length could be extended on the campus to include a switch and curve to a total length of $\sim$ 1 km.

• A 3 m diameter test wheel. The wheel is entirely non-magnetic, being constructed from fibreglass/epoxy resin, plywood and aluminium. A Ward-Leonard drive is provided to allow for a surface speed of 45 m/s. An additional rim loading of 200 kg ($\sim$ 20 kg/m) is possible, without any speed reduction.

4.2. Existing Research Contracts

Existing SRC contracts to investigate the levitation and propulsion of high speed vehicles using superconducting magnets are the following:-

1. The influence of ground simulation on the aerodynamics of high speed trains.

2. A study of the levitation, guidance, and propulsion of an electrodynamic system of advanced ground transport.

3. The effect of magnetic field oscillations on the losses in superconducting magnets for application to generators and high speed transport.

A core of expertise and experience on advanced ground transport systems has been established at Warwick over a number of years and the present team of Research Fellows and Technician Assistants is well qualified to undertake this proposed investigation of a LSM propulsion system.

4.3. Objectives of Proposed Research

General: To investigate the application of linear synchronous machines to advanced ground transport, including their use as a propulsion unit for wheeled trainsets.

Specific: 1) To extend the work under the present SRC contract on the wheel testing of the LSM i) to fully investigate "controllability" of synchronous machines under all likely operating conditions, and ii) to establish the required amount of feedback required for inverter control and establish the means of achieving a closed loop operation.

2) To establish experimentally and theoretically the behaviour of the machine at small air-gaps with high harmonic contents and to formulate the choices available for guaranteeing adequate ride and phase balance in the track circuits.

3) To design, commission and operate a scaled version of a LSM wheeled vehicle with steel rails for guidance.

4) To extract from test trials the likely parameters of importance in designing a full-size system and to establish correlation with theoretical analysis.

5) To study the design of a full-size prototype vehicle, embodying current railway practice and the most appropriate choice of cryogenic equipment available.

6) To formulate the requirements of a cryogenic system for operation in a transport environment.

7) To bring together a core of interested parties in industry and universities.

4.4. Proposed Strategy

The proposed strategy would fall readily into six parts, i.e.

1) Extend research on the test-wheel by adding a powered winding and superconducting magnets.

2) Perform further analytical studies to establish primary parameters and system sensitivity to changes in these parameters.

3) Perform an outline design for a scaled prototype vehicle.

4) Perform an outline design for a large-scale prototype vehicle with track and wheel results as input data.

5) Perform a cost analysis of a complete system.

6) Consider the necessity of constructing a larger scale vehicle.

5.0. Cooperative and Research Interests Group

1)	BICC	Track Winding Studies and Costing, Integration with Utility Supply.
2)	British Rail	Overall Conceptual View of place in Transport System, Current Practice Information, APT modification required Vehicle dynamics and suspension studies.

3)	Brush	Inverter & Power Electronics Track Winding (with BICC?)
4)	Farebrother & Partners	Guideway design, slab track, winding installation, Costing.
5)	Thor	Cryogenics, Cryostat Superconducting Magnets.
6)	Warwick	Test facilities Testing, Theoretical backup.

6.0. Costs Involved

6.1. Definition of Areas to be Covered

The research activity splits into four defined categories:

i) Wheel LSM using Liquid Nitrogen (LN_2) cooled coils

ii) Wheel LSM using superconducting coils

iii) Track LSM using LN_2 cooled coils

iv) Track LSM using superconducting coils

6.2 Wheel Research

6.2.1 Wheel LSM with LN_2 cooled coils

It is hoped that this activity will be fully met and completed during the existing SRC contract. The major cost of an inverter has been avoided by the generous loan from Brush of the 375 kVA inverter used on the Mickleover trials of linear induction machines.

Machine armature design will be checked using $\sim$ 200 kg conductor on the rim. If more conductor is required, the wheel speed must be derated from 45 m/s.

6.2.2 Wheel LSM with superconducting coils

Depending on how the LN_2 coils behave, it would be advantageous to provide a design case for a superconducting field arrangement. The operational results would extend the power output of the machine, by increasing the magnetic loading, and would provide a realistic base for an extrapolated design of full sized systems. The main problem areas to be expected lie in coil stability, low loss coil structures (electrical and thermal), mechanical integrity under dynamic conditions, and low cost transfer systems (power and cryogen).

To equip the wheel with a superconducting magnet array would cost ∿ £30k, for materials and fabrication labour. Extras for additional instrumentation and etc. would be minimal. Running costs for helium could add on another £9k for, say, 10 experimental test runs each requiring 200 l helium.

6.3 Track Research

6.3.1 Common Costs

The natural progression to linear track testing would be necessary to not only establish the operational constraints of the system, but to formulate solutions applicable to a full size system.

As a demonstration test bed the track value is hard to assess - but the first phase (LN_2 cooled coils) could have a very fast turn-around suitable for a demonstration facility.

The track installation would require some modification if it was to be used for major research. The breakdown of these costs are:

	£1000's
Fencing	2
Rough access along track	3
Permanent store/control room	5
Trackside distribution	7
Guide rails	20
Winding	10
Generatoring set	15
Control gear and electronics	5
	£67,000

These figures might well be less if, for example, second hand equipment was available.

6.3.2 Track LSM with LN_2 cooled coils

The expected LN_2 cooled copper coil cost of fabrication and commissioning is expected to be about £2,000.

6.3.3 Superconducting Coils

This is a more difficult sum to estimate, but modifying an earlier quotation obtained from the Rutherford Laboratory, to take inflation into account, it is expected to be of the order of £60,000 - £70,000.

