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A Feasibility Study on a 200 Volt, Direct Current, Aircraft Electrical Power System

by

The Staff of the Auxillary Power Systems Division

of Engineering Physics Department

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A FEASIBILITY STUDY ON A 200 VOLT, DIRECT CURRENT, AIRCRAFT ELECTRICAL POWER SYSTEM

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The Staff of the Auxiliary Power Systems Division
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SUMMARY

For comparative purposes, a 200 volt dc system for a large modern commercial aircraft has been designed and its weight compared with that of a conventional three-phase ac system. To obtain necessary design information, studies have been made of a 50 kW brushless dc generator, the problem of circuit interruption, conversion equipment and brushless motors. The vulnerability of the system due to the possibility of sustained arcs during fault conditions has also been examined.

It is concluded that until considerable weight reduction can be achieved in the design of conversion equipment and brushless motors, the dc system will not be lighter than the ac system.

It is also concluded that the 200 volt dc system would be vulnerable to catastrophic dc arcing at altitude especially in a military aircraft subject to combat damage.

Departmental Reference: EP 543

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* The work was directed by Dr. C. S. Hudson when in Instruments and Electrical Engineering Department, i.e., before the Auxiliary Power Systems Division was formed. Many of the Staff concerned in the study are now members of this new Division of Engineering Physics Department.

** Replaces RAE Technical Report 70012 - ARC 32640.

CONTENTS

1 INTRODUCTION

The present electrical power system in use in most modern aircraft is the 200 volt 400 Hz three-phase ac system introduced soon after the 1939-44 war. In this system the generators are driven at constant speed from the main engines of the aircraft through constant speed drives,and provision is made for automatic synchronisation and parallel running of the generators. With the rapid growth in recent years of installed generator capacity, aircraft constructors have become increasingly concerned about the weight of the electrical power generator and distribution system, now running at about 3-7% of the empty weight of the aircraft. Considerable attention has been given to the generator, drive, and associated control and protection equipment to reduce weight, but this is now an area of diminishing returns. However, the bulk of the weight of the overall electrical system is in the supply and distribution system. Little can be done to reduce the weight of this system other than by, either, increasing the operating voltage, or a fundamental change in the type of system used. The possibility of increasing the operating voltage e.g. to 400 volts has been examined on a number of occasions and has been found to show little advantage except in the case of very large aircraft with very long runs of cable. Considering the second, the present system is three wire with an earthed neutral, and for an operating voltage of 200 volts rms line-to-line, each cable is operating effectively at a voltage of only 115 volts rms to neutral, but has to be designed to withstand a peak voltage of at least 580 volts. Hence, the ratio of effective voltage to peak is only 115:580, i.e. approximately 1:5. This is a poor utilisation figure. However, by using a dc system having a single wire with earth return, the operating voltage could be made 200 volts, and the peak voltage the system has to withstand would be about 440 volts, giving a utilization factor of 1:2.2. Hence it would appear that a dc system should be appreciably lighter than the corresponding three-phase ac system.

A dc system operating at 112 volts was used in Valiant and Vulcan I aircraft, but was abandoned due to failure by commutator flashover of the generators used. However, in the last twenty years rapid advances have been made in semi-conductor devices. These have made possible the solutions of problems of power generation and conversion that could not have been solved in the days of the 112 volt system.

At a joint Institution of Electrical Engineers and Royal Aeronautical Society Colloquium in 1966 the topic of dc systems for aircraft was introduced by an R.A.E. paper entitled "A preliminary survey of a 200 volt dc system for aircraft". This paper was the result of some preliminary work done at the Royal Aircraft Establishment, and it suggested that the use of dc for the main aircraft electrical system should be reconsidered, proposing a 200 volt system for large aircraft and retaining 28 volts for small aircraft with limited power requirements. The system envisaged comprised a single pole earth return distribution network, and brushless dc generators driven directly from the engine, either externally as at present or built-in as an integral part of the engine. It was further suggested that equipment and loads which could not use dc power directly should have built into them lightweight interface units for converting the dc to the form required by the equipment.

Following this, a programme of further work by R.A.E. was approved. The object of this work was to examine in more detail the technical aspects of the system. This work has now been completed and is summarised in this Report.

2 THE PROGRAMME OF WORK

To enable an assessment to be made it was decided to compare the weights of two equivalent systems, one being dc and the other a conventional three-phase ac system. The weight comparison should naturally be made for an aircraft having a generator and load configuration as representative as possible of future practice. For this reason the generating system of the pre-production Concorde aircraft was chosen as a suitable basis for the comparison. The systems compared are described in Appendix A, the control and protection needed is discussed in Appendix C, and the weight comparisons are given in Appendix F.

In addition to this, a number of areas of work were defined in which it was considered that design information was needed before a dc system could be designed or an estimate of weight made. These comprise the following:

(a) Generator design

The generator needed would be a wide speed range dc machine comprising a brushless alternator with a polyphase bridge rectifier built into the end frame of the machine. Because of the switching action of the rectifier it is necessary to keep the subtransient reactance of the machine as low as possible to avoid serious commutation ripple. This, however, increases the weight of the machine and to obtain a reasonable assessment of weight, a machine operating over a speed range of 12000-24000 rev/min has been designed. This work is described in Appendix B.

(b) Switching

Work done some years ago by Mossop and Gill[1,2,3] at the R.A.E. in connection with the 112 volt dc system used in the Valiant and Vulcan I aircraft indicated that there would be a fairly serious problem of circuit interruption with 200 volt dc, particularly at high altitudes. Some further work has therefore been done and various methods of circuit interruption have been examined. This work is described in Appendix D.

(c) Power conversion

Motors are used for fuel pumping, driving air conditioning equipment, etc., and the total load may be an appreciable part of the installed power.

The modern three-phase ac induction motor in use in ac systems is a simple lightweight robust motor which is ideal for the purpose. A brushless dc motor may be achieved in various ways but the most suitable appears to be the use of an induction motor supplied from the 200 volt dc supply through a square wave inverter. Work needed to be done to establish that the motor would run satisfactorily on a square wave supply without appreciable loss of performance and efficiency and also to assess the weight of the motor-inverter unit compared with the equivalent ac induction motor.

Most equipments will need a built in 'interface' unit which receives power at 200 volt dc and converts it to the various levels of power required in the equipment. Design studies needed to be made to assess the weight of such units compared with the transformer rectifier units at present used in equipments.

This work is described in Appendix E.

(d) Vulnerability

A cause for concern was the possibility of greater arcing damage with a dc system if a fault occurred, particularly a short circuit to the airframe. Papers by Foust and Hutton[12], and by Cunningham and Davidson[13] indicated that some increase in arcing time was likely at altitude with high voltage dc. Their tests, however, were limited to moderate altitudes. Further tests have therefore been made at altitudes up to 60000 ft. These are described in Appendix G and in a separate report[4].

3 GENERAL DISCUSSION ON THE TECHNICAL ASPECTS OF THE 200 VOLT DC SYSTEM

3.1 Generation

The design and manufacture of a brushless 200 volt dc generator present no new fundamental problems. The generator would consist of a three-phase, rotating-diode, brushless alternator, feeding a silicon-diode, full-wave, rectifier to produce the required dc output. The output rectifier diodes would be mounted in the alternator case and cooled by the alternator coolant. This could be air, or, preferably, for high-speed aircraft, a suitable liquid. A permanent-magnet pilot exciter would be incorporated, to supply control and excitation power. A filter would be fitted to reduce the ripple voltage to an acceptable level; it too would be mounted in the alternator case.

The basic requirements of the generator for this application are the attainment of a low weight to power ratio, coupled with high reliability, particularly in respect of the bearings and the output rectifier diodes. A typical specification would call for the delivery of rated power over a speed range of 2:1, overload currents of 150% full-load current for 5 minutes and 200% for 5 seconds, and short-circuit currents of 300% for 1.5 seconds. The ripple filter would be required to reduce the full-load ripple voltage to no more than say 20 volts, peak-to-peak. In advanced aircraft oil cooling might be called for, with oil inlet temperatures of up to about 165°C.

The manner in which the basic requirements affect the design of the generator is discussed in Appendix B. It is shown that to minimise the weight to power ratio of the alternator itself operation at high speeds is required, and a speed range of 12000 to 24000 rev/min is proposed. This gives a weight to power ratio of about 1.2 lb/kVA at the minimum speed for the alternator alone, if oil cooled, which is appreciably less than for conventional 400 Hz, 8000 rev/min, machines of similar power (1.5 lb/kVA). In order to minimise the weight of the ripple filter a high alternator frequency is required, and a frequency range of 1200 to 2400 Hz is proposed. Since the alternator is feeding a rectifier it is operating in the switched mode. In order therefore to reduce the commutation loss the subtransient inductances should be made small and equal. This is most effectively achieved by means of a damper winding on the rotor. The transient switching voltage surges for a variable-speed machine tend to be higher than for a constant-speed machine, and on removal of full load from a machine running at top speed an initial voltage surge of the order of twice rated voltage could be expected from a speed range of 2:1. Under abnormal operation it is thought that the voltage could in fact rise to about 440 volt before being reduced by voltage-regulator action.

The overall weight of a 50 kW oil-cooled generator, including the weight of the rectifier and filter units, is estimated to be 105 lb, compared with a weight of about 90 lb for a conventional 60 kVA, 400 Hz, alternator of the same real-power output. But since the generator would be directly coupled to the engine drive and the constant speed unit, essential when generating ac, eliminated there would be a net weight saving of some 64 lb.

3.2 System control and protection

The proposals for system control and protection are discussed in Appendix C and in more detail elsewhere[5]. The use of main-line diodes is shown to achieve a number of simplifications in system-control circuitry. They give automatic and instant isolation of the busbars and consumers' loads from generator and generator-cable earth faults and generator under-voltage faults, thus providing a 'no-break' supply under such fault conditions. They also obviate the need for under-voltage protection circuits, and simplify over-voltage fault discrimination. Their main disadvantage is in size and weight, estimated at 1500 in^3 and 16 lb for a 50 kW unit capable of operating in ambient temperatures up to $70^\circ C$, at altitudes up to 70000 ft, with natural convective air cooling. A minor problem is that main-line diodes do not provide a positive means of disconnecting the generators from the busbars, for example when the first engine is being run up and the generated voltage is subnormal.

With regard to control problems, a dc system needs neither frequency regulators nor reactive-load sharing circuits, so parallel operation is much simpler than with ac, especially when main-line diodes are used. The only problem is that of compensating for the variations of gain round the generator voltage-control loop as the speed varies. This problem is met with in variable-frequency alternators and in 28 volt dc brushless generators, and is capable of solution at the expense of some added complexity in the voltage regulator[6].

With regard to protection in a dc system, over-frequency, under-frequency and phase-sequence protection are irrelevant, while under-voltage protection is achieved by the main-line diodes. On balance therefore the control and protection of a parallel dc system using main-line diodes is much simpler than for an ac system. This will tend to improve reliability since there are fewer circuits to operate inadvertently.

