(NASA-CR-162433) PRELIMINARY INVESTIGATIONS OF DESIGN PHILOSOPHIES AND FEATURES APPLICABLE TO LARGE MAGNETIC SUSPENSION AND BALANCE SYSTEMS (Southampton Univ.) 35 p HC A03/MF A01 CSCL 14B G3/09

N80-11104

Unclas 46077

UNIVERSITY OF SOUTHAMPTON

department of aeronautics and astronautics

PRELIMINARY INVESTIGATIONS OF DESIGN PHILOSOPHIES AND FEATURES APPLICABLE TO LARGE MAGNETIC SUSPENSION AND BALANCE SYSTEMS.

by

C.P. Britcher, P.W. Fortescue,
G.A. Allcock, M.J. Goodyer.

PRELIMINARY INVESTIGATIONS OF DESIGN PHILOSOPHIES AND FEATURES APPLICABLE TO LARGE MAGNETIC SUSPENSION AND BALANCE SYSTEMS

by

C.P. Britcher, P.W. Fortescue,
G.A. Allcock, M.J. Goodyer

Department of Aeronautics and Astronautics
University of Southampton
England.

November 1979

This report covers work undertaken on NASA Grant NSG-7523, entitled "Investigations into the Technology Required to Raise Reliability Levels of Magnetic Suspension". The Principal Investigator is Dr. M.J. Goodyer and the NASA Technical Officer is Mr. R.P. Boyden of NASA Langley Research Center.

CONTENTS

1. INTRODUCTION

This report, which would otherwise have simply represented a summary of work completed under Grant NSG-7523 to date, is written in the light of recent developments at NASA Langley Research Center, namely the acquisition of a magnetic suspension system and formation of plans for construction of a Large Magnetic Suspension and Balance System (LMSBS). It has been decided to incorporate into this report at least brief mention of all potentially useful new ideas and concepts that have surfaced in the past year whether or not these ideas are fully formed and experimentally verified and a résumé of the current thinking at Southampton on the likely architecture and features of a reliable LMSBS. This content is chosen so that early decisions made at LRC relating to the LMSBS are made with the widest available background of opinion.

The features of existing magnetic suspension and balance systems which are important in the context of this report are as follows. The test sections to which they are applied are small, ranging up to about 1 foot diameter, and the test dynamic pressures low in comparison to those in use in some types of wind tunnel. There is provision for the control of model attitude in three to six degrees of freedom depending on coil geometry, with an ability of the MSBS to resist the corresponding aerodynamic forces and moments. In the main the force/moment capability is adequate for the applications of the existing systems, except for the case of rolling moment.

There is no redundancy incorporated with the result that the MSBS has a reliability similar to other non-redundant electronic and electrical equipment. Power supplies are electrically noisy and uni-directional, features which combine to degrade the quality of suspension. Examples of this degradation are reductions of the stiffness of suspension of the model and the force capabilities of the electro-magnets.

The object of the research currently underway at the University of Southampton is to provide some of the technology which is required to allow the principles of MSBS to be applied to the high Reynolds number transonic testing of aircraft models. Such a test facility is currently pictured as comprising a pressurised transonic cryogenic wind tunnel, with the MSBS providing full six-degree-of-freedom control. The electro-magnets will be superconducting, fed from quiet, bi-polar power supplies. Redundancy will assist in providing the necessary reliability in conjunction with a model control system having some self-adaptive characteristics.

2. RELIABILITY OF MSBS'S

2.1 An Approach to Reliability Engineering in LMSBS's

An overriding objective in the development of a LMSBS must be to reduce the probability of a model flyaway to a very small level throughout the life of the system. If this cannot be achieved then such systems are not practical for normal use, since the consequences of model flyaway are potentially destructive.

LMSBS development will involve high technical risk. At least the first LMSBS will be absolutely unique in overall architecture and most of its subsystems can be expected to exhibit major innovations and considerable differences from any contemporary hardware in design, duty and environment. It thus seems highly unlikely, unless hardware redundancy is extensively applied and systems are configured and operated on a fall-back strategy, that a LMSBS could be designed with hardware sufficiently reliable and with sufficient integrity to make the probability of model loss very small. This opinion may be justified further:

1) Almost any hardware failure in a non-redundant MSBS is likely to result in loss of the model.

There are many hardware failures or service conditions which may cause simultaneous or cascade loss of many systems.

3) Most model position sensing systems appear to suffer a serious lack of integrity, that is they are more likely to fail to supply useful position information due to exposure to adverse environmental conditions than due to hardware failure.

4) Reliability data based on current hardware or gathered during the burn-in or shakedown of a LMSBS may not predict accurately the behaviour of that system in normal use.

It is thought that the architecture of a LMSBS should be configured from the very earliest stage such that hardware redundancy is incorporated wherever practicable. (It is difficult to envisage useful incorporation of redundancy into the model). Further, a key objective in the design of each subsystem and the system as a whole must be to contain and tolerate the effects of any conceivable hardware failure or service condition. To fulfil this objective all hardware failures and service conditions (and combinations of same) must be identified and analysed. In many cases fall back strategies must be defined and mechanisms for initiating and carrying out such strategies specified.

Two such fall back strategies are suggested here:

1) In response to the failure or loss of a major subsystem, such a coil or position sensing system, where redundancy ensures that the system survives that event, the optimum strategy to ensure safety of the model and of the overall system may be to initiate a secure model/power down/ dump tunnel q sequence (hereafter referred to as a power down sequence), perhaps automatically. The hardware remaining operational after a failure must be designed such that the probability of a second (or third or so on), now disastrous failure during the power down sequence is very small. The failed hardware will be repaired and the system fully checked out before the model is again suspended. It is interesting to note that this strategy is not available to, say, a flight control system designer, where the system task may not be rapidly terminated.

2) Even in the event of total loss of model position information, which renders the MSBS open-loop and inherently unstable there is an identifiable optimum strategy which would result in a model crash-land but with minimum damage to the model and/or tunnel.

2.2 Incorporation of Redundancy into the Coils/Power Supplies

Introduction of some form of redundancy into the array of coils and power supplies is necessary if sufficient force/ moment capability to maintain the model under control is to remain following a failure in this area. However an overhead is incurred on two counts:

a) Provision of surplus redundant ampere-turns. A coil set may be defined as a group of coils incorporating redundancy, where each coil in the set creates substantially the same field, configured such that the set is capable of supplying its maximum design field strength with one coil of the set failed. The set must incorporate more ampere turns than the equivalent non-redundant single coil and the factor

$$\frac{\text{total ampere turns in redundant coil set}}{\text{ampere turns in equivalent single coil}}$$

represents a coil cost factor which depends on the number of coils in the set.

b) Increased complexity in the design of the coil array. This is particularly important since provision of multiple separate dewars (for the superconducting electromagnets) may seriously compromise close packing of electromagnets around the working section. Separate dewars are likely to be required to prevent certain serious failures cascading through more than one coil. Failure to pack the coils closely causes larger coils to be required since the operational effectiveness of each coil is depleted.

The effect of a) is to decrease the coil cost factor with increasing number of coils per set whereas b) increases the cost factor with increasing number of coils per set. It is thus seen that there may be an optimum number of coils per set.

It is believed at the moment that the coil cost factor will be relatively small with the optimum number of coils per set due to three factors:

1) Use of Automatic Power Off (APO)

Without APO one worst case failure is a power supply runaway. In this event effectively two coils of a particular set are lost after one failure since the equivalent of one coil must simply neutralise the runaway coil. The reduction in the idealised cost factor with APO varies with the number of coils per set as shown in Fig.1. The system must be designed to cope with the current transient in the chosen APO procedure.

2) "Passive" Redundancy (PR)

For reasons other than provision of redundancy it seems certain that a major architectural feature of any future MSBS will be the positioning of electromagnets all around the tunnel working section with extensive symmetry. It is obvious that at least the mirror image of any coil set suffering failure may take all or part of the load previously taken by that set. If this fact is exploited the complexity of each coil set may be reduced. (Fig.1).

3) State of the art of superconducting magnet and dewar design

Rapid progress in these areas is being made by many teams engaged in design and construction of superconducting electromagnets for various applications, including experimental physics. It is interesting to refer to the Fermilab accelerator Energy Doubler/Saver electromagnets, currently under construction. These electromagnets are approximately 22 feet long and order 6 inches diameter. The dewars have to support the coils under design loads of up to 11,000 lbs total with static heat leakage into the LHe of 8 watts per coil. Only 3.3 cms ($\approx 1\frac{1}{4}$") radial distance is available for the whole support and thermal insulation system between 4.2K and room temperature. These electromagnets are now in large scale production. One may perhaps be optimistic that multiple separate dewars for LMSBS application may incur only small space penalties.

There seems to be no existing power supply capable of supplying controlled D.C. to a large superconducting coil, due to the high peak current and voltage requirements with near-zero load power dissipation. A concept for a switching supply which may be practical is detailed in Section 5 of this report. The feature of energy storage, not unique to this supply, implies that the supply can withstand main power feed interruption, since it can be arranged that the internal energy storage is sufficient to execute a balance power down sequence.