7. Track Installation Details

The specification for the track LSM is as follows:

Track:	
Length	550m
Test length	250 m
Acceleration and deceleration length resp.	150 m
Construction	existing
Winding:	
Double layer meander	
No. phases	3
Turns per pole per phase	1-4 (adjustable)
Winding width	0.8 m
Wavelength	0.8 m
Conductor radius	6.5 mm
Phase resistance	1.45 mΩ/m
Phase inductance	5.96 μH/m
Phase to phase mutual inductance	-1.51 μH/m
Total phase inductance	7.47 μH/m
Phase impedance @ 50 m/s	3.27 mΩ/m
Aluminium conductor mass	6 kg/m
Operating parameters:	
Speed	50 m/s
Drag force (theoretical)	3 kN
Inertial power	150 kW
Inverter frequency	62.5 Hz
Inverter voltage	280 V
Phase current	357 A
Inverter complex power	300 kVA
Power factor	0.78
Efficiency	0.64

Main feeder for the armature winding will be from a current pick-up system fitted to the sides of the track plinths which can be used for LIM or other propulsion tests with pantograph power collectors.

8. Benefits Resulting from a Cooperative Research Programme

All the participants are likely to achieve benefit from a cooperative research programme. It is apparent that the future of the railway industry lies in electrification. Unless the manufacturing groups involved strive to keep abreast of current technological developments throughout the world, the situation will arise whereby they have "nothing to offer" to prospective customers, compared to their competitors. It is worth noting for example that JNR technical assistance has been sought at near governmental level in China, Brazil and U.S.A. (in particular the N.E. Corridor Route of New York, Washington and Boston). Backing up the Japan Railway Technical Service (JARTS), the JNR and Ministry of Transport Group, is the Japan Rolling Stock Exporters' Association (JARSEA), whose members include Fuji, Hitachi, Kawasaki, Mitsubishi, Sumitomo, Toshiba and others.

Although there are export groups within the U.K., the potential of an across-industry research activity can only help to strengthen participants' claims to be in the forefront of the new transportation technologies. Particular benefits arising from this specific area of research are difficult to quantify. However, it must be expected that as the programme progresses patentable areas ranging from, say, cryostat fabrication techniques to machine convertor control strategies will arise which will be of immediate commercial value to the company involved. Access to the test facilities will also generate insight into problems encountered in participants' on-going designs, and provide valuable information ranging from current collection performance to the aerodynamic characteristics of train sets.

9. Conclusions

The outcome of a cooperative programme of research would establish the aims detailed in 4.3, i.e. to investigate the application of the linear synchronous machine to advanced ground transport systems as a propulsion unit for wheeled train sets.

The research activities will bring immediate and long term benefit to the participants in terms of patents and test facilities available, as well as association with a research activity into a new form of transportation technology.

The cost of the research depends on the final level of commitment. A low level approach would be achieved with cryogenically cooled superconducting coils on the wheel and would total £30k plus £9k for helium. An intermediate stage of nitrogen cooled coils on the track would cost ~£70k. To go to superconducting magnets on the track might increase the cost by another £60k - £70k.

COST SUMMARY

	ADDITIONAL COSTS
1. LOW LEVEL, LHe COILS, WHEEL	£30k + £9k
2. INTERMEDIATE, LN_2 COILS, TRACK	£67k + £2k
3. HIGH LEVEL LHe COILS, TRACK (Assumes (2) completed)	£60k - £70k

Table 1 LSM - Typical Magnet Details

Operating ampereturns	$1.2.10^6$
Maximum flux density	5.5 T
Insulation and interlayer thickness	0.7 mm
Layer width x height	102 x 100 mm
No windings per layer x No layers	30 x 40
Effective current density	118 A/mm^2
Meanturn length x width	1.12 x 0.7 m
Midline deviation from mean turn	5-15 mm
Wound conductor mass	238 kg
Operating current	1000 A
Short sample critical current	1250 A
Vacuum box weight	2.2 tonnes
Pole pitch	1.4 m
No coils per box	3
Box overall length x width x height	4.15 x 1.2 x 1 m
Coil ℄ to cryostat lower face	155 mm
Coil ℄ to track surface	< 255 mm

Table 2 LSM-Track Conductor Details (200-500 km/h)

Plinth size (height x width)	280 x 1005 mm
Cable voltage range	6-25 kV
No. Cables/pole/phase	2-6
No. phases	3
Cable current nominal	250 A
Cable cross section	100 mm^2
Nominal current density	2.5 A/mm^2
Section length	5-15 km
Expected temperature rise	40 K
Short time over-temperature	80 K
Transfer power	5-35 MVA
Conductor material	Al
Conductor makeup	Concentric lay stranded