3.3 Switchgear

In the environment experienced in modern high altitude aircraft, none of the existing types of aircraft switchgear, designed for 28 volts dc, 112 volts dc, or 115/200 volts ac systems, will function satisfactorily at 200 volts dc.

The ac switchgear relies upon the periodic zeros and reversals of the current to extinguish the arc very soon after it has been drawn. Dc supplies provide no natural zeros or reversals of the current, so purely-mechanical dc switchgear has to be specially designed to build up an arc voltage drop greater than the supply can maintain. The difficulty of dc switching therefore increases with the voltage. Because of these factors an investigation of many possible methods of switching 200 volts dc power, over a wide range of currents, was undertaken in order to find which would be the most suitable. These studies are briefly described in Appendix D and are fully reported on elsewhere[7,8,9]. The following is a brief summary of the findings.

Conventional aircraft switchgear is purely mechanical in operation. That used in 112 volts dc systems was unsealed, and achieved current interruption by using multiple gaps or deion grids to produce a number of arcs in series. The same techniques are proposed for 200 volts dc, though even for low rated currents a multiple-gap switch would require eight short series gaps. This would demand careful manufacture to achieve virtually simultaneous opening of the gaps in order to minimise the arcing times amd maximise the endurance. For high rated currents and for rupturing fault currents deion grids, used in conjunction with four long gaps, are the proposed solution. With either type however it might prove difficult to achieve the sort of contact endurance figures currently provided by modern aircraft switchgear (50000 operations). A sealed contact enclosure with oil or compressed air or nitrogen might provide a lighter and more durable switch than the unsealed air-break types, at the expense of considerable development work to prove seal integrity and contact endurance.

The application of forced-commutation techniques to ac-type mechanical switchgear and to thyristors to achieve dc switching is quite feasible, though the technique has several disadvantages. A large and heavy commutation capacitor is required, the size of which is related to the maximum overload capacity of the switch, and short-circuit fault currents cannot be ruptured. In the thyristor switch, the commutation circuit imposes an overvoltage across the load during switch-off, whilst a large heat sink is necessary to dissipate the heat generated in the thyristor. The heat generation and the heat sink can be eliminated by the connection of mechanical back-up contacts across the thyristor, resulting in a large weight reduction, but the operational disadvantages of forced commutation remain. These include the possibility of the thyristor failing to conduct, when it would be unsafe to open the back up contacts.

Estimates of weight, volume and cost for various types of dc switch for two representative ratings are summarised in Table 1, together with estimates for ac switchgear of the same real-power handling capacity. The purely mechanical type of dc switch is several times lighter, smaller and cheaper than any other dc type, but even so it is some 50-100% heavier than equivalent ac switchgear. Furthermore it might not have a comparable contact endurance, at least without considerable development effort and/or further weight increase. Penalties of this sort are inevitable, since the interruption of direct current is inherently more difficult than that of alternating current.

3.4 Power conversion

Replacement of the 400 Hz ac supply by a 200 volts dc supply would involve the introduction of, or the redesign of, input-power convertors in practically all the existing consuming equipment. The major types of equipment affected would be:-

(a) Electric motors
(b) Flying-control equipment
(c) Navigational equipment
(d) Communication equipment
(e) Power convertors to supply the 28 volts dc system

The following three types of power convertor are proposed to supply the affected equipment, of which the first two are discussed in more detail in Appendix E.

(i) Square-wave invertors to supply electric motors (a). The use of the robust ac squirrel-cage induction motor fed by a relatively unsophisticated, square-wave, thyristor invertor is proposed for continuous-running duties. The invertor must be rated for the maximum motor current, which normally occurs on starting, and so to reduce the weight of the associated invertor it is proposed to reduce the frequency and voltage at starting. This both reduces the current and increases the torque, at the expense of increased circuit complexity. The weight of the invertor is very much dependent upon the type and quality of cooling employed. For ambient temperatures of 70°C at low altitudes the weight of an invertor employing forced-air cooling and frequency control varies with kVA rating in the manner shown in Fig.3. It is about 1.6 times the weight of an induction motor designed to run at 10000 rev/min. In the case of fuel pump motors some weight reduction would be possible if the fuel were cool enough to act as a heat sink for the thyristors.

(ii) Dc transformers. To generate dc power at various voltage levels in each item of electronic consuming equipment (b), (c) and (d), and to supply the 28 volts dc system (e), it is proposed to use 'dc transformers'. The dc transformer comprises a square-wave thyristor invertor, a transformer, a rectifier and, where necessary, a filter. In order to minimise the weight of the transformer and the filter it is desirable to operate the invertor at the highest practicable frequency, and 3 kHz is feasible with modern fast-turn-off thyristors. On this basis a dc transformer and a 400 Hz transformer/rectifier unit rated at 1 kW would weigh about the same, although there would be a weight penalty against the dc unit for the rather smaller ratings found in most electronic-equipment power packs. While the thyristors considered in these estimates would function satisfactorily on a 200 volts dc supply, they could not withstand the switching surges expected in a practical 200 volts dc aircraft system. Unfortunately the requirements of high voltage rating and fast turn-off are incompatible, and in the event of the manufacturers being unable to increase sufficiently the voltage rating of their fast-turn-off thyristors it would then be necessary to use slower thyristors. This would require a lower operating frequency which would result in a greater weight penalty.

(iii) Sine-wave invertors are needed to generate reasonable-quality 400 Hz ac power at various voltage levels in electronic consuming equipment (b), (c) and (d). Depending upon the exact requirements, sine-wave invertors weigh some 3-5 times as much as square-wave invertors, as shown in Fig.3. They would be required in those equipments which finally use power in ac form and normally obtain it by straight transformation from the primary 400 Hz ac power system. For equipments which require precision-quality ac power and obtain it, even in 400 Hz ac power systems, from invertors fed by the 28 volts dc system, no further weight penalty would arise by changing the primary power system to 200 volts dc.

3.4.1 Reliability and cost of power convertors

With practically every item of consuming equipment containing a built-in fixed- or variable-frequency invertor to feed it, the reliability and cost of the equipment can hardly fail to be worsened. Furthermore, the rather low maximum junction temperature permitted in thyristors implies a greater sensitivity to the ambient air temperature and pressure and a greater use of cooling fans, which, except for motor invertors, would themselves require invertor drives if run continuously. Radio interference problems would also be more severe.

The only mitigating feature is the possibility of incorporating fast-acting voltage regulation into the invertors of types (ii) and (iii) to improve the quality of their output, and thereby reduce the risk of failures in the consuming equipment due to voltage surges and spikes.

3.4.2 The use of transistors

The magnitude of the load-switching voltage surges expected in the 200 volts dc system precludes the use of transistors in the invertors[10], and forces the designer to use thyristors instead. These require the additional weight and complexity of commutation circuitry. A reduction in the nominal system voltage to about 50 volts dc would enable transistors to be used, at least in the lower power ratings.

3.5 Weight comparisons

An 'aircraft electrical system' normally comprises all the equipment and cabling used in the generation, storage and transmission of electrical power, in any form, up to the busbars; together with the protective devices, switchgear, control units, cabling, etc. necessary to distribute the power and to operate consumer equipment. It does not normally include electrical items forming part of the consumer equipment, nor does it include engine accessories such as constant speed drives. However in making a comparison between two basically different forms of electrical power, it is of course necessary to take into account, as far as possible, the effect of the new power supply on the weight of consumer equipment and whether any items may be eliminated or have to be added to the installation.

3.5.1 Power system differences affecting weight

(a) As dc generators can be run in parallel without close speed control, the constant speed drives of the ac system can be eliminated.

(b) Since a parallel-running dc system is simpler and easier to control and protect than ac, some saving in weight should be obtained.

(c) Dc can be distributed with a single wire using earth (airframe) return, thus replacing the three wires of a three-phase system with one wire.

(d) 200 volts dc switchgear will in general be heavier because of the inherently greater difficulty of extinguishing dc arcs.

(e) In order to avoid unreliability and rapid brushwear, all 200 volts dc continuously-running motors must be brushless, thus necessitating the use of invertors to supply them.

(f) There will be a requirement for some 400 Hz ac power, in sine-wave form, at three-phase 200 volt and single-phase 115 volt and 26 volt. This means adding further invertors to the dc installation.

(g) Equipment for transforming dc voltages within consumer equipment is of greater complexity and weight than that for transforming ac voltages.

A detailed weight comparison undertaken to assess the overall effect of the foregoing differences between ac and dc systems and based on the system layout and consuming equipment used in the pre-production Concorde, is described in Appendix F.

3.5.2 Summary of the weight comparison

The total weights of the 200 volt ac and dc primary electrical power systems are shown in Table 5, while Table 7 gives a breakdown of the weight differences for the individual parts of the systems. Table 7 considers two alternative methods of utilisation-circuit protection:- (A) by means of manual circuit-breakers in both ac and dc systems, and (B) by means of fuses, wherever possible, in both systems. Table 5 is for method (A) only.

It will be seen that in most areas the dc items are the heavier, but this is almost offset by substantial weight savings in cables and by the elimination of the C.S.Ds. and their control gear. The saving in cable weight is 610 lb, which is in fact equal to one half the weight of those ac cables on which a weight saving is possible (i.e. all the 200 volts, three-phase, cables and those 115 volts, single-phase, cables which are greater than minimum size).

There are two areas in which the 200 volts dc system is considerably heavier:- (a) in the provision of secondary power, where there is a weight increase of 330 lb, and (b) in the use of invertors for driving ac motors, where there is a weight increase of 542 lb. Both of these figures will vary from aircraft to aircraft, but any reduction in the secondary-power requirement or in the motor load must also reduce the amount of primary power to be produced. This in turn will reduce the size of generators, C.S.Ds. and the quantity and size of cable used. Thus a reduction in the weight of invertors would be partially offset by a smaller saving in cable weight and by the elimination of lighter C.S.Ds.

On balance the dc system is heavier by 234 lb when both systems use manual circuit-breaker protection, or by 160 lb when fuses are used where possible. However these two figures form only 3.1% and 2.1% of the overall electrical installation weight (7600 lb). Very broadly, the weight penalty or advantage of a 200 volts dc system will be governed by the following two principal considerations:- (a) the greater the length of cabling from the generators to the busbars and to the major consumers the greater will be the weight advantage; (b) the greater the proportion of motors and other ac consumers the greater will be the weight penalty. Concorde rates highly on both points, and may therefore be said to be a fair choice of aircraft for making the comparison. Thus, making due allowance for estimation errors, there is unlikely to be a large weight saving by using 200 volts dc in any aircraft with the type of mixed load pattern common at present.