2.3 Redundancy and Reliability in Model Position Sensors

Most model position sensing systems so far used or proposed suffer, as previously mentioned, a serious lack of integrity, even though the hardware used may be quite reliable. Specifically:

1) Optical Systems (See Section 3). The type of system most widely used to date in which quantities of light passing certain points on the model are measured in an analogue fashion is inoperable in any environment where rapid variations of the transmittivity of the optical path are encountered. Such variations must be expected to occur relatively frequently in a cryogenic wind tunnel, for instance with free stream condensation.

Methods which measure either in an analogue (e.g. TV scanning) or in a pseudo digital fashion (SSPD arrays) the position of either a target affixed to, or of a suitable part of, the model may be designed to tolerate the conditions mentioned above, but all optical systems will fail in conditions of severe degradation of the optical path.

2) Electromagnetic Sensors (EPS). Any high intensity burst of electromagnetic radiation of suitable frequencies and/or characteristics will "white-out" an EPS. Such bursts of radiation might occur for instance during electrical storms or catastrophic failure of one electromagnet or power supply. At present, considering the problems experienced by the known users of EPS systems in filtering electromagnet power supply noise it seems unreasonable to assume that the white-out problem may be easily overcome.

It would seem reasonable to consider the application of special analytic techniques to the position sensor outputs in order that spurious information from any or all position sensing arrays is rejected. Techniques of analytic redundancy, that is the detection of sensor failure by comparison of all available sensor outputs with predictions derived from a real-time mathematical model, seem appropriate and such techniques are under development at LRC and elsewhere for other purposes. Kalman-like filtering of sensor outputs may be desirable anyway and this, together with analytic redundancy may be thought of as state estimation.

If analytic redundancy can be successfully applied it may not be necessary to strive for more than, say, two completely independant position sensing systems. Key hardware in each system may still feature localised redundancy (for instance light sources) and there may be considerable redundancy of information (for instance with more than six independant items of position/attitude information) but the inclusion of near identical wholly redundant systems would not be fruitful since all systems of a similar type would suffer common-mode failure on exposure to adverse environmental conditions.

As mentioned earlier, even if all position sensors are lost there is still a "crash-land with minimum damage" fall-back strategy.

2.4 Reliability in Control Systems

It is probable that all the control system of an LMSBS will be realised with digital computers and thus there seems no particular difficulty in the incorporation of overall redundancy in the control system. Much effort is currently expended (at LRC and elsewhere) in the development of super-reliable digital computers. Triply redundant super-reliable digital computers would form an ultra-reliable control system and be the foundation of a successful LMSBS design. There would be little point in implementing complex or advanced failure tolerance algorithms coping with rare hardware failures or service conditions with an unreliable computer.

A triplicated control loop would allow fairly simple majority voting procedures to be adopted at the inputs to each power supply, to cope with computer failure, perhaps with a power down sequence initiated immediately on the detection of a voting discrepancy.

In a pressurised transonic cryogenic tunnel the aerodynamic loads on the model often greatly exceed those due to the weight of even a solid metal model. These loads may be unsteady and/or strongly non-linear functions of model attitude and dynamics (for example, lift forces near stalling incidence). The quality of suspension is fundamentally limited by the maximum field slewing rate that the balance electromagnets can achieve. Electromagnet and power supply design is made more difficult for high values of slewing rate. The problem must therefore be faced of controlling the excursions of the model from its desired position and attitude in the face of very powerful disturbances with an overall system "stiffness" somewhat less than is usual with a mechanical support.

In view of the above, the employment of control algorithms with some self adaptive characteristics appears desirable, so as to keep the behaviour of the system near-optimum at all times.

This type of control system appears to complement failure tolerant features since the control system may adapt to certain hardware failures.

The tasks that must be carried out by the MSBS, under command of the control system are as follows:

1) Control of the model state to a predetermined sequence.

2) State estimation (particularly the attitude and kinematics of the model).

3) System identification (including the aerodynamic characteristics of the model).

These objectives must be persued in the expectation that there will, with some models, be states in which the aerodynamic forces and moments may exceed the capability of the system.

It is thought that the structure of a MSBS best able to achieve the above objectives is one based on a comprehensive real-time mathematical model held within the main control computers. This model will represent the complete system, including magnetic, electrical and aerodynamic aspects. The aerodynamic portions of the model will be continuously updated throughout any test sequence and will constitute a prime means of acquiring the data required from the tests. For each new wind tunnel model the magnetic force/moment portions of the model must be established by pre-calibration and this may be planned as a system identification programme, somewhat similar to the wind-on testing.

A series of tests is expected to progress from states in which small aerodynamic forces/moments are expected to those with large values. At every stage the likely values of forces/moments and the system dynamics in the next stage will be predicted, so as to avoid the hazard of exceeding the magnetic force/moment capability of the system.

The model will play a key role in the Kalman-like filtering of multiple position sensor information to achieve the best estimate of the model state at any time.

Loss of a model without hardware failure should <u>never</u> occur in a properly designed and operated system and avoidance of this event should take very high design priority.

A possible architecture for a reliable MSBS incorporating many of the features discussed in this section is shown in Fig.2.

3. POSITION SENSING:

SELF-SCANNED PHOTODIODE ARRAYS (SSPD ARRAYS)

It is thought that SSPD arrays represent a real alternative choice for a model position sensing system and appear to offer many advantages over current optical types. Further they may prove invaluable as a means of rapidly calibrating other types of position sensors. SSPD arrays are now available in many forms and are under continuous development for application in solid state TV cameras. The devices consist of linear or area arrays of individual photodiodes, typically of very small area and spacing, each capable of analogue measurement of incident light intensity. Included on the same chip as the photodiodes is circuitry by which the elements (photodiodes) may be sequentially scanned and a serial pseudo-video output signal generated (Fig.3).

By exploiting the fact that the array output yields the spatial distribution of received light as well as its intensity it is believed that suitable interpolative algorithms may be developed to allow the position of the model to be accurately deduced even in conditions of degradation (mist, smoke etc.) of the optical path, as illustrated in Fig.3. If this is so the arrays are a practical candidate for a primary position sensing system.

Linear arrays are considered to be most applicable to MSBS position sensors. Such arrays are currently commercially available with element spacing of 16μm (0.00063 inches) and up to 2048 elements in a line. Elements may be scanned at approximately 10MHz e.g. a simple 2048 element array may be completely scanned in 0.2ms. Current manufacturing techniques permits arrays of up to approximately 4500 elements and whilst element scanning speeds are likely to remain roughly constant, the use of multiple parallel scanning circuitry would permit somewhat faster array scanning speeds.

It is proposed that the arrays be mounted in lens assemblies focussed onto diffusely illuminated black/white targets somehow affixed to the model as shown in Fig.4. The best useable resolution of the optical edge is approximately one array element spacing. The spatial resolution depends on the focal length of the lens assemblies but will be, for a 4096 element array, approximately 0.025% of full range. This compares favourably with other methods of position sensing currently in use. Arrays may be mounted end to end to improve this figure further and it is expected that improvements in manufacturing techniques will result in arrays longer than 4096 elements in the foreseeable future.

Since the ideal spatial resolution is a function only of the mechanical alignment of the array/lens assembly and is unaffected by modest sensitivity or light intensity variations it is expected that the calibration of the system may be held very nearly constant over indefinite periods of time. The linear distribution of array elements is almost perfect and thus the arrays represent an excellent choice for a "reference" position sensing system by which other systems more prone to drift, etc. may be calibrated.

There is no objection to operating the arrays at low ambient temperature, even down to LN_2 temperature, but the problem of mechanical movement with large temperature changes is important.

4. SPANWISE MAGNET ROLL CONTROL

The scheme is based on the symmetrical distribution of magnetic material primarily in the wings of the model with spanwise magnetization. Wing cores so magnetized will generate a rolling moment in a vertical field with transverse gradient. There are two major subclasses of the scheme, based on the use of permanent magnet or soft iron wing cores. Both are DC systems.

4.1 Permanent Magnet Wing Cores (Figs.5,6,7)

The use of very high coercivity rare earth cobalt (REC) permanent magnet materials in wing cores allows high intensity magnetic fields to be developed at the wing tips, where the moment arm is greatest. The high length to thickness ratio of the wing magnets renders this system superior in moment capability to the through-wing magnets previously used at Southampton. The only primary force interactions are in the lateral plane, where it is thought they are of least inconvenience since the aerodynamic forces in the lateral plane of the model are not generally dominant. The entire wing volume is not useable since REC materials exhibit relatively poor mechanical properties. There will also be an as yet unquantified depletion in the maximum useable moment when high fields are being used to create other forces/moments, since the maximum field strength at any point on the wing cores must be less than the coercive force of the core material.

The maximum moment available with this scheme using the best currently available REC materials, at room temperature with a 1m span model of 8:1 aspect ratio and 10% thickness: chord ratio will be of order 450 Nm. Greater moments may be generated at low temperature if the changes in magnetic properties of the REC materials are fully exploited. A permanent magnet fuselage core must be used.