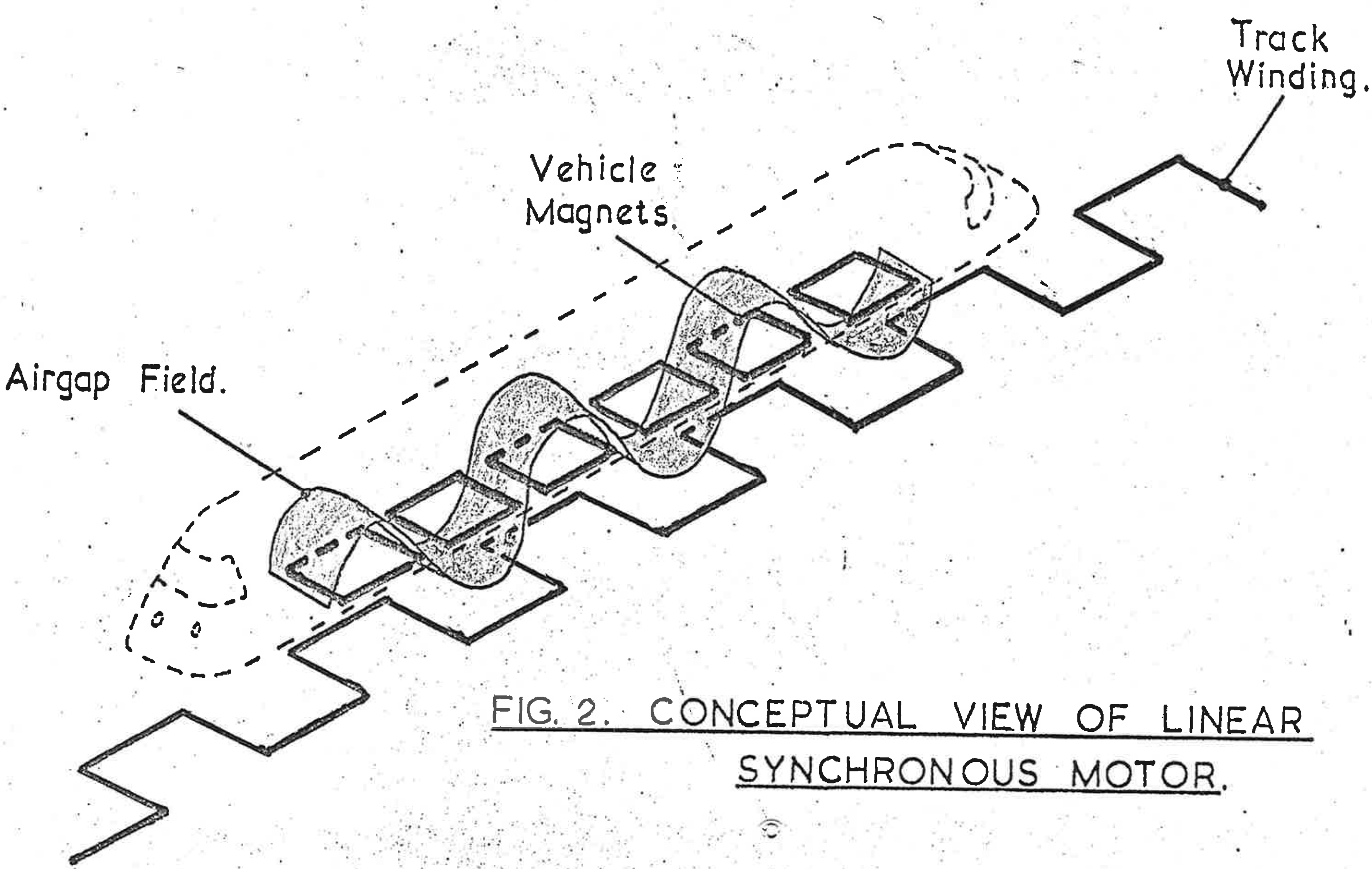
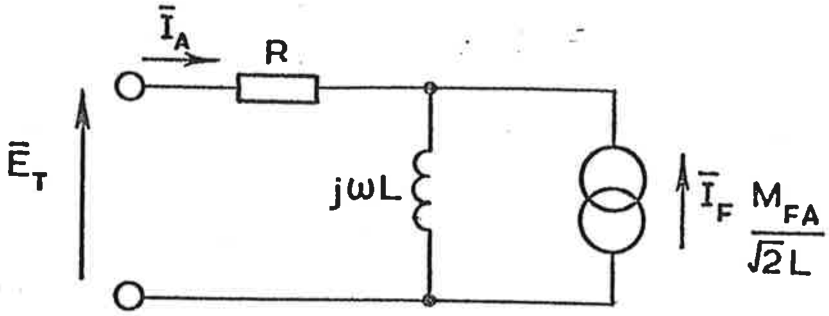
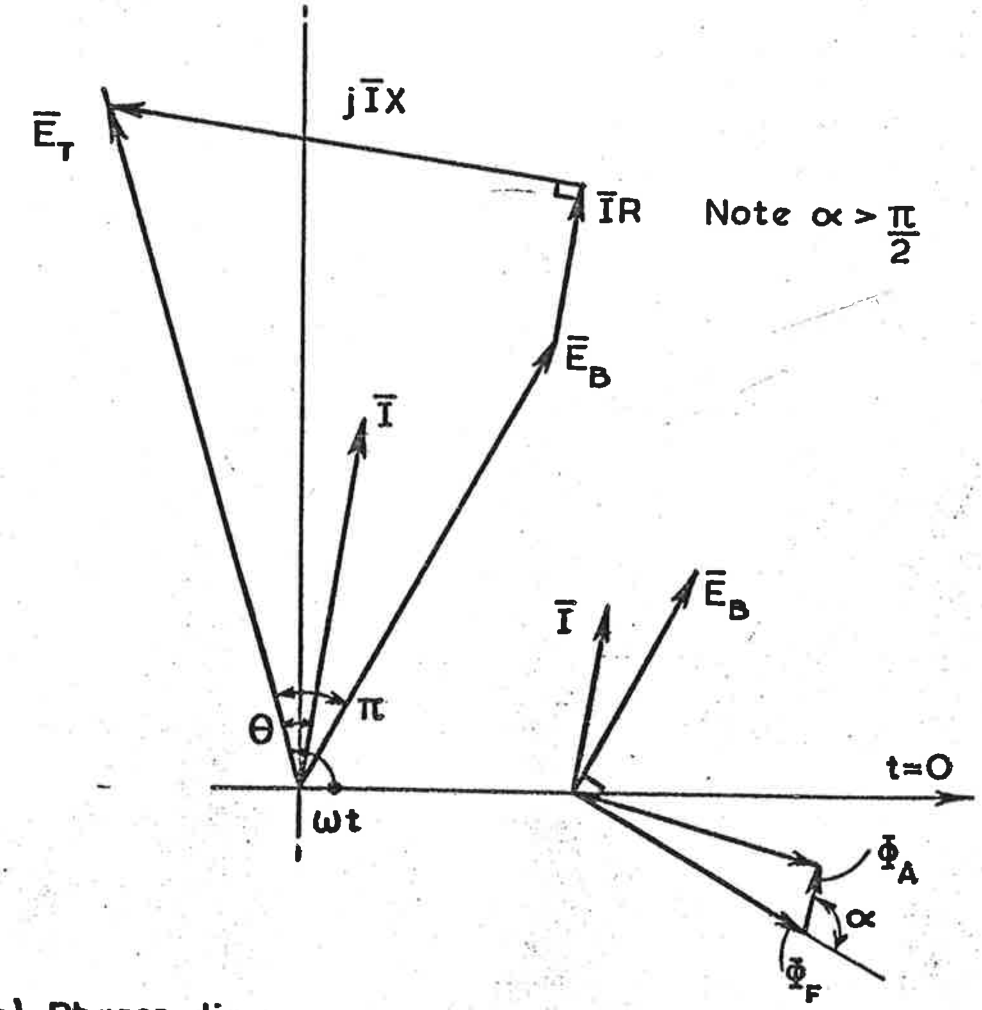