3.6 Arcing

Some tests were made to compare the maximum length of arc which could be sustained by a 200 volts dc system with that for a 200 volts ac system, over a range of altitudes[4]. The arcs were struck between large brass electrodes in a high-altitude chamber by the fusing of strips of aluminium foil connected between them. The power supply was 200 volts, 400 Hz, ac (line-to-line connection), or 200 volts dc, and the arc current was limited by a series resistance of about 1 ohm. The test procedure is described in Appendix G, and the dc results are plotted in Fig.4. This shows the maximum gap length across which an arc could be sustained, as a function of altitude. It will be seen that at 60000 ft a dc arc could be sustained over a 7 inch gap, the arc current and voltage being approximately 110 amperes and 90 volts. If the limiting resistance were removed, to simulate an earth fault, the arc current would rise and the gap length could be further increased. In contrast, with a 200 volts ac supply it was not found possible to sustain an arc with any gap down to 1/16 inch, even at altitudes of up to 80000 ft.

These tests indicate that in the event of an earth fault at high altitude the damage that would be caused by the arc before extinguishing itself would be very much greater in the dc system than in the ac system. Indeed the dc arc might never extinguish itself if, for example, it occurred between a main generator cable and an adjacent large structural member, and the arc might burn right back to the generator. Of course the occurrence of a sustained arc does depend upon the simultaneous existence of an earth fault and a failure of the generator overcurrent sensor or the de-excitation relay in the protection scheme outlined in Appendix C. The tremendous arc damage that could result from such a double failure serves to underline the vital importance of these particular protective devices.

It is to be noted that there is some difference between the British[4] and American results[12,13] of arcing tests. The series resistance used to limit current in the R.A.E. experiments would have had a stabilizing effect on the arcs, but a more important difference was in the voltages used.

4 CONCLUSIONS

(1) For the type of aircraft considered, namely the large commercial aircraft, the dc system proved to be slightly heavier than the corresponding three-phase ac system. This is due mainly to the weight of the power conversion components needed, and until there is a technical break through resulting in a considerable reduction in the weight of conversion equipment and brushless motors there is little prospect of the 200 volt dc system showing a weight advantage over the ac system.

Furthermore, with most consuming equipment incorporating fixed or variable frequency invertors to provide suitable supplies, the reliability and cost of the equipment would probably be worsened.

(2) It is considered that the dc system is simpler than the ac system. It is a single wire, earth return system; no constant speed drives are required; control and protection and, in particular, load sharing require less complicated circuits; and by the use of main line diodes interruption of the supply to loads is avoided in the event of a generator failure.

(3) A serious drawback of the 200 volts dc system is that under fault conditions sustained arcing may occur with a consequent increase in the risk of fire damage to the aircraft.

(4) If fuel pumping and deicing loads become non-electric, the total power demand will be considerably reduced, in which case a dc system operating at a lower voltage (e.g. 50-100 volts) might show an advantage.

Appendix A

DESCRIPTION OF THE SYSTEMS CONSIDERED IN THE WEIGHT COMPARISON

(see section 1)

A.1 The 200 volts, three-phase, ac system (Fig.1)

The ac system consists of four generating channels, each of 60 kVA, with four main busbars MBB, each main bar normally connected to an essential busbar EBB via a change-over contactor COC. The total aircraft load can be met fully even with the loss of one generating channel.

The four channels may be run singly or up to all four in parallel. A 30 kVA hydraulically-driven emergency generator is installed to feed any one or all of the essential bars via the change-over contactors upon the loss of main power.

For ease of comparison no load-shedding arrangement is depicted on the emergency system, although this may well be required to cover the case of a four-engined flame out.

The 28 volts dc power supply is obtained from 150 amperes transformer/rectifier units, two of which are connected to the inner main busbars and two connected to the outer essential bars. Two transformers of 1400 VA output are fed from the inner essential bars to provide a supply of 26 volts ac for synchros, etc.

A.2 The 200 volts dc system (Fig.2)

The 200 volts dc generating system has been devised to function in a similar manner to the ac one, but it has been arranged to make use of diodes and fuses, i.e. static components, in place of the ac contactors and logic protection. Such a change is intended to improve reliability and simplify control.

The system consists of four channels, each of 50 kW, feeding four sets of main and essential busbars via separate line diodes. Owing to the relative simplicity of dc control it is intended to run all the channels in parallel, unless there is a failure in at least two, causing overloading of the two sound machines, when it will be necessary to split the main bars. However all essential bars will continue to receive power as long as one generator is functioning. The 25 kW hydraulically-driven emergency generator will only be required upon the failure of all four main power sources.

Dc transformers (28 volts, 150 amperes each) are connected, two to the inner main busbars and two to the outer essential busbars, and two invertors (26 volts ac, 1400 VA) are connected to the inner essential bars.

Appendix B

FACTORS INFLUENCING THE DESIGN OF THE GENERATOR

(see section 2(a))

B.1 Factors which influence the power to weight ratio of the alternator

The weight of an alternator for a given power rating and a given number of poles is roughly inversely proportional to its operating speed. Consequently the minimum operating speed should be set as high as possible, taking into account the limitations on the maximum operating speed imposed by the need for bearing reliability and long life, and by the rotational stresses imposed upon the rotor with its windings and diodes.

Tests made on the bearing system for a high speed alternator have shown that with present bearings and oil seals, operation over the speed range 12000 to 24000 rev/min is possible, resulting in a weight to power ratio of 1.2 lb/kVA at the minimum speed for an oil cooled alternator.

A high utilization factor for the alternator can be obtained by using a three-phase, full wave, rectifier arrangement, for which the kVA rating of the alternator need only be 1.05 × kW rating of the dc output. This assumes perfect commutation but to allow in practice for some loss of kVA due to commutation overlap the kVA rating of the alternator should be increased to an estimated value of 1.2 × kW rating of the dc output.

To meet the requirements of the 50 kW dc system outlined in Appendix A, it is estimated that an alternator rated at 60 kVA weighing 72 lb would be required.

B.2 Factors which influence the choice of alternator output frequency

In a dc system of the type being considered the frequency of the ripple voltage, which appears as a component of the dc output voltage, is proportional to the basic generated frequency. Since the weight of the ripple voltage filter unit is inversely proportional to the frequency of the ripple voltage it is essential, for the purpose of weight saving, for the alternator output frequency to be high.

The output frequency of the alternator is given by:

$$f = \frac{n\,p}{120} \text{ Hz}$$

where n = speed in rev/min

p = number of poles.

From this it can be seen that the frequency is dependent on both the operating speed and the number of poles. It has already been stated that a high operating speed is desirable in order to minimise the weight of the alternator and it is seen here to be desirable for minimising the weight of the filter unit.

The number of poles which can be accommodated on the rotor is determined by its diameter, which is itself limited by the rotational stresses. Therefore the number of poles is a function of the maximum operating speed. For alternators operating at up to 24000 rev/min the number of poles could vary between 8 and 12 depending on the detailed requirements. For this application a 12 pole rotor would be suitable, resulting in an output frequency range of 1200 to 2400 Hz.

Before the value of the maximum frequency can be finally settled it is essential to ascertain that the alternator will operate efficiently when supplying a rectifier load at the chosen frequency, the criterion being the time taken by a phase to commutate. The commutation time should not be greater than $\frac{T}{6}$ for a three-phase full-wave rectifier, where T is the periodic time. An expression given by Shilling[11] permits the commutation time to be calculated from the alternator parameters and it has been found that for an alternator of 50 kW rating a maximum output frequency of 2400 Hz would be acceptable.

B.3 The characteristics of the alternator which affect its operation in the switched mode

If an alternator is to operate efficiently in the switched mode, that is when supplying rectifiers, the values of its subtransient inductances L''_d and L''_q must be small and equal in magnitude, since for efficient operation the commutation time must be short. The relevant time constant is given by:

$$T_a = \frac{L''_d}{r}$$

where r is the phase resistance, including that of the rectifier,

and L''_d is the direct-axis subtransient inductance ($L''_d = L''_q$).

The values of the subtransient inductances can be reduced by at least 60% and made equal in magnitude by fitting a complete damper winding on the rotor, as shown by tests previously reported[14]. Consequently for this application the alternator would have to be fitted with a damper winding. This would not add a significant amount to the weight of the alternator but it would introduce a difficult design problem with regard to the mechanical stability of the rotor, owing to the high rotational speeds involved.

B.4 Diode assembly

In order to obtain a high utilization factor for the alternator, a three-phase, full-wave, rectifier arrangement is required. The diode assembly would be integral with the alternator and the diodes would be liquid cooled, the liquid being pumped through channels formed in the diode mounting ring.

For the purposes of the weight comparison it has been assumed that the diodes will be required to pass a maximum short-circuit current of 300% full-load current (750 amperes) for 1.5 seconds and to operate in an ambient temperature of 200°C when cooled by a liquid coolant having a maximum inlet temperature of 165°C. To meet these requirements two 250 ampere diodes connected in parallel would be required for each arm of the bridge. The combined weight of the 12 diodes would be approximately 5 lb and allowing for the weight of mountings, housing and connections, it is estimated that the diode assembly would weigh 18 lb.

For generators of this type the weight and reliability of the diodes is greatly affected by the coolant inlet temperature. For example if in this case the inlet temperature were reduced to 120°C only one diode per arm would be required and the need for selection and pre-ageing the diodes might not arise.

B.5 Ripple voltage filter unit

Tests carried out on a high-frequency alternator (40 pole, 8000 rev/min) supplying dc via a three-phase, full-wave, rectifier circuit indicated that the unsmoothed ripple voltage of a brushless 200 volts dc generator under full-load, full-speed conditions could be as much as 70 volts peak-to-peak.

A filter capable of reducing the ripple voltage to an acceptable level could be made using the design methods developed by Hinton, Meadows and Caddy[15]. The unit would consist of a modified low-pass filter network in which the inductance elements would consist of ferromagnetic tubes mounted on copper rods. For a 50 kW generator the capacitor would have to be capable of passing approximately 20 amperes. The unit would weigh approximately 15 lb. The output ripple voltage would not exceed 10 volts peak-to-peak.

B.6 Type of alternator

Of the available known types of machine the rotating diode, wound field, salient-pole alternator is preferred for this application, since it has a lower weight to power ratio than any of the solid-rotor types when operated at the speeds considered permissible with the bearings and oil seals presently available.

Should bearings and oil seals which permit the use of operating speeds over the range 24000 to 48000 rev/min become available the solid-rotor types would become more competitive on a weight to power comparison, but they would still be inferior electrically because their leakage inductances are approximately three times greater than those of the equivalent rotating diode machine. It would be essential to fit the solid-rotor machines with damper windings to minimise their pole-face losses and subtransient inductances; consequently their rotors would no longer be simple homogeneous structures capable of operation at the maximum stress limit of the rotor iron.

B.7 Summary of estimated weights of generator components

It is estimated that the complete 50 kW dc generator would weigh 105 lb, made up as follows:-

weight of alternator to give 50 kW dc	72 lb
weight of complete rectifier assembly	18 lb
weight of complete filter assembly	15 lb
Total	105 lb

Based on these estimates the weight to power ratio of an oil cooled, brushless, 50 kW dc generator suitable for this application is 2.1 lb/kW.