4.2 <u>Soft Iron Wing Cores</u> (Figs.6,8)

The replacement of the permanent magnet wing cores with magnetically soft cores appears attractive. All the wing volume may now be utilised since materials with suitable magnetic and good mechanical properties are available. Higher flux densities in the spanwise direction can be generated since the saturation flux density of iron/steel type materials is typically double the remanent flux density of REC's. Further, there is no absolute limit to the tolerable through wing flux so it may be hoped that the moment capability of soft iron spanwise magnets will significantly exceed the capability of spanwise permanent magnets. Considerable theoretical and experimental verification is required however before this system may be considered fully practical, and such work has commenced.

If no system of magnetic rolling moment generation succeeds in providing sufficient moment capability it may be possible to utilise moment generated aerodynamically by active model ailerons, driven internally (Ref.5).

5. FURTHER THOUGHTS

5.1 Power Supplies

Conventional power amplifiers with Class A, B or similar output stages will be incapable of driving a large superconducting electromagnet, since in a high current "coasting" phase, near zero terminal voltage but high current would be required from the amplifier, resulting in enormous power dissipation in the output stage. Thyristor power supplies have been used with superconducting electromagnets (at the University of Virginia) and very high capacity thyristor supplies are certainly practical. The electrical noise inherent with the thyristor switching into an inductive load is most undesirable but difficult to reduce (see 5.2). Transistors may replace the thyristors to some advantage since the switching process may now be very much better controlled. High rating power transistors are becoming available that can withstand high voltage drops or very high currents (not simultaneously except under transient conditions) and the safe operating area of a typical device is shown in Fig.9. A proposal for a switching supply is shown in Fig.10. A key feature of this supply, the thyristor supplies at UVa and, it is thought, of any other suitable supply is load energy storage and return. Since there is near zero power dissipation in superconducting electromagnets it seems appropriate to effectively control the current by transferring stored energy into the electromagnets when current increase is required and similarly removing energy when current decrease is required. The energy may be efficiently retained as charge on large capacitors. A balance is formed, where the sum of the energy stored in the electromagnets magnetic field and as charge on the reservoir capacitors is constant. Power input to the system is only required to offset losses. The electromagnets may "coast" either through a pseudo short circuit or fed by a low voltage power supply. The latter case may yield a higher quality of steady state suspension.

5.2 EPS Filtering

If thyristor power supplies are used with an EPS system there is considerable pick up of firing spikes. If the thyristor firing could be synchronised with sample and hold circuits at the outputs from each EPS demodulator it is thought that a big improvement in system performance could be affected. The action of such circuits is shown in Fig.11.

5.3 Magnetic Position Sensing (MPS)

Since the model is magnetized, a component of the field at any point on the test section wall is due only to the presence of the model. Accurate knowledge of the current in every electromagnet and hence its field at any point will be available and it may thus be possible to derive useful position information from measurements of the magnetic field at various points around the test section, provided that the field components due to the model may be accurately resolved from the total. The system is in a sense a zero frequency EPS but is entirely passive, relying on signals naturally occurring in any MSBS.

5.4 Other Types of Position Sensor

The employment of Electromagnetic Position Sensing in an electromagnetic suspension system seems philosophically undesirable, because there will always be coupling effects between any EPS coil and force electromagnets or other EPS coils. The system is susceptible to external interference of all kinds (including radio frequencies) unless special precautions are taken in design. It is for these reasons that optical detectors, despite their many problems, have been so widely used.

However, the fundamental disadvantage of optical systems cannot be overcome and it is thus felt that thorough investigations of other types of position sensor should be made. New types may utilise sensing principles fundamentally different to existing systems, such as electrostatics, or may seek to exploit more favourable areas in the electromagnetic spectrum than those occupied by the EPS and optical systems.

An experiment conducted at the University of Southampton involved mounting radioactive sources in the tip of the blades of a model helicopter rotor rig and connecting the body of the helicopter to a voltage source. The electric field at the blade tips was measured by the radioactive sources, the ionisation of the alpha particles having the effect of increasing the atmospheric electrical conductivity. The current output from the radioactive sources supplied amplifiers whose output became a measure of helicopter attitude. (Refs.6, 7,8).

This has so far been merely a feasibility study totally unconnected with magnetic suspension. The system has the serious disadvantage that the model becomes an active element in the detection process and there will be problems in extracting the output signals from a freely suspended model. Nevertheless electrostatics should not be lightly dismissed as a contender for a viable measuring system.

5.5 Changes of Model Core Magnetic Properties with Temperature

The magnetic state of the model core must be known at all times otherwise aerodynamic forces/moments cannot be accurately resolved.

The state of a soft iron model core tends to be a weak function of its permeability or other properties and is mainly dependant on external magnetic fields. The small (few percent) variations in permeability of typical materials over the temperature range 80K to 300K are thus likely to have only second order effects on system calibration.

REC permanent magnet materials on the other hand exhibit quite large changes in magnetic properties with temperature (Fig.12). The changes are favourable insofar as the force/ moment capability of REC cores will increase with falling temperature, but the remanence changes will cause shifts of system calibration with temperature. It is expected that these changes will be accurately predictable and repeatable provided that model core temperature can be deduced. Calibration shifts with an Alnico model core have been observed and measured in the magnetic suspension/cryogenic wind tunnel facility at the University of Southampton (Ref.1).

6. CURRENT STATUS OF MAGNETIC SUSPENSION WORK AT SOUTHAMPTON UNIVERSITY

6.1 Work Completed in the Contract Year

Major practical work completed includes:

1) Complete replacement of the balance control system with all new purpose built modular electronics, to provide a "baseline" system for future development.

2) Revision and improvement of the optical position sensors mainly to improve compatibility with the 0.1m cryogenic wind tunnel.

3) A second series of aerodynamic tests on a body of revolution and measurements of the influence of low temperatures on the model core using the cryogenic tunnel/magnetic suspension facility. The facility and tests are described in Ref.1.

4) Relocation of the balance and all ancillary equipment to a new laboratory which will be entirely devoted to magnetic suspension work for the duration of relevant NASA contracts.

5) Construction of two new electromagnets (expected complete November 1979) matching six existing. The eight identical electromagnets will facilitate experimental measurements of rolling moment for the schemes described in Section 4 and will eventually allow revision of the balance into a fundamentally symmetric configuration for future work.

6) Exploratory measurements of rolling moment with soft iron spanwise magnets. The results of this effort were somewhat inconclusive due to the low field capability of the electromagnets used.

7) Revision of a computer program kindly supplied by MIT to allow calculation of rolling moments with spanwise permanent magnets. (See Section 4.1).

Personnel currently engaged on MSBS research, and their general areas of activity are as follows:

Dr. M.J. Goodyer (part-time)	-	Principal Investigator. Degree Supervisor for Mr. C.P. Britcher.
Mr. P.W. Fortescue (part-time)	-	System reliability and control systems. Degree Supervisor for Mr. C. Bouchalis.
Mr. G.A. Allcock (part-time)	-	Electronic systems. Power supply design.
Mr. C.P. Britcher (full-time)	-	Roll control. System configuration. Reliability. Digital systems. SSPD position sensors.
Mr. C. Bouchalis (full-time)	-	Adaptive control systems. Digital systems. System modelling.

7. REFERENCES

1. Proceedings of the First International Symposium on Cryogenic Wind Tunnels. University of Southampton April 1979.

2. Proposal for grant NSG-7523 renewal. Submitted June 1979.

3. Rare Earth Permanent Magnets. E.A. Nesbitt, J.H. Wernick.

4. Temperature Dependence of Coercivity for Co-Sm Permanent Magnet Alloys. D.L. Martin, M.G. Benz. IEEE Trans. Mag. Sept. 1972.

5. The Magnetic Suspension of Wind Tunnel Models. M.J. Goodyer. University of Southampton. April 1968.

6. Applications of Radio Active Sources to Helicopters. C.C. Thompson. Dept. Electrical Eng. Univ. Southampton. May 1978.

7. Electrostatic Attitude Sensing. C.W. Arkell. Dept. Electrical Eng. Univ. Southampton. May 1978.

8. Attitude Control of Aircraft using Atmospheric Electric Field. N.L. Kitson. Dept. Electrical Eng. Univ. Southampton. May 1978.