FIG. 2. CONCEPTUAL VIEW OF LINEAR SYNCHRONOUS MOTOR.



a) Current source equivalent circuit.



b) Phasor diagram.

Figure 3. Equivalent circuit and phasor diagram for representative phase of air cored LSM.

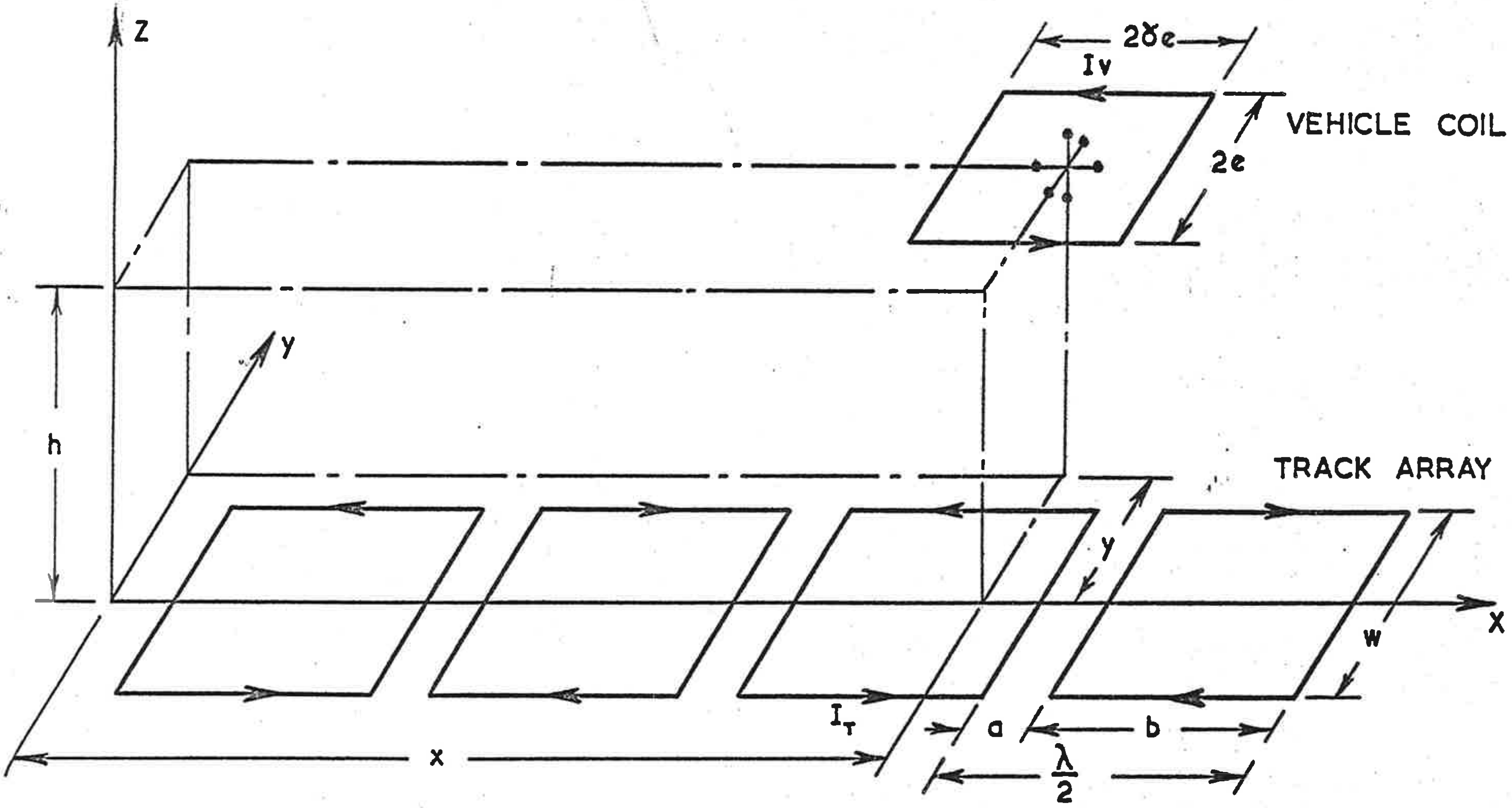


Figure 4. Coordinates for mutual inductance, vehicle coil to track coil array.