Appendix C

PROPOSALS FOR SYSTEM CONTROL AND PROTECTION

(see section 2)

C.1 The use of main-line diodes in the generator cables

On an ac system the generators are brought onto line and the busbars and generators isolated under fault conditions by means of three-phase contactors. In a dc system isolation can be achieved by the use of main-line diodes placed in the generator cables adjacent to the busbars (see Fig.2). These have a twofold advantage since:-

(a) the diodes automatically and instantaneously isolate the busbars from generator and generator-cable earth faults, and from generator under-voltage faults, and therefore obviate the need for under-voltage protection circuits; and

(b) they simplify the problem of discrimination when there is an overvoltage fault on a generator, since the output voltage of the healthy generators remains normal.

Parallel operation is made easier since the generators automatically come on to line when their voltage is correct. However in the case of a persistent earth fault on a busbar or load feeder cable the main-line diodes cannot rupture the fault current as an ac generator-control contactor would. The diodes must therefore be capable of carrying the fault current until the fuses have ruptured and the generator has been de-excited. This could penalise the diode arrangement as far as weight and size are concerned when compared with an individual dc circuit-breaker. However more circuit-breakers than diodes would be required for transfer and isolation so that on balance there may be little difference in overall size and weight.

A possible operational disadvantage in the use of main-line diodes is that they do not provide a positive means of disconnecting the generators from the busbars. Thus, while the first generator is being run up and is in course of exciting itself to 200 volts (or while the last generator is being run down) any loads connected to the busbars will experience under-voltage conditions for a period of time dependent upon the engine acceleration and the excitation characteristics of the generator. This period of time could be shortened by holding off the excitation until the generator speed is within its normal range.

If there were any loads likely to be connected during this under-voltage condition and likely to be damaged by it, one solution would be to fit generator-control contactors and under-voltage trips, but a simpler and lighter solution might be to fit under-voltage trips to the individual sensitive loads.

Size and weight estimates have been made for a main-line diode assembly for a 50 kW generating channel which has to pass a continuous current of 250 amperes and a fault current of 750 amperes for approximately 1.5 seconds over an ambient temperature range of -40 to +70°, at altitudes up to 70000 ft. With each assembly consisting of three parallel diodes relying on natural convective air cooling from heat sinks, the approximate dimensions of the unit would be 22 in × 8½ in × 8 in, with a weight of approximately 16 lb. With forced cooling the size of the unit could be reduced, but the additional complications in air ducting or other forms of coolant circulation would be such as to make any overall weight saving unlikely. Main-line diodes with forced cooling could be less reliable than those with natural cooling due to possible failure of the cooling system.

C.2 Control[5]

With modern aircraft engines the speed range between ground idling and top speed is approximately 1:2. With ac systems at constant frequency the speed variation is taken up in the constant speed drive, which however still has to be speed controlled. Thus with ac systems there are two parameters which have to be controlled, i.e. the voltage and the frequency (speed), whereas with a dc system only voltage control is required.

In parallel operation the dc system is simpler since reactive-load sharing circuitry is not required. Real-load sharing may still be necessary with a paralleled dc scheme, depending on the load-droop characteristics of the generator.

The voltage regulator for a dc system may have additional complications over that used on a constant-frequency system because of the speed variation of the generator. It is usual to provide the power for both control and protection from a separate permanent-magnet pilot exciter mounted on the same shaft as the main machine. With the constant-frequency arrangement the pilot exciter output is constant in voltage and frequency. In a dc system the generator speed will vary and thus both voltage and frequency of the pilot-exciter output alters accordingly. Brushless generators are themselves two-stage devices and the incremental gain from the main exciter field current to the output voltage is approximately proportional to the speed squared. The added speed-dependent term of the pilot exciter results in a speed-cubed term in the overall incremental gain of the machine combination. To counteract this speed effect adds some complexity to the design of the dc voltage regulator[6].

C.3 Protection[5]

Some of the protection devices needed on both an ac and a dc system are similar in nature e.g. over-voltage, over-current, cable and generator earth-fault protection (Merz Price) and busbar protection. In the dc system outlined in Appendix A a faulty busbar is isolated by the rupturing of the bus-tie fuse feeding it, and by de-excitation of the generator on the faulted channel. The sensing of large direct currents can be achieved by the use of magnetic amplifiers[5] and this should present no great difficulties.

Such protective devices as over-frequency, under-frequency, under-voltage and phase sequence are not required on the dc scheme. Under-voltage protection is automatically achieved by means of the main-line diodes, though under-voltage indication is still necessary.

Appendix D

SURVEY OF METHODS OF SWITCHING FOR 200 VOLT DC SYSTEMS[7,8,9]

(see section 2(b))

D.1 General principles of current interruption

There appear to be two alternative basic principles for interrupting the current in any circuit:-

(i) Insertion of an increasing impedance into the circuit by means of a switching device. This principle is employed in dc purely mechanical switchgear and in certain types of solid-state switch, such as those using transistors.

(ii) Reversal of the voltage across the switching device, so as to achieve complete electrical isolation in it when the current through it falls to zero. This is the principle normally employed in ac switchgear because of the natural periodic reversal of both the voltage and the current in the circuit. In dc circuits there are no natural current zeros, but voltage reversal can be achieved by connecting a charged capacitor across the switching device, a technique known as 'forced commutation'. This can be applied to ac-type mechanical contacts or to thyristors.

D.2 Switchgear required in 200 volt dc systems

The switchgear required in a typical 200 volts dc main power-distribution system (such as Fig.2) is minimal, and consists only of a ground-power contactor GPC and an isolating or 'on line' contactor to separate the paralleled channels. In addition, the load circuits will require contactors or manually-operated switches or circuit-breakers, just as in normal 115/200 volt ac systems. If it should prove impracticable to develop small dc circuit-breakers with adequate fault-rupturing capacity, and clearance times sufficiently short to protect the diodes in the system, then a fuse would be needed instead, together with a manual switch if connect/disconnect facilities were also required.

A new family of switchgear would therefore be required, capable of handling normal load currents ranging from about 1 ampere to 250 amperes, in ambient temperatures between $-40^{o}C$ and $+85^{o}C$ and at altitudes of up to 70000 ft in the worst cases. A moderate overload-rupturing capacity of a few hundred per cent would normally be essential as a bare minimum. In addition an ability to rupture high fault currents would be required of certain switchgear if the use of fuses or main-line diodes should prove unacceptable. It is desirable that load switches shall be capable of switching currents flowing in either direction. For isolating contactors this is essential. Modern ac switchgear has an endurance of 50000 operations, and a similar figure is desirable for dc switchgear.

D.3 Types of switchgear for 200 volt dc systems

D.3.1 Purely mechanical switchgear

The simplest types of dc purely mechanical switch are the unsealed air-break types. These achieve current interruption by using either deion grids or multiple gaps to create a number of arcs in series requiring a total arc voltage greater than the supply can maintain. For low rated currents, of the order of 10 amperes, the multigap type, employing eight short series gaps, is the more suitable. Careful mechanical design, manufacture and assembly are needed however to ensure that the eight pairs of contacts open practically simultaneously in order to minimise the arcing times and achieve maximum endurance.

For high rated currents, of the order of 100 amperes, an unsealed multigap switch would require ten series gaps, with the possible addition of main bridging contacts to reduce the total contact volt drop and the heat generated in the contact block. This would involve a rather unwieldy construction, and the problems of mechanical design and tolerancing would be more severe than for the smaller ratings. The use of four long gaps fitted with deion grids is thought to be a better proposition, particularly if grid designs can be improved. With either type, however, arcing tends to last rather longer than in 400 Hz ac switchgear, so it may prove difficult to achieve contact endurances of 50000 operations on dc working, particularly since metal transfer will in most cases be unidirectional. Nevertheless both types are basically bidirectional (so long as permanent magnets are not used to provide magnetic arc deflection) and both have the ability to rupture very high fault currents.

The use of oil or compressed air or nitrogen in a sealed contact enclosure should enable a rather more compact and lighter contact assembly to be used. However, a considerable amount of development work would be required to determine the possible overall weight saving and to establish adequate seal integrity. A type of sealed switch which has been commercially developed recently is the dry-reed switch. It can be used in the 200 volt dc system for currents up to 0.5 ampere, but little extension of the simple reed structure beyond this dc rating can be foreseen.

D.3.2 Use of solid-state devices having a natural turn-off ability

Neither transistors nor gate-controlled switches can provide feasible 200 volt dc switches at present, since they are not available with V_{CEO} voltage ratings which can withstand the transient switching surges expected in the system. Even with increased voltage ratings, the current ratings of gate-controlled switches and pnp transistors (for which control circuits for negative-earth systems are much simpler than those for npn types) are at present limited to only a few amperes. Both devices also possess limited overload- and fault-rupturing capacities, and would require relatively high control powers.

D.3.3 Mechanical switches and thyristors, with forced commutation

All the remaining feasible methods of switching 200 volts dc power involve forced commutation, but this has several drawbacks. A large and heavy commutation capacitor is required, the size of which is directly related to the highest overload current which the switch must be capable of interrupting. Short-circuit fault currents cannot be ruptured and a fuse must be included for this purpose. The switch is suitable only for unidirectional current flow. The detection of the true state of the switch for indication and interlocking purposes is not achieved as readily as with purely mechanical switchgear. In the thyristor switch, the commutation circuit, when turning off the thyristor by means of a reverse voltage, imposes an overvoltage across the load of up to 100%. The heat generated in the thyristor by the load current demands a very large heat sink, if cooled naturally, owing to the low density and the high temperature of the cooling air, and the relatively low maximum junction temperature permitted (125-150°C). Nevertheless the thyristor does provide a purely static switch with no moving parts to wear out. It can therefore offer a very high endurance, provided that its components are carefully chosen and conservatively rated to stand the unfavourable electrical and thermal environment.

The addition of mechanical back-up contacts to the dc thyristor switch would enable the steady-state losses and the heat sink to be eliminated, with a considerable saving in weight. The development of thyristors with shorter turn-off times will reduce the weight and size of the commutation capacitor, and might make this hybrid type of switch competitive, in respect of weight and volume, with the purely mechanical dc contactor. Even so it would still be more expensive, it would induce very high spike voltages in the system, and would possess the many operational limitations of forced commutation.

A further disadvantage is that failure of almost any component, including failure of the back-up contacts to make, would result in a situation where it would be impossible to switch off the load.

D.4 Estimates of weight, volume and cost

In order to make quantitative comparisons between the various types of dc switch, estimates of weight, volume and cost have been made for two representative continuous ratings: 10 amperes and 100 amperes. The environment specification includes ambient temperatures of up to 85°C and altitudes of up to 70000 ft. The 10 amperes switch would be manually controlled, and equivalent as far as possible to conventional modern 115/200 volts ac aircraft lever-operated switches. The 100 amperes switch would be remotely controlled, and equivalent as far as possible to conventional modern electro-magnetically operated 200 volt ac aircraft contactors. Weight, volume and cost estimates have also been made for ac switchgear of the same real-power handling capacity, assuming power factors of 0.8. All the estimates are summarised in Table 1, and it can be seen that the lightest and smallest type of dc switch is the purely mechanical one. Even so, the weight, volume and cost penalties of small 200 volt dc lever-operated switches when compared with their ac equivalents are approximately 100%; for large 200 volt dc contactors the penalties are approximately 50%.