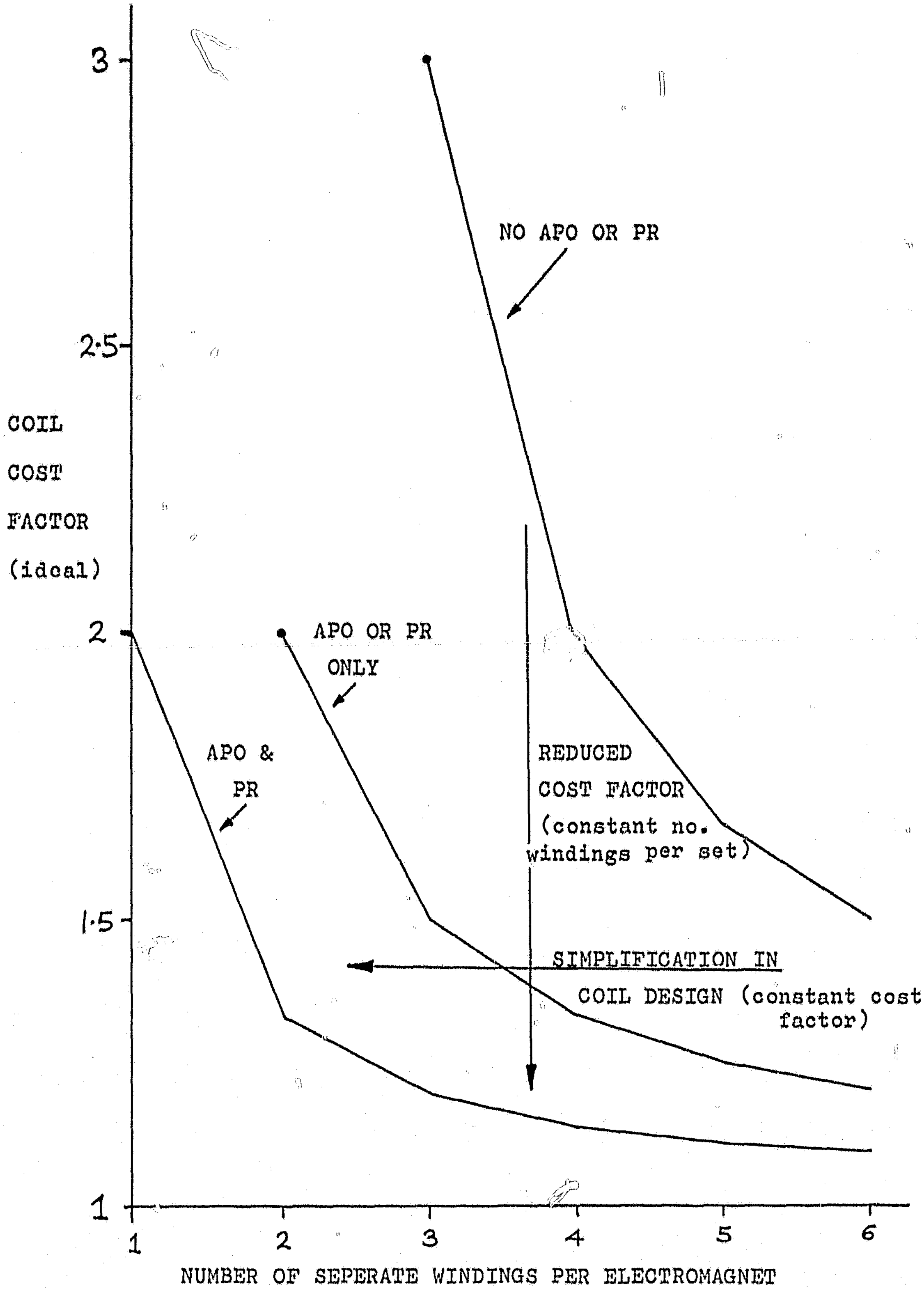


FIG.1 EFFECT ON COIL COST FACTOR AND COIL DESIGN OF USE OF AUTOMATIC POWER OFF (APO) AND PASSIVE REDUNDANCY (PR)

FIG.2 SCHEMATIC DIAGRAM OF A MAGNETIC SUSPENSION SYSTEM, INCORPORATING REDUNDANCY, FAILURE TOLERANCE AND SELF-ADAPTIVE FEATURES.

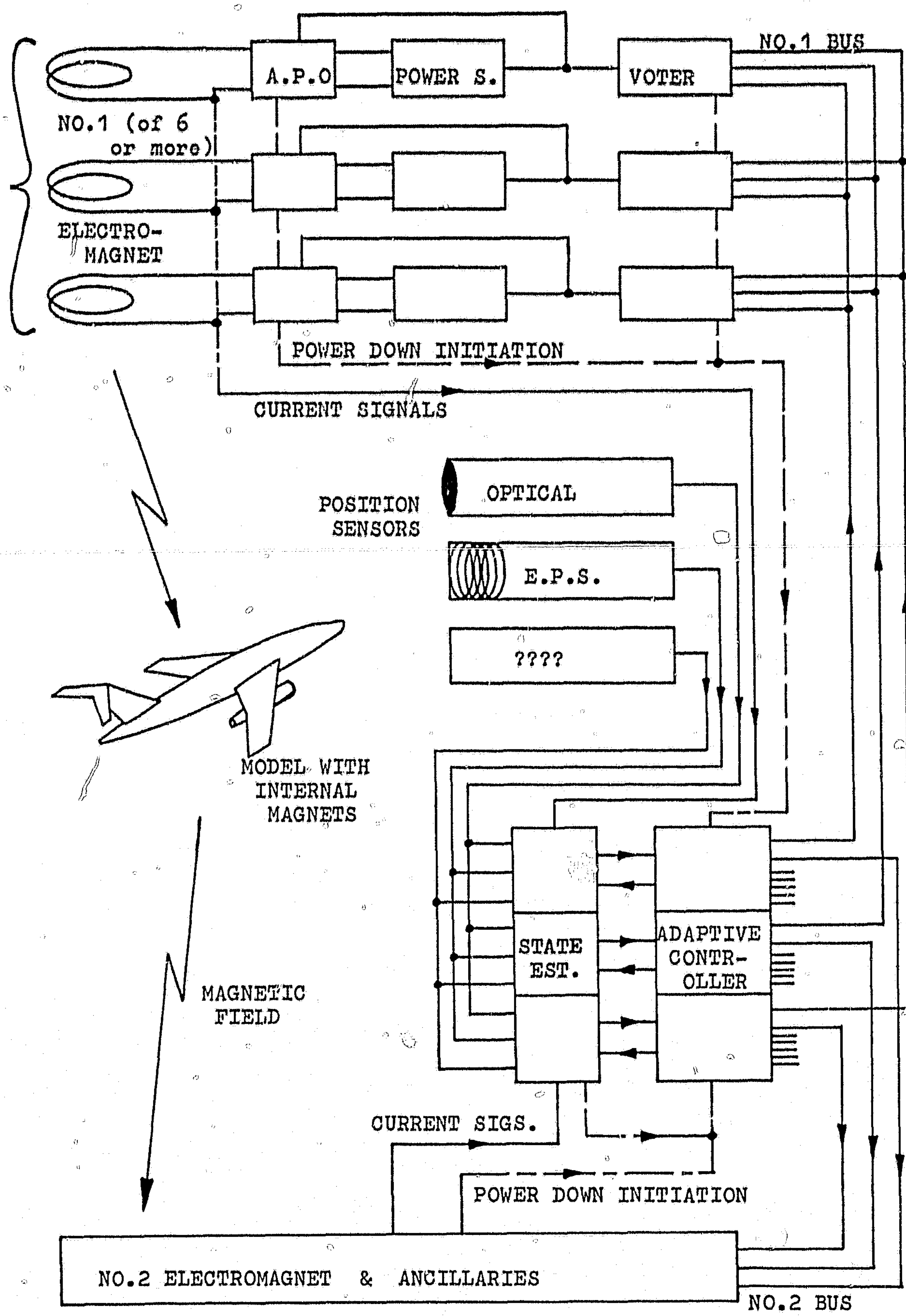
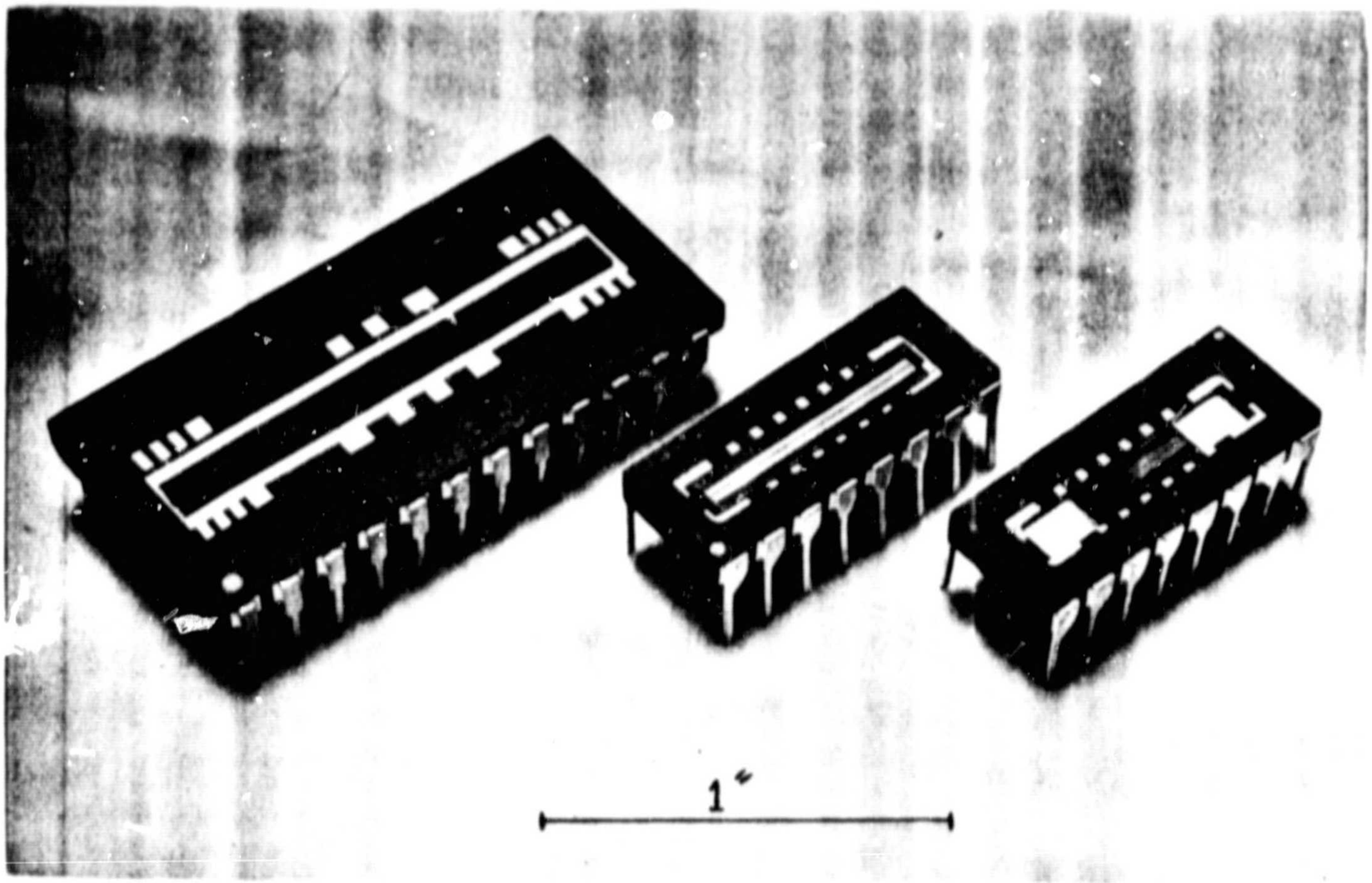
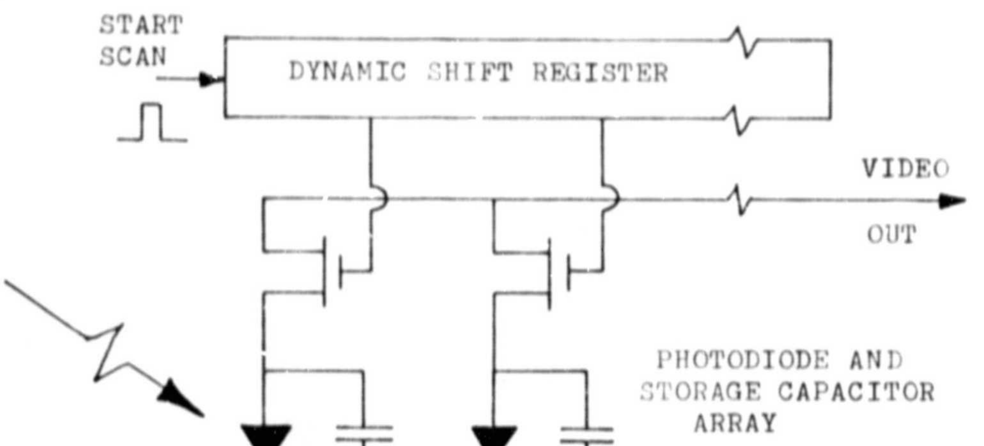