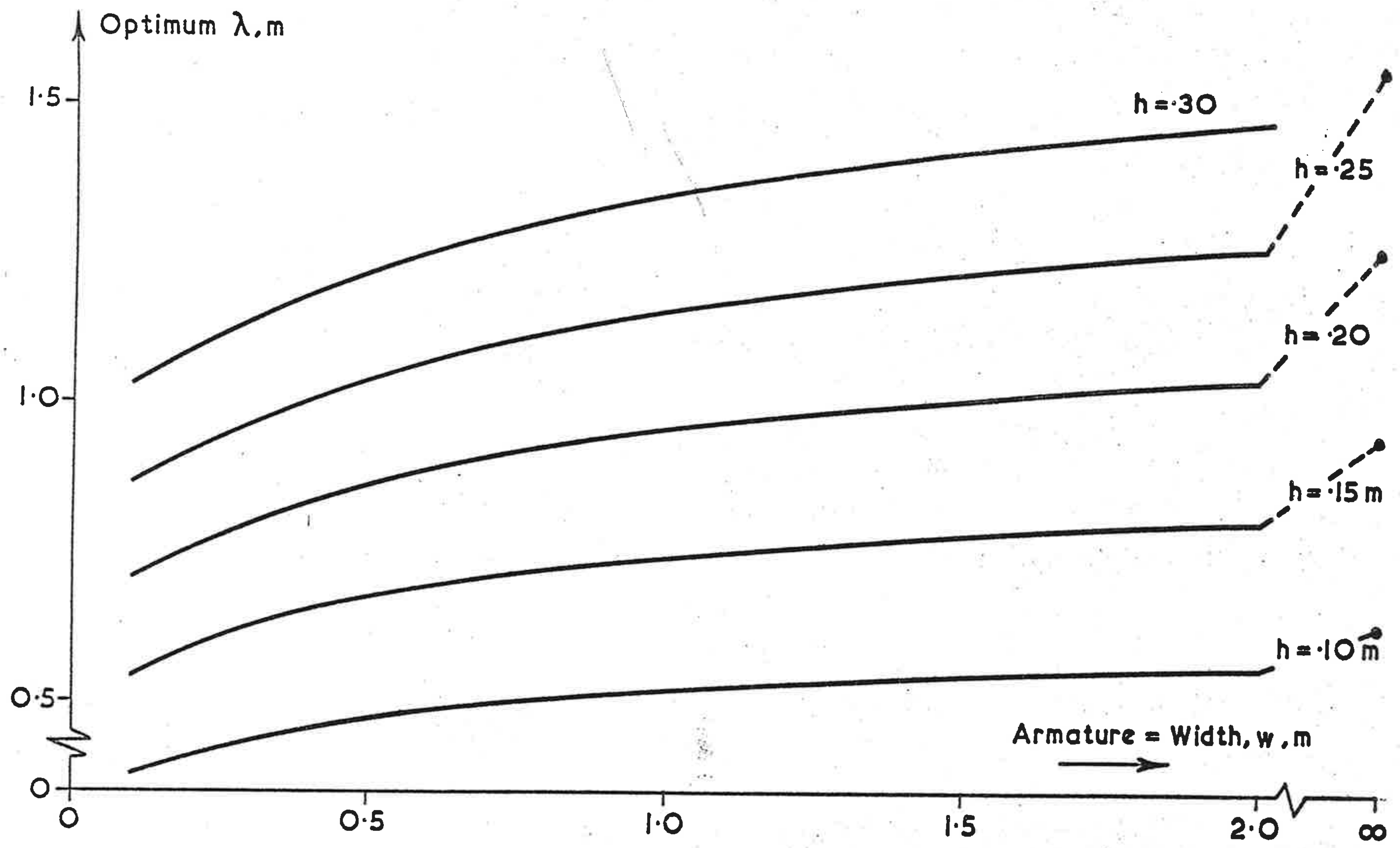


Figure 5 . Optimum wavelength for machine width w, and airgap h.