The problems of designing small dc manually-operated circuit-breakers have not been studied in any detail. However, assuming that it is possible to avoid flash-overs in a compact switch when rupturing fault currents at high altitudes, the weight penalty is estimated at approximately 75%.

Appendix E

TYPES OF POWER CONVERTOR PROPOSED FOR MOTORS AND SECONDARY DC SUPPLIES

(see section 2(c))

E.1 Electric motor drive units

A dc commutator motor could be energised directly from the dc supply without the need for an intermediate stage of power conversion, and would be lighter than a combined ac motor and invertor. However the use of a continuously-running dc commutator motor operating directly from the 200 volt dc line would not be regarded as acceptable in high-altitude aircraft due to the danger of flashover, abnormal brush wear, and the cost of brush and commutator maintenance. A brushless type of motor would therefore be required for such applications. The invertor-fed ac induction motor would appear to be the best choice for brushless motor drives since the motor itself is cheap, robust, highly reliable and is the lightest type of ac motor.

The only serious alternative to the ac induction motor would be what is commonly referred to as the 'brushless dc motor', i.e. a permanent-magnet synchronous type motor, which, like the ac induction motor, would require a dc to ac power convertor. Besides this it would also require some form of rotor-position sensor to simulate the function of the commutator of the dc motor, which would increase its cost. Whilst the brushless dc motor might offer some marginal advantages over the ac induction motor in the smaller fractional horse-power sizes, the induction motor would be cheaper and would have a better power to weight ratio in the larger sizes.

When supplied from a square-wave source the induction motor has been shown[19] to function satisfactorily and with negligible loss of performance as compared with that obtained on a sinusoidal supply. The relatively unsophisticated square-wave invertor would then suffice for motor supplies.

It is a normal characteristic of electric motors that the starting current is much higher than the normal full-load current. The associated invertor must either be designed to provide this heavy current at a considerable weight penalty, and with a poor utilization factor under normal running conditions, or have some form of control to limit the current on starting. To limit the starting current of a dc motor would result in a decrease of starting torque, but in the case of the induction motor, by initially reducing the input frequency and voltage, the starting torque can be increased whilst the starting current is reduced.

Cooling of thyristors in the invertor is a severe problem in high-speed, high-altitude aircraft when the ambient air temperature is high (over 70°C) and its density is low. The heat-sink surface area and therefore the heat-sink weight increases rapidly with increasing ambient temperature and with falling air density. The heat-sink temperature has to be kept well below the maximum permitted junction temperature of the thyristors (125-150°C) due to the thermal impedances between the junction and the heat-sink. In aircraft applications the ambient temperature may well approach the limiting heat-sink temperature, and the required heat-sink surface area would then approach infinity. At high altitudes, due to the reduction of air density, the effectiveness of convective cooling is considerably reduced and it can be assumed that, except for low-power invertors, forced-air cooling or, where convenient, liquid cooling must be used. Forced-air cooling may not represent a severe burden in motor drives as the motor may have its own cooling fan which could also be used to draw air over the heat-sinks. Liquid cooling may conveniently be used for the invertors of fuel pump drives if the fuel temperature is not too high.

Based on experimental work and estimates by both manufacturers and R.A.E., the curve of Fig.3 has been constructed to show the relationship between the kVA ratings and the weights of invertors. The curve for the square wave invertor can be represented by:-

$$\text{Invertor weight} = 8.2\ (\text{kVA})^{0.55}\ \text{lb.}$$

In most normal applications the invertor would weigh about 1.6 times as much as a motor designed for a speed of 10000 rev/min.

In some applications, e.g. flying controls, the motor is required to deliver peak loads of some 3 to 4 times the normal load and the invertor must be rated for such peak loads.

The weight data are based on a maximum ambient temperature of 70°C under low-altitude conditions, with natural cooling.

E.2 Dc transformers

The dc transformer comprises a square-wave invertor, a transformer, rectifiers, and, when required, a filter. In order to minimise the weight of components, in particular the transformer, it is desirable to operate the invertor at a frequency of approximately 3 kHz. At this frequency a 1 kW dc transformer would weigh approximately the same as a similarly-rated 400 Hz transformer/rectifier unit (TRU). Larger TRUs are often designed with forced-air cooling of the transformer, which results in a reduction in the weight/power ratio. Forced-air cooling is unlikely to be of any benefit to the dc transformer (unless required for high-temperature and/or high-altitude environments) since the transformer itself contributes only a small fraction of its total weight, while the weight of the invertor may not be reduced, owing mainly to the added weight of the blower motor and its own invertor. Therefore, in the larger ratings, dc transformers would be heavier than equivalent TRUs. In the lower-power ratings, which would be widely used in electronic-equipment power packs, dc transformers are again heavier than their equivalent ac-fed power packs, owing to the fairly steeply increasing weight/power ratio of invertors as their rating falls (see Fig.3).

More detailed and accurate weight comparisons can really only be made on the basis of particular specifications, but generally it can be expected that in a typical 200 volt dc system there would be an increase in weight in respect of the use of dc transformers.

During the commutation sequence a voltage of approximately 2.3 times the supply voltage appears across thyristors. It is normal practice to allow a small safety margin and ensure that the thyristors are rated for at least $2.5 \times V_{max}$. In the 200 volt dc system transient line-voltage surges of up to 440 volts are envisaged under abnormal conditions, so that thyristors rated at 1100 volts would be required. Since it is desirable to operate invertors at 3 kHz to reduce transformer weight, fast-turn-off thyristors (e.g. 8 μs) would be needed.

The requirements of fast turn-off and high reverse voltage are not compatible, and suitable thyristors are not currently available. An attempt is being made by one manufacturer to select from production thyristors having the required attributes, but at the time of writing none has become available. If suitable thyristors cannot be obtained then the invertors must be designed to use 1100 volt devices with longer turn-off times. These would give an increased transformer weight owing to the need to run the invertor at a lower frequency.

Appendix F

WEIGHT COMPARISON BETWEEN 200 VOLT AC AND DC SYSTEMS

(see section 2)

In order to get realistic figures it was decided to base the comparison on the Concorde electrical system. However it must be borne in mind that the result should not be regarded as specifically for Concorde, because a much more detailed study of all aspects of a change from ac to dc power, including consumer equipment design, would be necessary before attributing figures to a specific aircraft.

As already stated the Concorde electrical system is extremely complex and of necessity many estimates and simplifications have had to be made in order to keep the exercise within reasonable limits. Only a detailed study of every circuit and every piece of equipment using electrical power can give an accurate picture of the full effect that a change from ac to dc will have on circuit layout, equipment design, or even the amount of ac power still required.

It has therefore been assumed for the purpose of this comparison that all utilisation circuits will remain fundamentally unchanged in both cases and that the cabling layout and switching control will be identical for ac and dc. It is also assumed that a small amount of 400 Hz ac power at 200 volts and 26 volts will still be required for certain services. In both cases utilisation equipment and cables which change in weight are the only ones considered. The 28 volts dc system is omitted from the weight comparison as it will remain unchanged whatever the type of primary power source.

The weights of the basic electrical systems shown in Figs.1 and 2, including C.S.Ds., utilisation switchgear and cables and motor invertors, are detailed in Tables 2 and 3.

The quantity of switchgear used in the Concorde ac system has had to be estimated from the total figures as a breakdown could not be obtained. Owing to the large variety of switchgear used it has been grouped, for simplification into three classes - protective, relays or contactors, and lever-operated switches. For the 200 volts dc system a suitable percentage weight increase has been added to each class.

In a similar way the ac cable weights have had to be estimated from the total cable weights. Furthermore, owing to the large variety of cable types and sizes used in Concorde, a simplification has had to be made by choosing a single cable of suitable rating and size for each circuit, based on the circuit current and the numbers of cables bunched together. Cable ratings due to bunching have been taken from B.S. Specifications[16,17,18] for standard cables and have been applied, for ac, to nyvin 10 and larger as three cables bunched or to minyvin 12 and smaller as twelve cables bunched; for dc, to nyvin 10 and larger as a single cable or to minyvin 12 and smaller as twelve cables bunched.

It is also possible to reduce the size of wiring to some 115 volts, single-phase, ac equipments when the voltage is increased to 200 volts dc. Only items consuming more than 460 VA (4 amperes) will benefit as the minimum practical size wiring would already be used where the consumption is less than 460 VA.

The need to use 200 volts dc brushless drives for all continuously-running duties such as fuel pumps, fans etc. will incur a weight penalty by the addition of square-wave invertors to the existing simple, ac squirrel-cage induction motors. Table 3 therefore records only the weight of such invertors.

Services such as engine and intake controls, instruments, navigation, radio aids, etc., when supplied by a 200 volt dc system, will require dc transformers and invertors for their internal needs. An estimate has been made from the prototype Concorde electrical load sheets of the amount of dc power at other than 200 volts, and the amount of 200 volts, three-phase, 400 Hz ac power, which would be required thereby. This is shown in Table 4 in the form of the amount of power, both ac and dc, which would be required from each of the four main and four essential busbars. Under the heading of ac invertors is also given the estimated weight of the separate invertors needed to supply such power from each bar, while under the heading of dc transformers is given the number of equipments fed from each bar with their total power requirement and the estimated increase in equipment weight due to the use of dc transformers within the units.

Table 5 gives the total weights of the 200 volt ac and dc systems, derived from Tables 2, 3 and 4. The figures given relate only to the primary power system. When the circuits and systems unaffected by the change in the primary power system from ac to dc (such as the 28 volts dc power system and many of the utilisation circuits) are added the total electrical system weight rises (in the Concorde) to about 7600 lb. This includes 3500 lb of cable and 1600 lb of fixed installation fittings, i.e. clips, ducting and panels. The weight of the secondary systems is unaffected by the change in the primary power system from ac to dc.

F.1 The use of fuses instead of manual circuit-breakers

In Concorde, manual circuit-breakers are used at the busbars for protecting utilisation circuits; this is quite usual in civil aircraft, although fuses are favoured in military aircraft. The different outlook is due mainly to the fact that in civil aircraft it is usually easier to provide more accessible siting of these items, for resetting, than it is in military aircraft. Unless resetting can be undertaken in the air, the general use of manual circuit-breakers is unwarranted. A direct comparison of ac circuit-breakers with their dc equivalents shows that the latter are 49 lb heavier (113 -(27.7 + 36.6) lb, see Tables 2 and 3). However Table 6 shows what happens to the weight of the utilisation-circuit protective gear when fuses are substituted, wherever practicable, in both the ac and the dc systems (manual circuit-breakers having to be retained for the three-phase circuits). The dc fuses are now 25 lb lighter than the ac.

Table 7 gives a breakdown of the weight differences between the ac and the dc systems, with the two methods of utilisation-circuit protection.