FIG.3



TYPICAL SSPD ARRAYS (1024 , 512 & 256 elements)



SIMPLIFIED REPRESENTATION OF OPERATION OF SSPD ARRAY

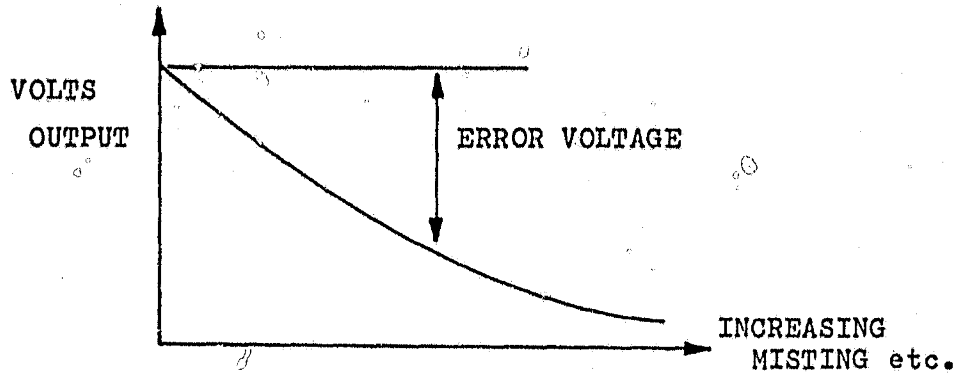


FIG 3b THE EFFECT OF LIGHT PATH DEGRADATION ON THE OUTPUT OF A CONVENTIONAL OPTICAL POSITION SENSOR

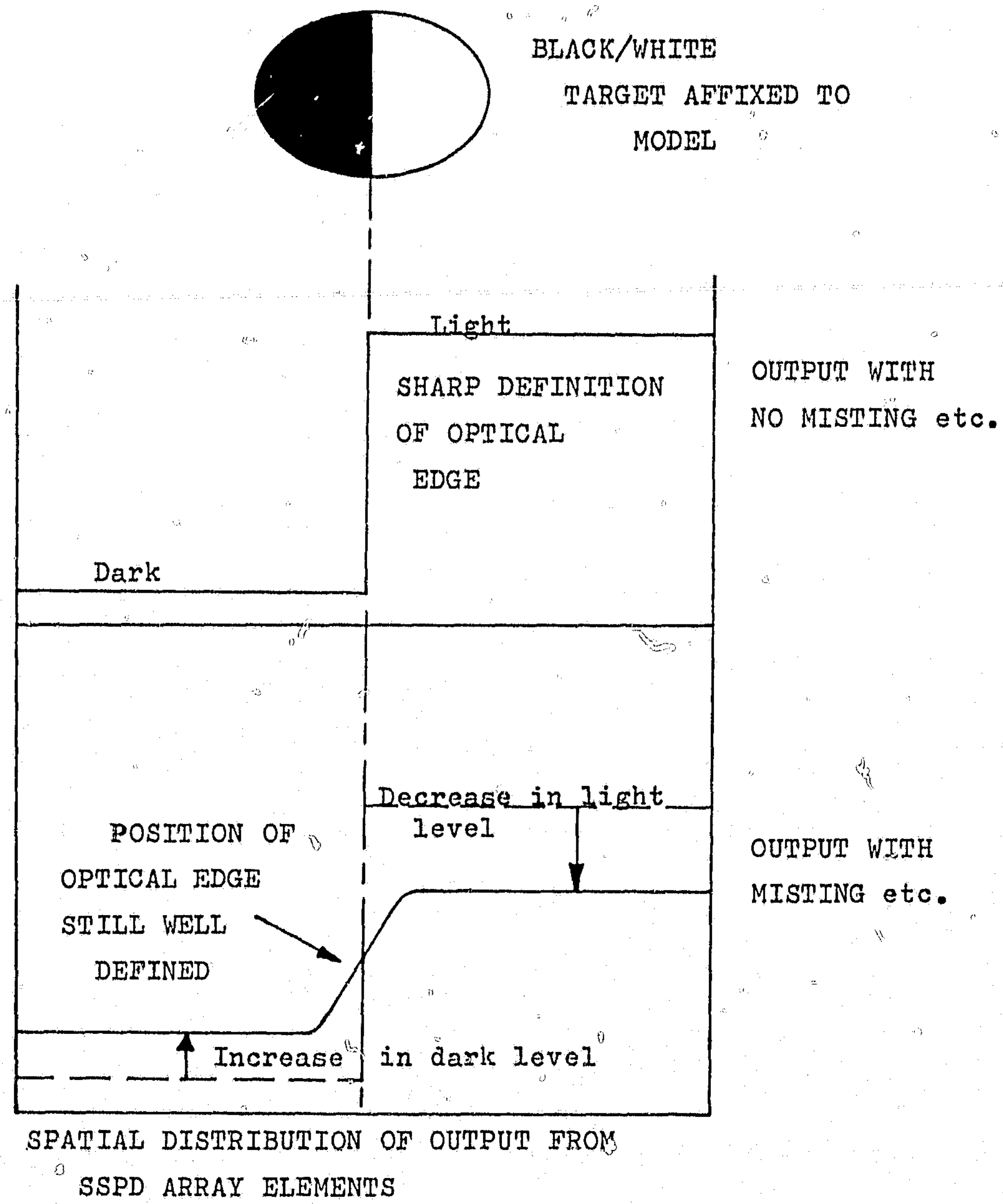


FIG 3c THE EFFECT OF LIGHT PATH DEGRADATION ON THE OUTPUT OF A SSPD ARRAY POSITION SENSOR