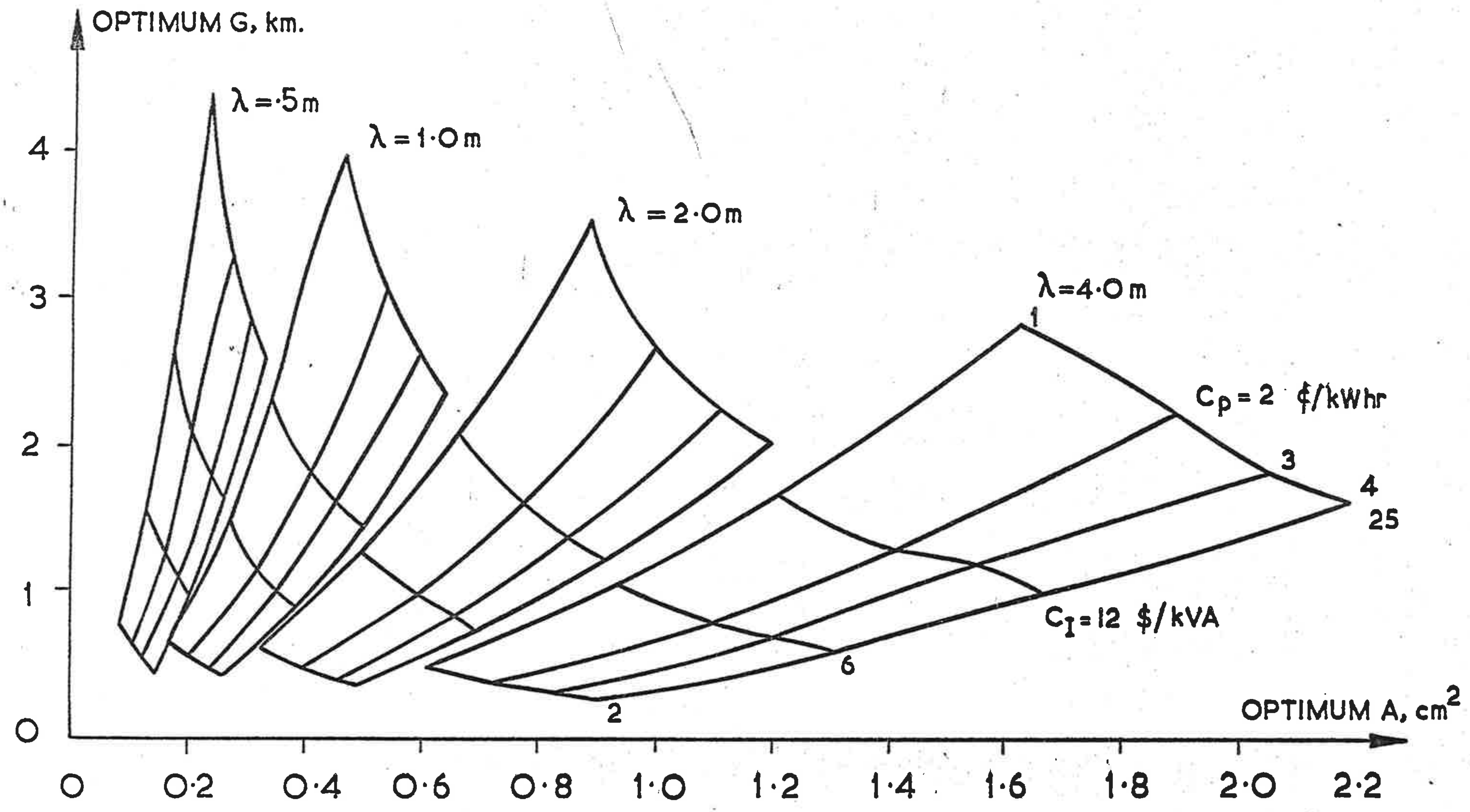


Figure 6. Loci of optimum G, A, for different λ.

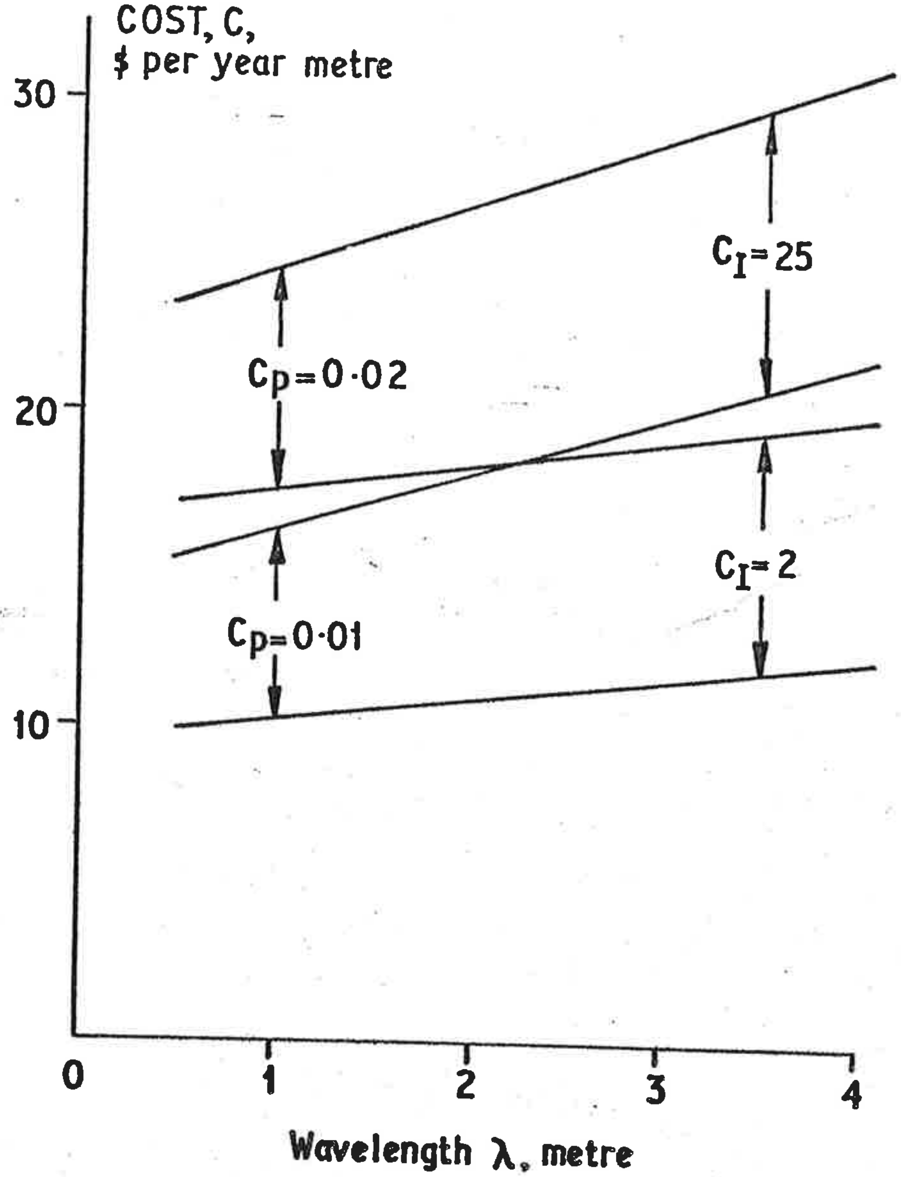


Figure 7. Costs as a function of wavelength.