Appendix G

ARCING TESTS[4]

(see section 2(d))

An arcing gap of variable length was set up in a high-altitude chamber, using replaceable brass cylindrical electrodes of 1 inch diameter. Arcs were initiated by fusing strips of aluminium foil wired to the two electrodes. This method was not completely reliable, probably owing to fouling of the electrodes which made it necessary to replace them frequently and to repeat a negative result a number of times before accepting it as significant. The source of power was a Type 158 aircraft alternator, used in conjunction with a three-phase bridge rectifier for the dc tests. For the ac tests two lines were used. The open-circuit voltage across the gap was regulated to 200 volts in each case. The current was limited by a series resistance of approximately 1 ohm.

The test procedure was either, at a given altitude, to try a range of gaps to find the maximum at which a sustained arc could be formed or, at a given gap, to find the minimum altitude. A sustained arc is defined, somewhat arbitrarily, as one that persists for more than three seconds, since inspection of current and voltage oscillograms suggests that an arc which persists for that time is likely to persist indefinitely. Results of the dc tests are plotted in Fig.4. The broken line is the upper envelope of the points, so that for conditions to the right and below this line a sustained arc is liable to be formed while for conditions to the left and above this line a sustained arc is unlikely.

With a 200 volt, 400 Hz, ac supply it was not found possible to sustain an arc with any gap down to 1/16 inch even at altitudes of up to 80000 ft.

Table 1

ESTIMATES OF WEIGHT, VOLUME AND COST FOR DC AND AC SWITCHGEAR OF EQUIVALENT RATINGS

Ambient temperatures up to 85°C

Altitudes up to 70000 ft

Rating	Type of switch	Weight lb	Volume in^3	Cost £
200 V, 10 A, 2 kW, dc	Multigap (8 gaps)	0.22	3.3*	5
	Mechanical with forced commutation	2.2	45	15†
	Thyristor	4.0	580	21†
	Thyristor with back-up contacts	1.4	27	21†
115 or 200 V, 2.5 kVA, ac	Lever-operated switch	0.11	1.7*	2.4
200 V, 100 A, 20 kW, dc	Deion grid (4 gaps)	4.0	96	120
	Mechanical with forced commutation	11	240	69†
	Thyristor	20	1700	150-200†
	Thyristor with back-up contacts	16	420	160†
200 V, 25 kVA, ac	Contactor	2.8	63	80

* Body only, excluding operating lever.

† Excludes assembly costs and overheads.

Table 2

EQUIPMENT WEIGHT FOR THE 200 VOLT, THREE-PHASE, AC SYSTEM

Equipment	Current amps	Quantity	Unit wt lb	Total wt lb
Generating system				
Constant-speed drive	-	4	79	316
Constant-speed drive controller	-	4	2.5	10.0
Generator 60 kVA	175	4	86	344
Control and regulator unit	-	4	8	32
Current transformers	175	8	1.1	8.8
Contactor, three-phase	175	11	4.25	46.8
Contactor, three-phase (De-ice isolation)	75	4	3.0	12.0
Contactor, three-phase changeover	35	4	3.1	12.4
Contactor, three-phase for TRU	25	4	1.3	5.2
Circuit-breaker, three-phase manual	35	8	0.33	2.6
Circuit-breaker, three-phase manual	25	4	0.33	1.3
Transformer, 26 V ac 1400 VA	54 output	2	3.11	6.2
Transformer rectifier unit, 28 V dc	150 output	4	15.5	62.0
Alternator, 30 kVA emergency	86	1	55	55.0
Circuit-breaker, single-phase manual	15	2	0.092	0.2
Switch, on/off (C.S.D. disengage)	10	4	0.092	0.4
Switch, on/off (B.T.C. operate)	10	4	0.092	0.4
Switch, on/off (emergency changeover)	10	4	0.092	0.4
Control unit (ground power, phase sequence)	-	1	5.0	5.0
Cables		Cable size	Wt per 100 ft	
Cable for main alternators	175	Uniefglas 0 Nyvinal 00	39.0 20.2	187 267
Cable for instruments	-	Minyvin 22	0.34	10
Cable for ground power	175	Nyvin 0	37.6	21
Cable for distribution (sub-feeders)	25	Minyvin 12	2.36	30
Cable for TRU supply	14.5	Minyvin 12	2.36	23
Cable for emergency generator	86	Nyvin 6	10.7	34
Cable for transformer 115/26 V	13	Minyvin 12	2.36	7
			TOTAL	1500
Switchgear in utilisation circuits (ac only)				
Circuit-breaker, single pole	3 to 35	301	0.092	27.7
Circuit-breaker, three-pole	1 to 35	111	0.33	36.6
Contactors and relays, various	2 to 60	185	From 0.042 To 2.9	62.6
Switches, lever-operated, various	10	157	From 0.092 To 0.198	20.3
			TOTAL	147.2

Table 2 (Contd.)

Equipment		Current amps	Quantity	Unit wt lb	Total wt lb
Cable in utilisation circuit			Cable size	Wt per 100 ft	
Rain dispersal	three-phase	3.4	Minyvin 22	0.34	3
Windscreen anti-ice	three-phase	9.6	" 14	1.59	9
Wing and intake de-ice supply	three-phase	46	Nyvin 10	4.33	102
Wing and intake mats, cyclic	three-phase	40.5	" 10	4.33	107
Wing and intake mats, continuous	three-phase	51.5	" 8	6.67	52
Windscreen heater	single-phase	11.0	Minyvin 14	1.59	1
Air intake sensor heater	single-phase	12.3	" 14	1.59	24
Window de-misting	three-phase	2.0	" 22	0.34	3
Engine feed pumps (2.5 kVA)	three-phase	7.2	" 14	1.59	52
Main tank pumps (2.5 kVA)	three-phase	7.2	" 14	1.59	76
Trim pumps (5.8 kVA)	three-phase	16.8	Nyvin 10	4.33	34
Scavenge and No.7 tank pumps (1.2 kVA)	three-phase	3.5	Minyvin 20	0.51	13
Fuel flow and reheat (assume 50% total as three-phase)		0.84	" 22	0.34	54
Map display	three-phase	0.72	" 22	0.34	1.5
High frequency	three-phase	0.46	" 22	0.34	1.5
Loran	three-phase	0.94	" 22	0.34	1.5
Humidity	three-phase	14.4	" 12	2.36	2.0
Fans 1 and 2 forward	three-phase	5.1	" 20	0.51	8.0
Fans 3 forward and rear	three-phase	1.1	" 22	0.34	
Inertial platform heater	three-phase	2.9	" 22	0.34	1.0
Reheat ignition	single-phase	7.0	" 16	0.97	23.0
Landing lamp	single-phase	8.7	" 14	1.59	1.2
Taxi lamp	single-phase	5.2	" 20	0.51	4.0
Cabin lights	single-phase	4.5 3.7	" 20	0.51	15.0
Intake supplies	single-phase	5.2	" 20	0.51	82.0
				TOTAL	671.0

Continuously running motors		
Engine feed pumps (2.5 kVA)	12	Identical ac motors used on both ac and dc. Additional invertor weight for dc supply given in Table 3.
Main tank pumps (2.5 kVA)	12	
Trim pumps (5.8 kVA)	4	
Scavenge and No.7 tank pumps (1.2 kVA)	6	
Fans 1 and 2 forward (1770 VA)	2	
Fans 3 forward and rear (373 VA)	4	
Vacuum pump (58 VA)	2	
G.T.S. fuel pump (400 VA)	2	
Windscreen wiper pump (1170 VA)	2	

Table 3

EQUIPMENT WEIGHT FOR THE 200 VOLT DC SYSTEM

Equipment	Current amps	Quantity	Unit wt lb	Total wt lb
Generating system				
Generator 50 KW	250	4	105	420
Control and regulator unit	-	4	8	32
Transductors	250	8	1	8
Contactor, double pole	1 at 200 1 at 50	1	7	7
Contactor, three pole	1 at 187 2 at 155	1	15	15
Contactor, single pole (for de-ice isolation)	130	4	5	20
Contactor, single pole	30	4	1.8	7.2
Diode	250	4	16	64
Diode	35	8	3.5	28
Fuse size 5	200	4	0.5	2.0
Fuse size 2	50	8	0.3	2.4
Fuse size 0	25	4	0.07	0.3
Fuse size 0	15	2	0.07	0.1
Dc Transformer, 28 V	150 output	4	22	88
Invertor, 26 V ac 1400 VA	54 output	2	50	100
Emergency generator 25 KW	125	1	60	60
Cables		Cable size	Wt per 100 ft	
Cable for main generators	250	Uniefglas 00 Nyvinal 000	51 24.8	82 109
Cable for instruments	-	Minyvin 22	0.34	3.5
Cable for ground power	250	Nyvin 00	48.9	9.1
Cable for distribution (sub-feeders)	35	Nyvin 10	4.33	18.5
Cable for dc transformers	25	Nyvin 10	4.33	13.9
Cable for invertors	8.5	Minyvin 14	1.59	4.8
Cable for emergency generator	125	Nyvin 4	16.9	17.8
			TOTAL	1113
Switchgear in utilisation circuits (200 V dc only)				
Manual circuit-breakers, single pole	1 to 70	412	75% increase	113
Contactors and relays, various	2 to 80	185	50% increase	93
Switches, lever-operated, various	10	157	100% increase	40
			TOTAL	246
Cable in utilisation circuits		Cable size	Wt per 100 ft	
Rain dispersal	5.9	Minyvin 18	0.8	2.1
Windscreen anti-ice	16.7	Nyvin 10	4.33	8.0
Wing and intake de-ice supply	80.0	Nyvin 8	6.67	53
Wing and intake mats, cyclic	70.0	Nyvin 8	6.67	55

Table 3 (Contd.)