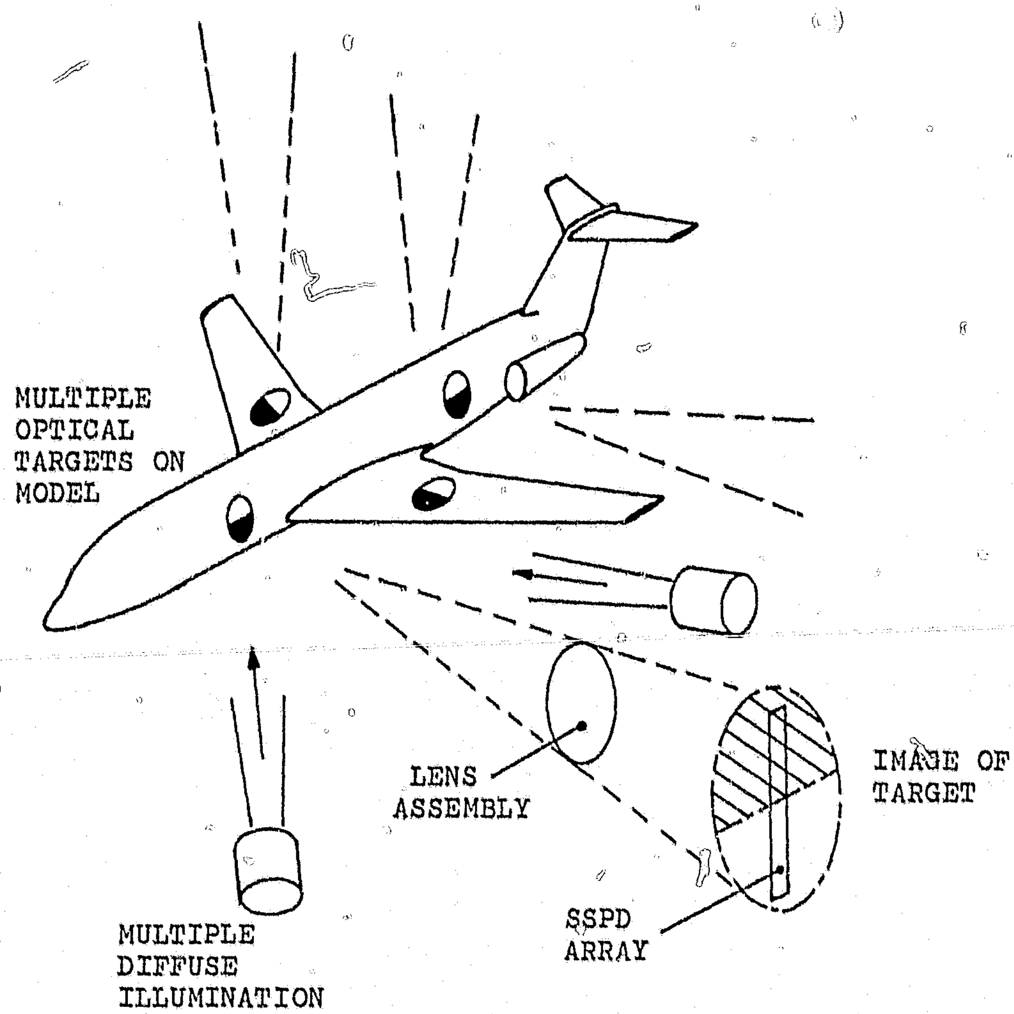


FIG.4 SCHEMATIC DIAGRAM OF TYPICAL LAYOUT OF SSPD POSITION SENSORS

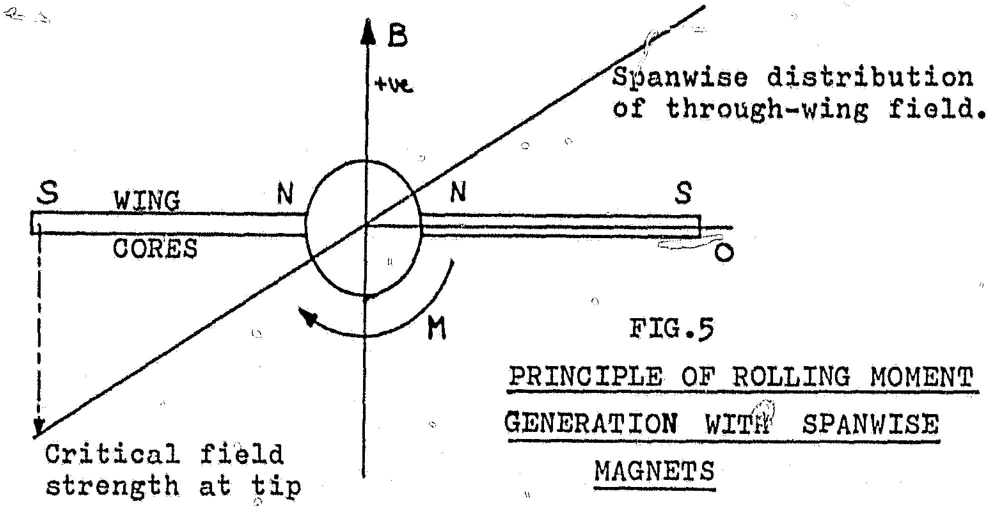


FIG.5

PRINCIPLE OF ROLLING MOMENT GENERATION WITH SPANWISE MAGNETS

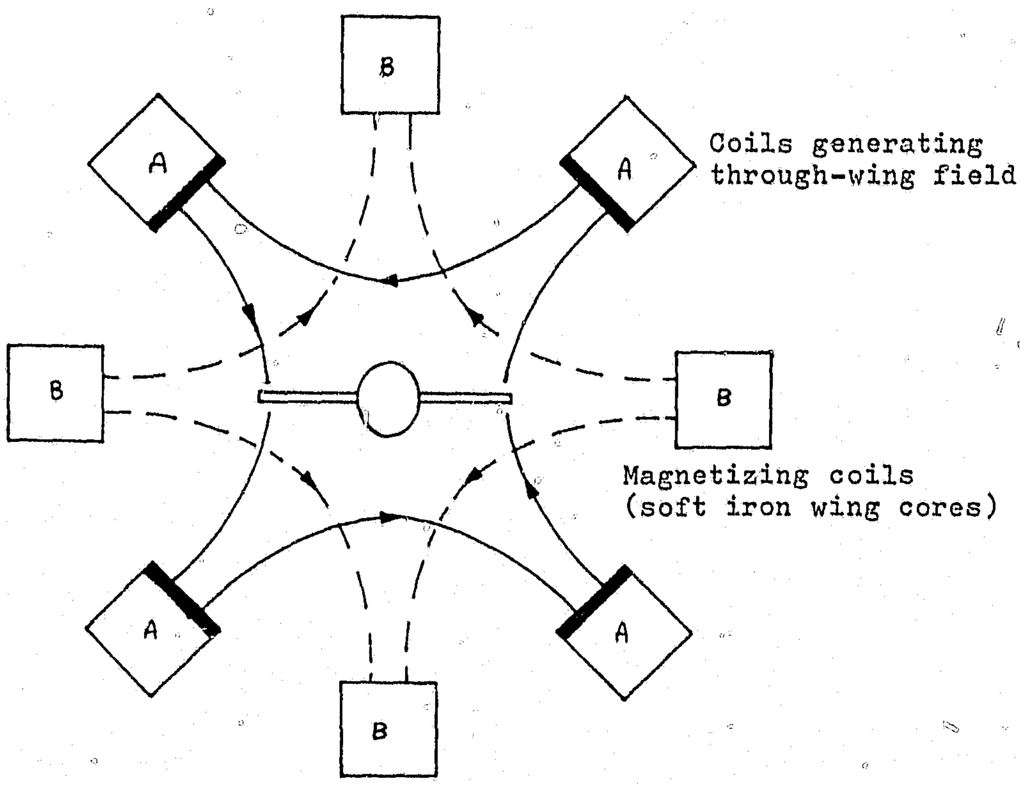
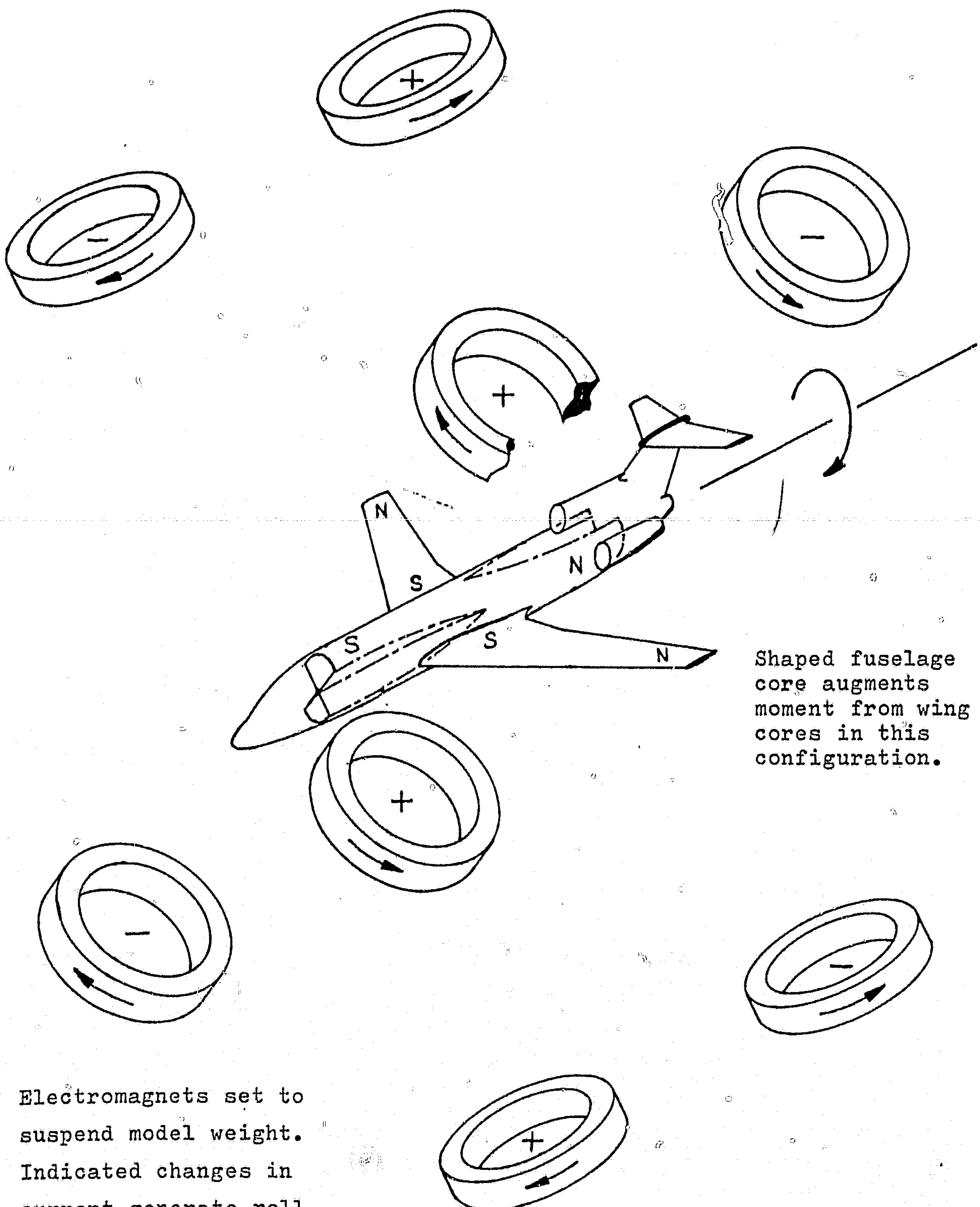