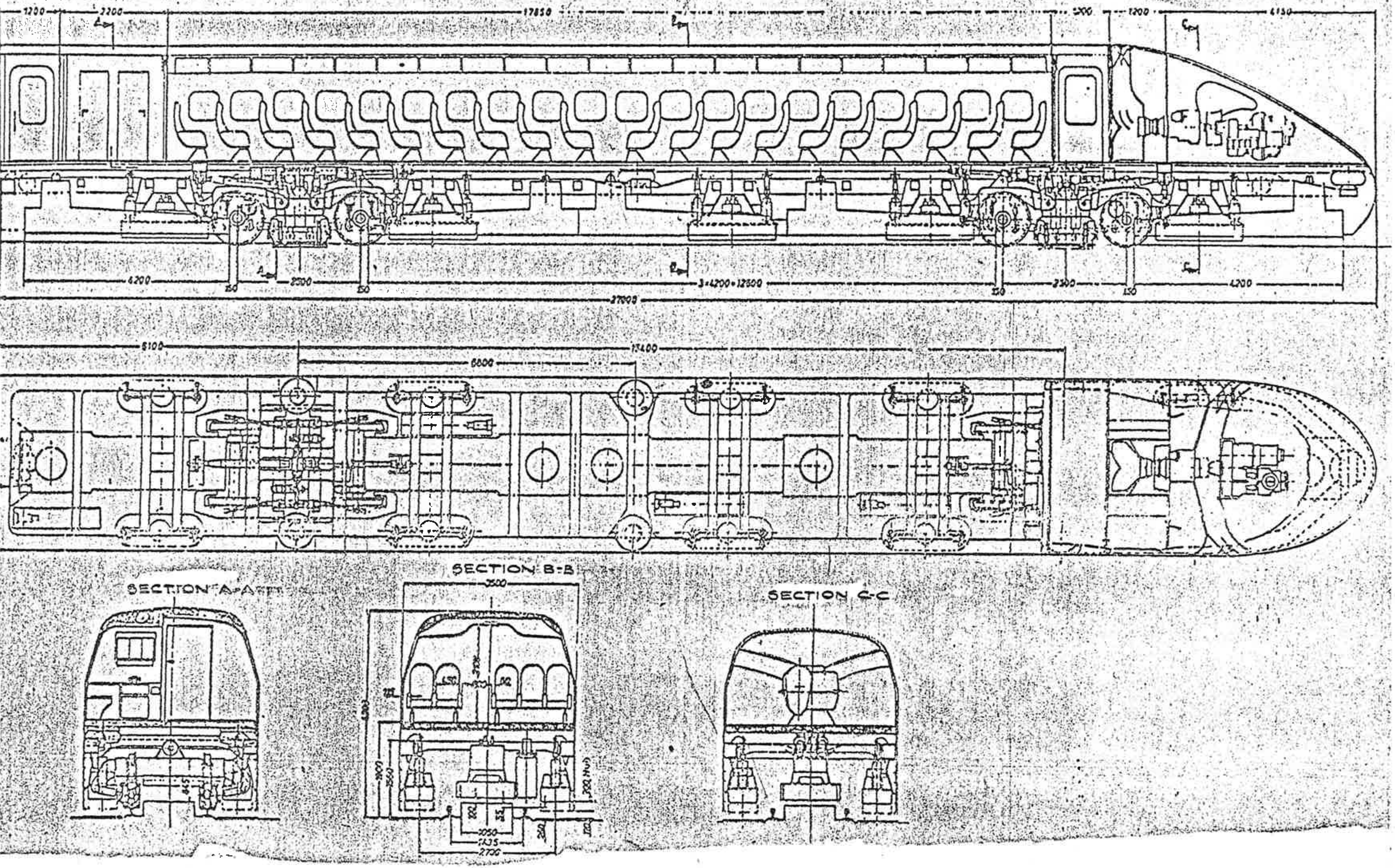


Fig. 8. EDS Passenger vehicle, AVF / P06.