Equipment	Current amps	Quantity	Unit wt lb	Total wt lb
Cable in utilisation circuits (Contd.)		Cable size	Wt per 100 ft	
Wing and intake mats, continuous	89	Nyvin 6	10.7	28.5
Windscreen heater	6.7	Minyvin 16	0.97	0.6
Air intake sensor heater	7.1	Minyvin 16	0.97	14.5
Window de-misting	3.5	Minyvin 22	0.34	1.0
Engine feed pumps (2.0 KW)	10.0	Minyvin 14	1.59	17.3
Main tank pumps (2.0 KW)	10.0	Minyvin 14	1.59	25.3
Trim pump (4.7 KW)	23.5	Nyvin 10	4.33	11.3
Scavenge and No.7 tank pumps (0.96 KW)	4.8	Minyvin 20	0.51	4.3
Fuel flow and reheat (assume 50% total at 200 V dc)	1.4	Minyvin 22	0.34	18.0
Map display	1.0	Minyvin 22	0.34	0.5
High frequency	0.64	Minyvin 22	0.34	0.5
Loran	1.3	Minyvin 22	0.34	0.5
Humidity	25	Nyvin 10	4.33	1.2
Fans 1 and 2 forward	7.1	Minyvin 16	0.97	4.0
Fans 3 forward and rear	1.5	Minyvin 22	0.34	
Inertial platform heater	5.0	Minyvin 20	0.51	0.5
Reheat ignition	4.0	Minyvin 22	0.34	8.0
Landing lamp	5.0	Minyvin 20	0.51	0.4
Taxi lamp	3.0	Minyvin 22	0.34	2.7
Cabin lights	1.95	Minyvin 22	0.34	10.0
	1.58	Minyvin 22	0.34	10.0
Intake supplies	2.4	Minyvin 22	0.34	54.0
Earth cables (for earthing 200 V dc equipment)	-	Various	-	60.0
			TOTAL	381
Invertors for continuously running motors			Invertor wt only	
Engine feed pumps (2.0 KW)	10.0	12	13.5	163
Main tank pumps (2.0 KW)	10.0	12	13.5	163
Trim pumps (4.7 KW)	23.5	4	22	88
Scavenge and No.7 tank pumps (0.96 KW)	4.8	6	9	54
Fans 1 and 2 forward (1416 W)	7.1	2	11.5	23
Fans 3 forward and rear (300 W)	1.5	4	4.8	19.2
Vacuum pump (46 W)	0.23	2	1.7	3.4
G.T.S. fuel pump (320 W)	1.6	2	5	10
Windscreen wiper pump (936 W)	4.7	2	9	18
			TOTAL	542

Table 4

WEIGHT OF INVERTORS TO SUPPLY 200 VOLT, THREE-PHASE, 400 Hz, AC FROM 200 VOLT DC, AND INCREASE IN EQUIPMENT WEIGHT WHEN USING DC TRANSFORMERS

Busbars	Ac invertors		Dc transformers within equipment		
	Total VA required	Weight lb	Number of equipments	Total watts required	Weight increase
Main 1	1465	45	7	779	8.6
Main 2	307	15	6	548	7.1
Main 3	909	33	8	770	9.5
Main 4	1190	40	12	749	12.1
Essential 1	871	33	8	880	9.4
Essential 2	250	11	6	231	4.3
Essential 3	500	22	4	640	5.1
Essential 4	240	11	5	223	3.8
	TOTAL	210		TOTAL	59.9

Table 5

TOTAL WEIGHTS OF 200 VOLT AC AND DC SYSTEMS

200 V three-phase ac	Weight lb	200 V dc	Weight lb
Generating system	1500	Generating system	1113
Utilisation switchgear	147	Utilisation switchgear	246
Utilisation cable	671	Utilisation cable	381
		Invertors for motors	542
		Invertors for 200 V ac	210
		Increased equipment weight for dc transformers	60
TOTAL	2318	TOTAL	2552

Table 6

WEIGHT COMPARISON OF UTILISATION-CIRCUIT PROTECTIVE GEAR USING FUSES WHERE POSSIBLE

Ac system				Dc system			
Item	Qty	Unit wt lb	Total wt lb	Item	Qty	Unit wt lb	Total wt lb
Manual C.B. 3-phase	111	0.33	36.6	Fuse size 0	320	0.011	3.52
Fuse size 0	250	0.011	2.75	Fuse size 2	62	0.066	4.1
Fuse size 2	51	0.066	3.35	Fuse size 3	30	0.33	9.9
Fuse holder 10 way	25	0.11	2.75	Fuse holder 10 way	32	0.11	3.52
		TOTAL	46			TOTAL	21
All manual C.Bs. (ac)		TOTAL	64	All manual C.Bs. (dc)		TOTAL	113

Table 7

BREAKDOWN OF WEIGHT DIFFERENCES

Item	Ac system lb	Dc system lb
Constant-speed drives	+316	not requd.
Generators (4 main + 1 emergency)		+81
Control gear and regulator (including C.S.D. control gear)	+16	
Switchgear for generating system (including contactors, diodes, fuses, switches)		+64
Secondary supplies (invertors and transformers) 26 V ac, 28 V dc		+120
200 V ac	not requd.	+210
Generator system cabling	+320	
Utilisation switchgear and protection with:-		
(A) manual C.Bs. for both ac and dc systems		+99
or (B) 3-phase manual C.Bs. and single-phase and 200 V dc fuses		or +25
Cable in utilisation circuits	+290	
Invertors for motors	not requd.	+542
Weight increase in equipment due to use of dc transformers	not requd.	+60
Totals with A	+942	+1176
Totals with B	+942	+1102

Dc system 234 lb heavier with protective gear A.

Dc system 160 lb heavier with protective gear B.

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Further papers are being prepared by the R.A.E. relating in more detail to certain aspects of equipment for the 200 volt dc system. The subjects will include:-

(a) Some notes on the design and performance of medium-voltage brushless dc generators.

(b) Some notes on the factors affecting the design and weight of power-conversion equipment.

Legend

BTC	Bus tie contactor
CB35	Manual circuit-breaker 35amp
CB25	Manual circuit-breaker 25amp
CB15	Manual circuit-breaker 15amp
COC	Change-over contactor
EBB	Essential busbar
GCC	Generator control contactor
GPC	Ground power contactor
MBB	Main busbar
SSC.	Split system contactor
T	Transformer 115/26 volt ac
TRC	Transformer-rectifier contactor
TRU	Transformer-rectifier unit

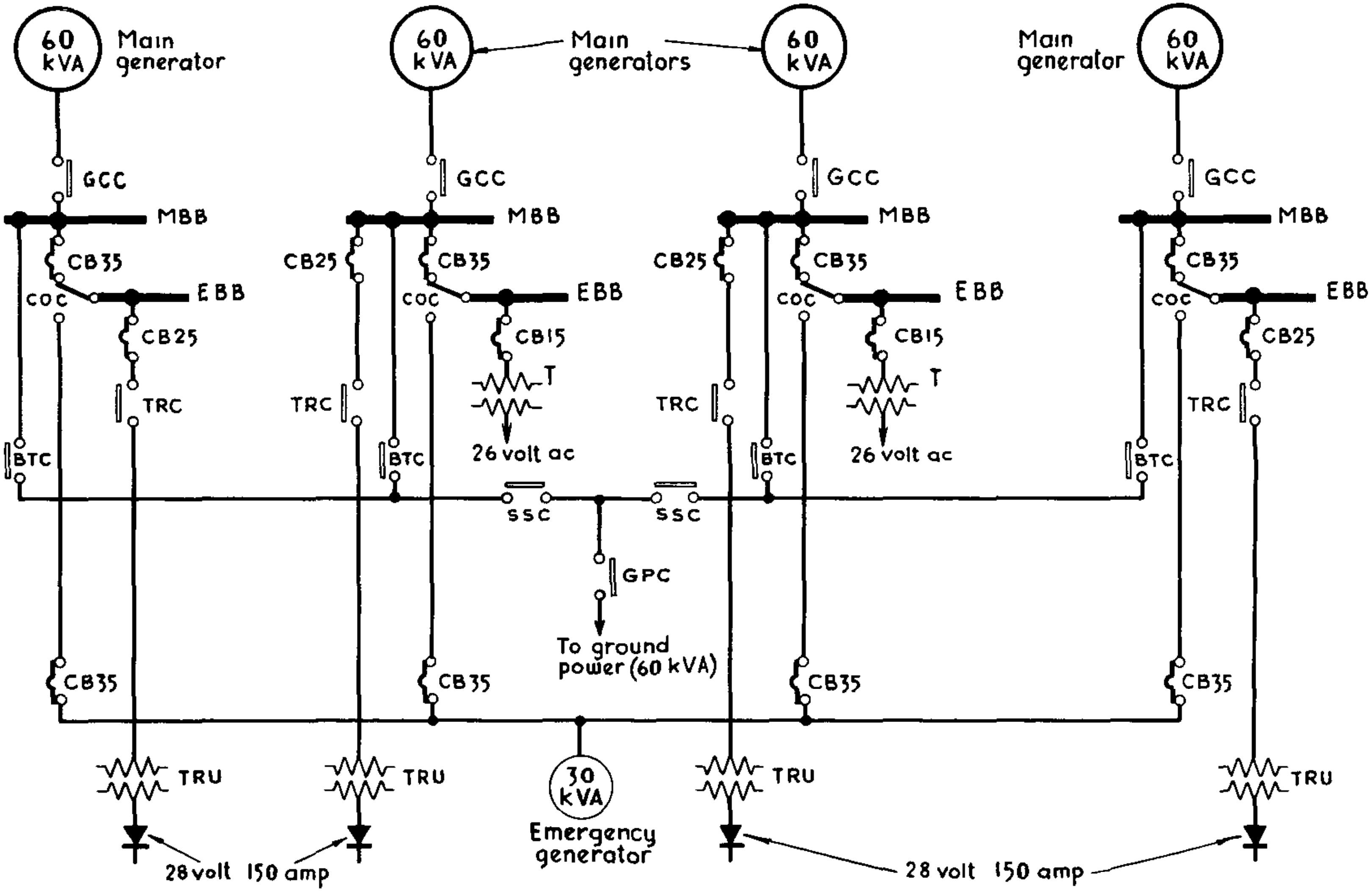

Fig. 1 Typical 4 generator system, 200 volt ac, based on Concorde

Legend						
D250	Diode 250 amp	F50	Fuse 50 amp	MBB	Main busbar
D35	Diode 35 amp	F25	Fuse 25 amp	OLC	Overload contactor
EBB	Essential busbar	F15	Fuse 15 amp	T	Transformer 200/28volts dc
F200	Fuse 200amp	GPC	Ground power contactor	TC	Transformer contactor