FIG.6 TYPICAL ELECTROMAGNET ARRAY FOR ROLLING MOMENT GENERATION WITH SPANWISE MAGNETS

FIG.7

AN 8-COIL, PERMANENT MAGNET, 6-COMPONENT BALANCE LAYOUT

-- SPANWISE MAGNET ROLL CONTROL



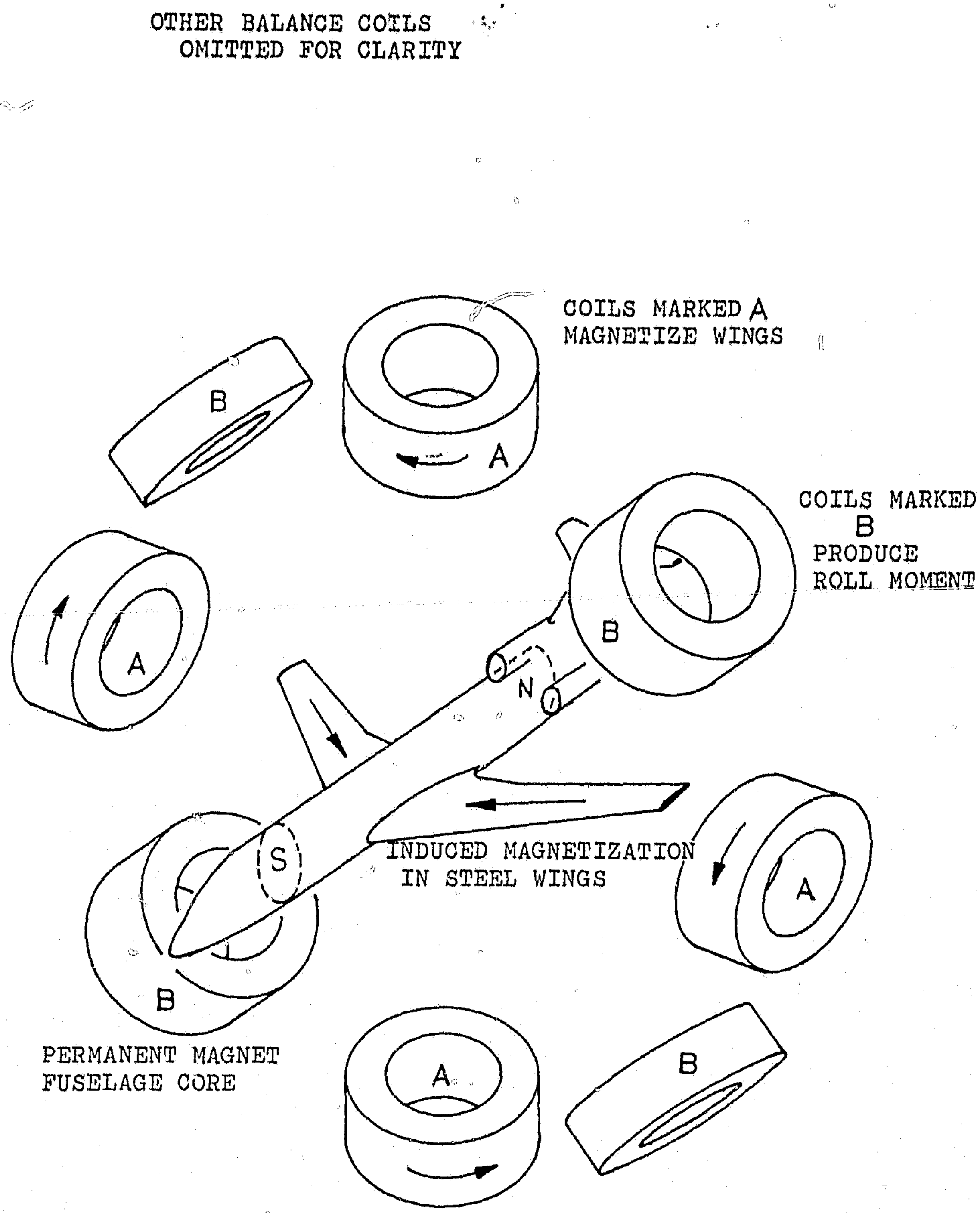
Shaped fuselage core augments moment from wing cores in this configuration.

Electromagnets set to suspend model weight. Indicated changes in current generate roll moment as shown.