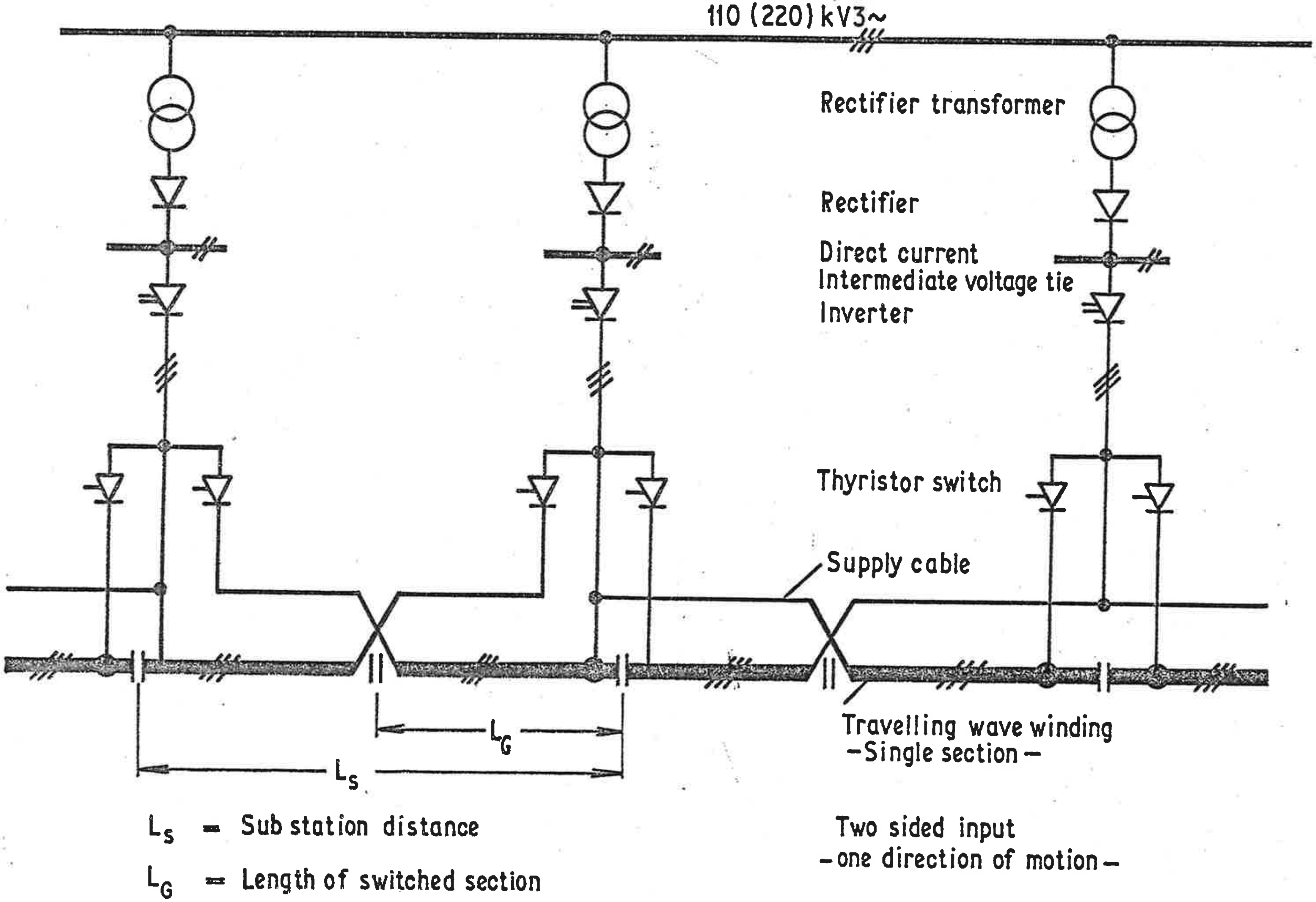


Fig. 10 Distribution diagram for the EDS long stator motor propulsion.

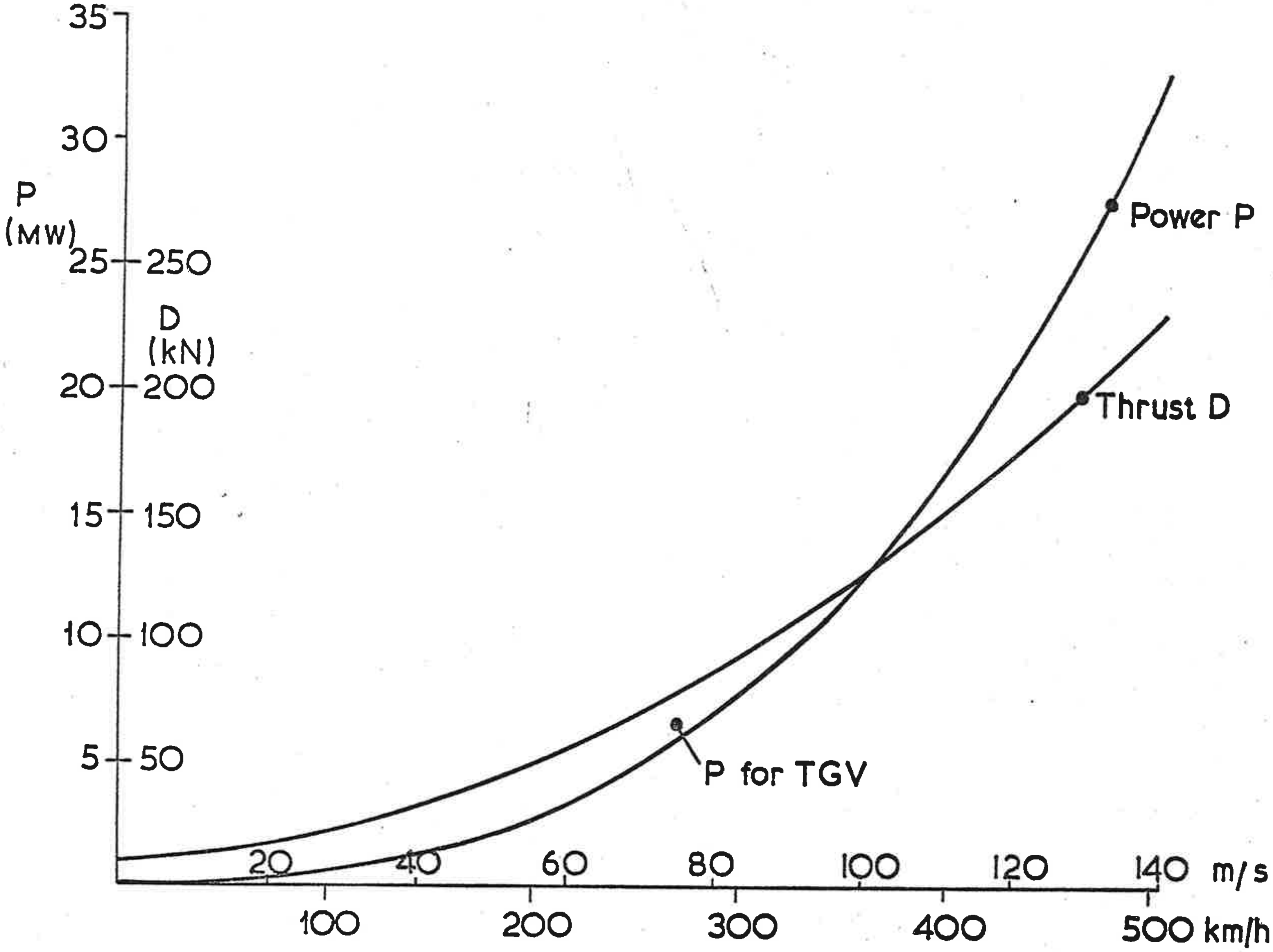


Figure 11. Power requirements for APT.

Fig. 12.
CRYOSTAT SECTION.

SCALE 1:10

COIL MEAN TURN
SIZE 700 WIDE
X 1120 LONG