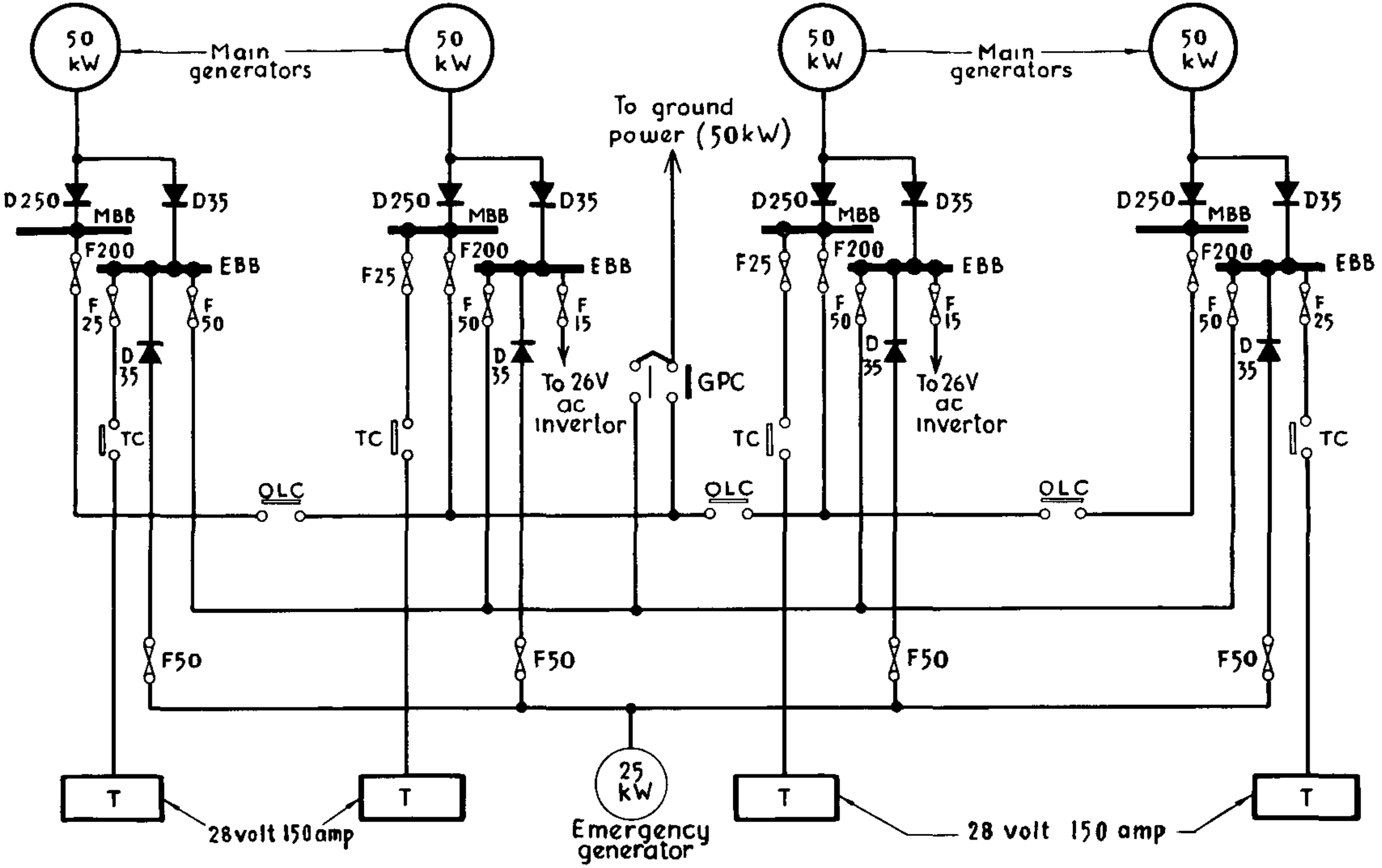

Fig.2 Typical 4 generator system 200volt dc, equivalent to Fig.1

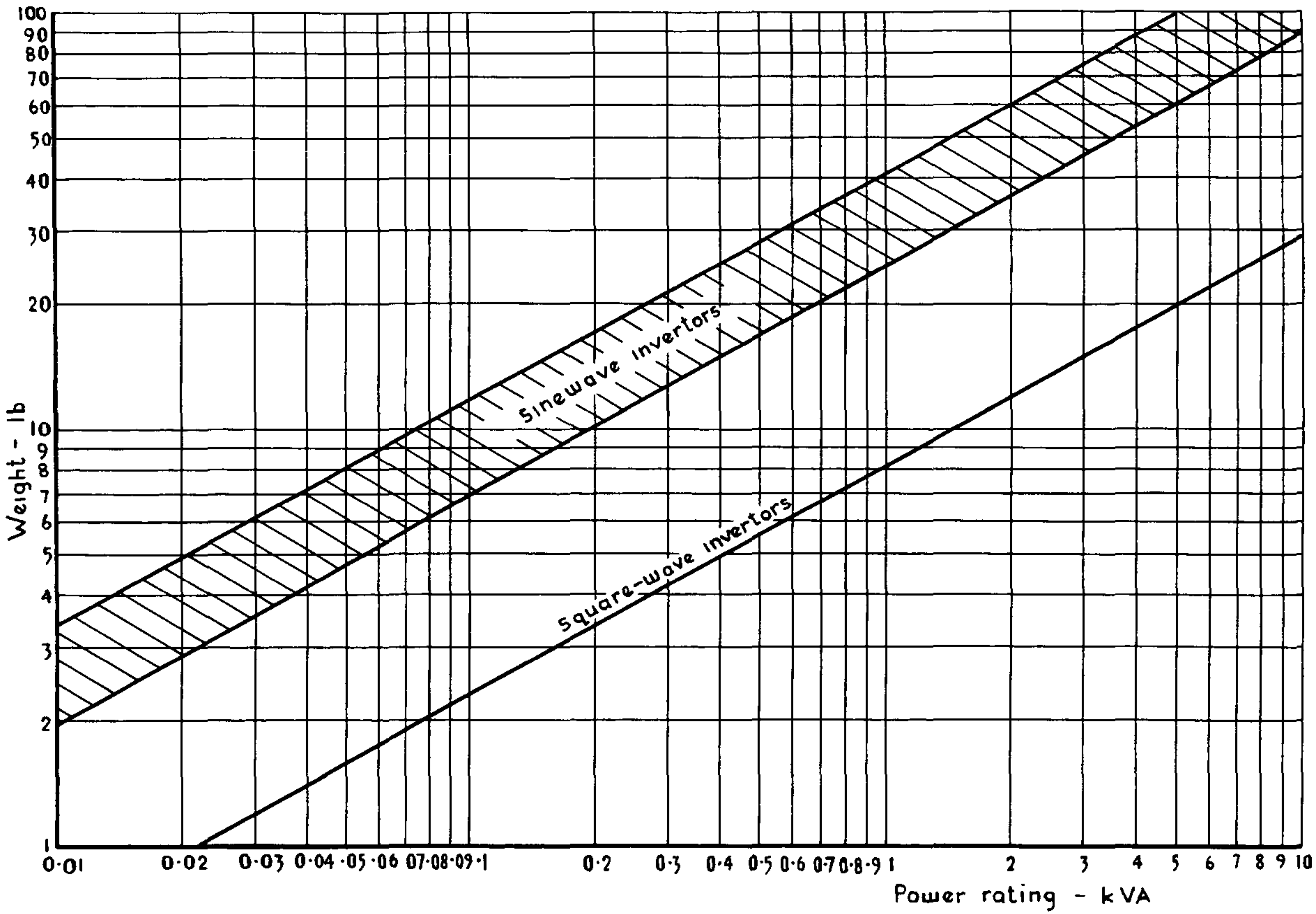

Fig.3 Variation in static invertor weight with power rating (low altitude, 70°C ambient)

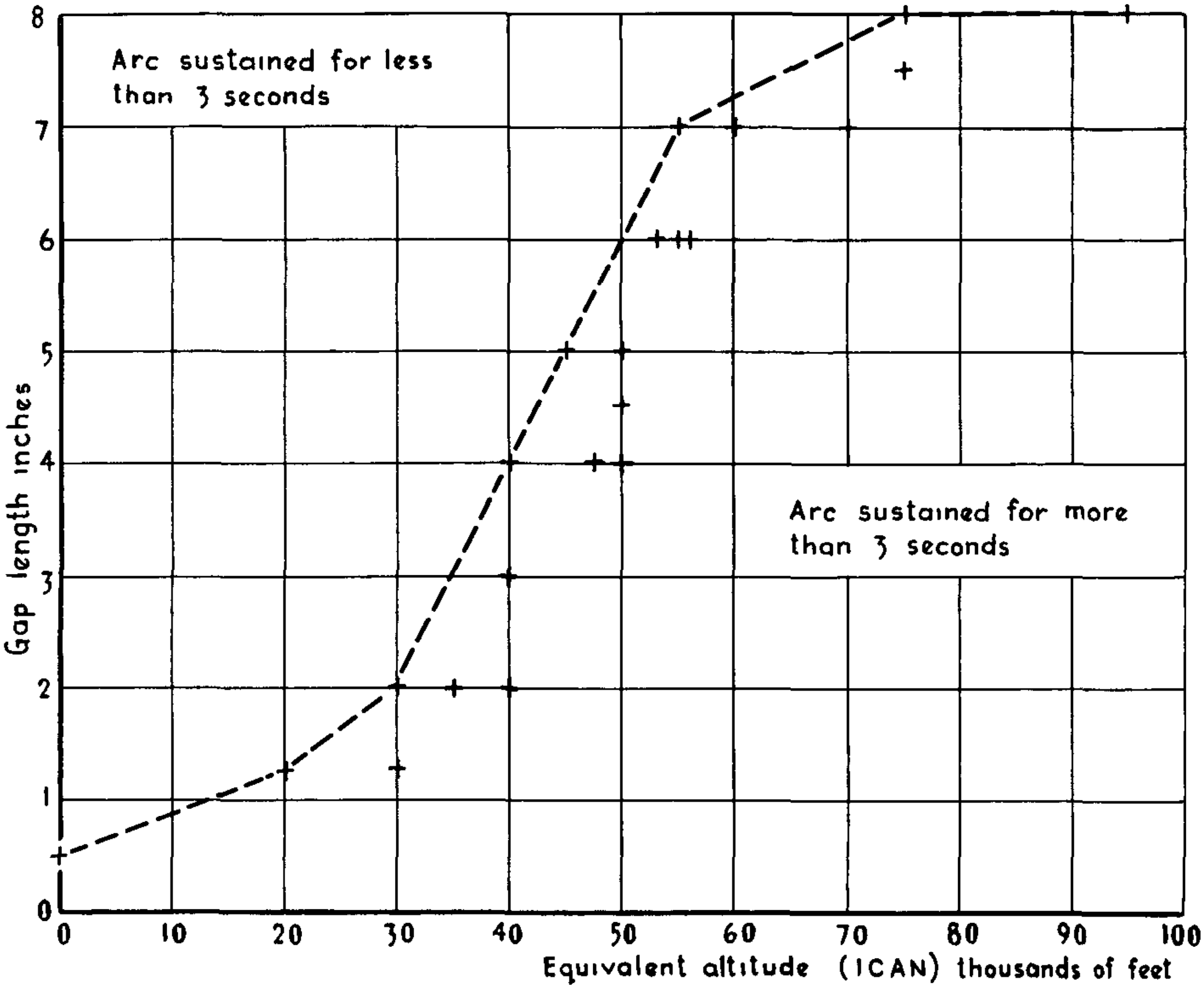

Fig. 4 Length of sustained dc arcs vs altitude

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Division of Engineering Physics Department

A FEASIBILITY STUDY ON A 200 VOLT, DIRECT CURRENT,
AIRCRAFT ELECTRICAL POWER SYSTEM

For comparative purposes, a 200 volt dc system for a large modern commercial aircraft has been designed and its weight compared with that of a conventional three-phase ac system. To obtain necessary design information, studies have been made of a 50 kW brushless dc generator, the problem of circuit interruption, conversion equipment and brushless motors. The vulnerability of the system due to the possibility of sustained arcs during fault conditions has also been examined.

It is concluded that until considerable weight reduction can be achieved in the design of conversion equipment and brushless motors, the dc system will not be lighter than the ac system.

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(over)

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