FIG. 8

AN 8-COIL ROLLING MOMENT GENERATION SYSTEM, WITH 360 DEGREE CAPABILITY

--- 'SOFT IRON' SPANWISE MAGNETS



COIL SETS A AND B SWITCH FUNCTIONS AS ROLL ANGLE INCREASES

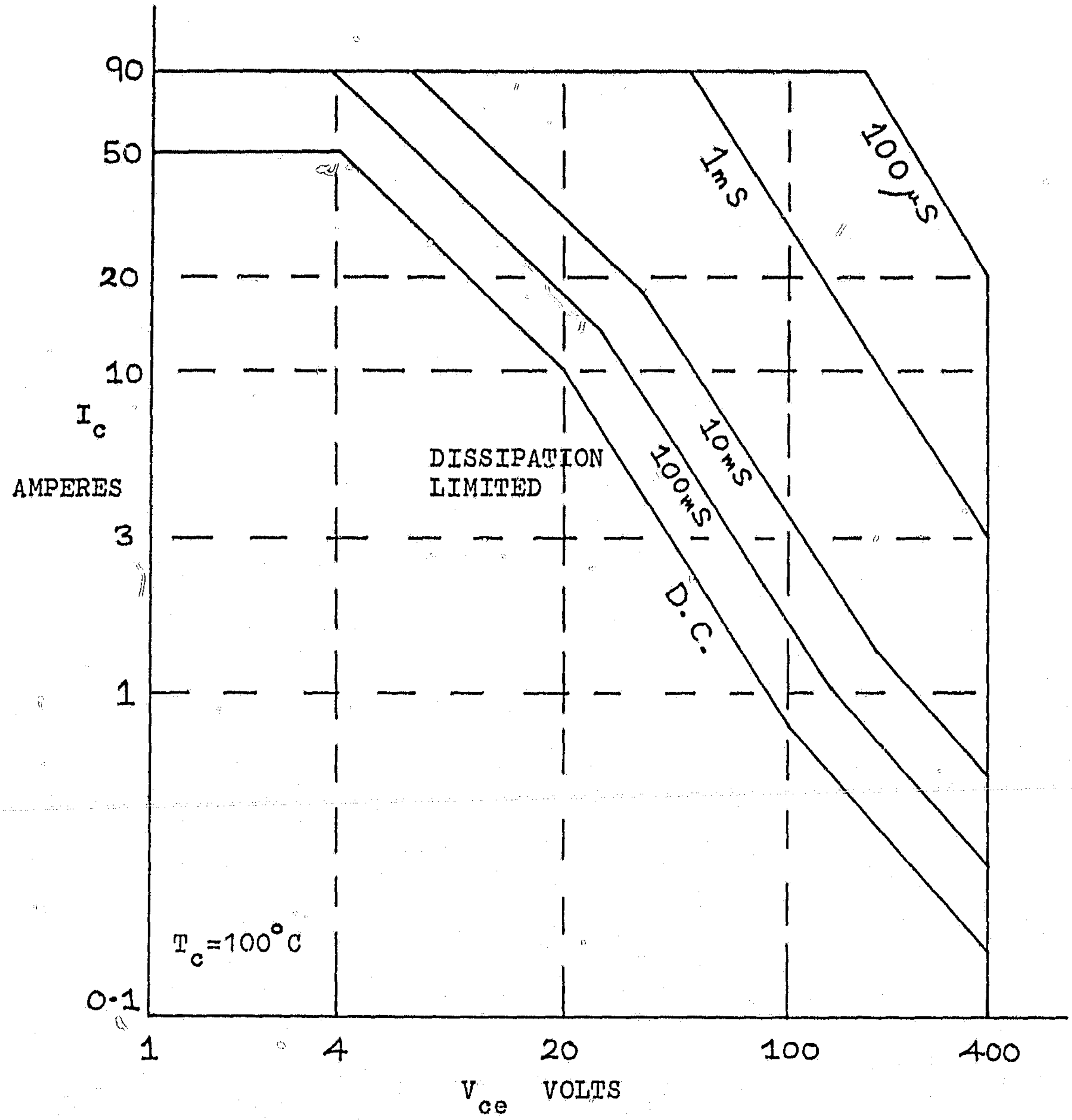
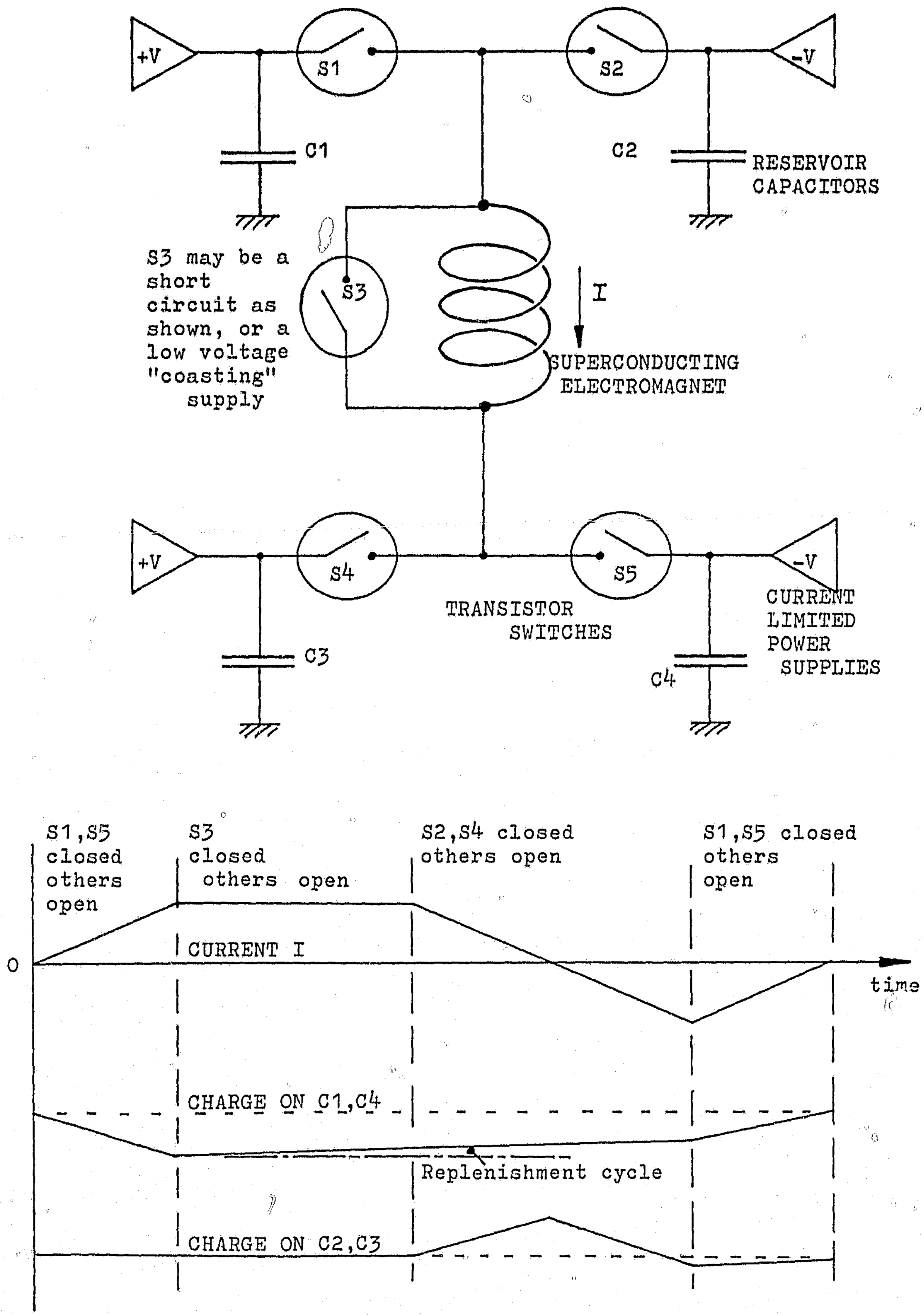


FIG.9 SAFE OPERATING AREA OF PT3523
HIGH-CURRENT TRANSISTOR
(PowerTech Inc.)

FIG.10 FUNCTIONAL DIAGRAM OF A SOLID-STATE, BIPOLAR, SEMI-QUIET POWER SUPPLY FOR SUPERCONDUCTING ELECTROMAGNETS, FEATURING ENERGY STORAGE AND RETURN.

A TYPICAL SECTION OF DUTY CYCLE IS SHOWN



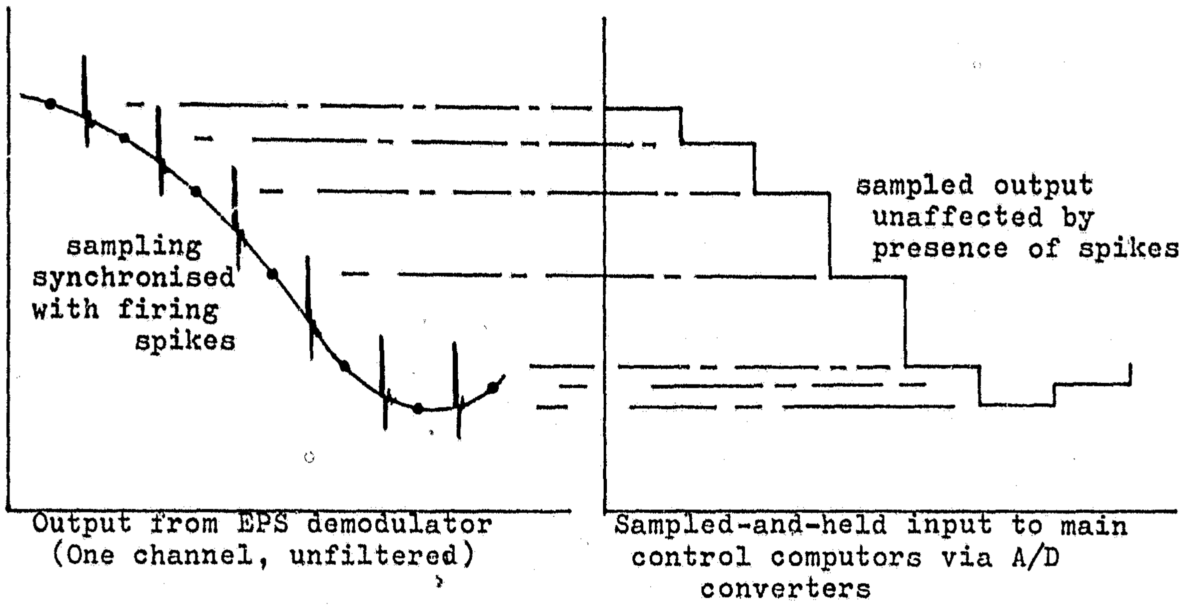


FIG.11 SAMPLE-AND-HOLD CIRCUITS FOR FILTERING OF THYRISTOR SPIKES IN EPS OUTPUT

FIG.12

RELATIVE VALUES OF MAGNETIC PROPERTIES OF RARE-EARTH COBALT MATERIAL (typical)