RADIO INTERFERENCE FROM CAR IGNITION SYSTEMS

by

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ABSTRACT

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Radio Frequency Interference from vehicle ignition systems presents a problem both for the vehicle user and for those external to the vehicle. The pollution of the electromagnetic spectrum causes disruption of communications reception in terms of quality and reliability. The object of this interference study is to compare the various types of ignition interference suppression components currently available and to isolate the various parts of the ignition system that produce the most persistent interference.

Two methods of approach are undertaken. In one, the earth current of an ignition system was monitored under laboratory conditions, and in the other a similar system was used inside a Ford Capri and the antenna voltage monitored. In both cases results were taken on Long, Medium and V.H.F. wavebands.

Various voltage measurements were taken to gain insight into the production of interference during spark gap breakdown.

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CHAPTER 1

INTRODUCTION

1.1 Incompatibility

The first reported interference problem from a car ignition system appears to have occurred in 1902[1,2], though no difficulty was thought to exist at the time because the scarcity of automobiles and transmitter/receivers produced little interaction. However, between the two World Wars development of electrical and electronic apparatus mushroomed due to technical breakthroughs in the design of valves, and electrical power generation and transmission. It became apparent that radio frequency interference was an increasing problem with complex communications systems and deserved proper definition and control.

A discussion on the subject was held by the Institute of Electrical Engineers in 1933. A committee entitled "Committee on Radio Interference" was formed by the I.E.E. in 1937. In the same year C.I.S.P.R. (Comité International Special des Perturbations Radio-electriques) was formed to ensure international collaboration in interference specifications and instrumentation control. C.I.S.P.R. recommendations have in the majority of cases been adopted by United Kingdom Regulations and British Standards.

Electromagnetic Compatibility[3] is defined as the ability of a system to work satisfactorily under the influence of external electromagnetic effects. This new term in engineering has arisen to define the satisfactory operation limit of communications and other equipment.

1.2 The Problem of Radio Interference

Man-made Radio Frequency Interference is the unwanted by-product of electrical and electronic technology. Its effect upon the electromagnetic spectrum is similar to the effect environmental pollution has upon our lives. The degradation in quality of radio reception reduces the efficiency and capacity of the communication system. There are four categories of man-made interference sources:

(i) Co-channel. Two independent signals sharing the same frequency allocation.

(ii) Spurious. Out-of-hand transmission from communications systems.

(iii) R.F. heating. Radiation from diathermy, plastic welding and cooking apparatus, etc.

(iv) Electric arc. Inadvertant R.F. energy released from car ignition systems, electric motors, etc.

The fourth category represents the research topic of this thesis. Radio frequency interference from car ignition systems is impulsive in nature and resists most forms of suppression. There are three avenues of action, two of which are normally necessary to provide adequate suppression. These are:

(a) Action at source of interference. Usually adequate.

(b) Intermediate suppression along signal path. Used if a. provides unsatisfactory results.

(c) Action at reception of interference. With a. and b. optimum results are obtained.

Avenue a. entails suppressing the spark gaps from interference generation, b. is provided by the metal construction (e.g. body) surrounding the ignition system. Action at the receiver, c., may be by special antenna configurations or by electronics[4] to alter reception characteristics during interference bursts.

The object of this research into radio interference from car ignition systems was to measure and compare the various types of ignition suppression components currently available on the motor vehicle market.

An interference reference level is measured for three wavebands (Long and Medium Wave, and V.H.F.) after which the suppression combination is altered and the change in interference level duly recorded. As the measurement systems are atypical, absolute measurement is unnecessary. The relative effectiveness of the choice of suppression components provides evidence as to the character and mechanism of ignition interference generation and propagation. Two different approaches were undertaken to provide results to achieve this goal. The methods provide measurements from a different characterisation of the ignition system. One facilitates the measurement of radio frequency earth current generated from a laboratory mounted ignition system (Earth Cone) and the other monitors ignition interference from a motor vehicle by way of the vehicle aerial (Ford Capri) (see Chapter 5).

The cost of interference suppression is of importance[5] to vehicle manufacturers for they have to bear the extra expense. It is in their interest to find the most efficient combination of suppressors both for suppression and cost (see Section 4.4).

CHAPTER 2

VEHICLE INTERFERENCE

2.1 The Suppression of Vehicle Interference

If a comparison were made between the average transmitted power levels of radio stations in the United States of America and Great Britain, it would be found that the U.S.A. transmitted significantly higher power levels throughout the communications wavebands. This increased available signal strength produces a greater immunity of received signal from undesired co-channel (narrow band) and broadband interference. Vehicle mounted receivers in Great Britain have to produce acceptable results[6] with a lower signal strength, and are more susceptible to radio frequency interference (R.F.I.). It is desirable to achieve a higher degree of suppression in British vehicles even though the various interference sources have been suppressed below the recommended external levels (see Section 2.3).

In the U.S.A. reduction of vehicle interference has been aided through radio frequency bonding[7,8,9] (earth braids) of the chassis, engine, bodywork, etc., to inhibit any part of the vehicle raising its R.F. potential above that of the mean vehicle earth. Bonding decreases the secondary radiation by increasing the screening effect of the bodywork and associated metal panels. There is a practical limit to the efficiency of bonding due to the vehicle body screen being far from complete. By increasing the number of R.F. bonds a trend of diminishing returns is found[5]. It must also be borne in mind that the reliability and effectiveness of the earth bonding straps is dependent upon the bond to metal earth connection which deteriorates with time unless a low potential galvanic series metal[10] is used, but the expense may be prohibitive.

R.F. bonding does not necessarily reduce interference levels to those required for satisfactory receiver performance in Great Britain, even when used in combination with suppression at the interference source, the primary radiator.

A list of primary interference radiators is given in Table 2.1[8,11]. Here detected sound characteristics may be used to determine the source of interference in conjunction with an A.M. or F.M. receiver. Table 2.2 provides a list of possible secondary interference radiators which may be R.F. bonded to reduce their radiative effect.

Most forms of primary sources of interference are resolved by the application of a suitable low pass frequency filter network[12] across the radiative terminals of the involved apparatus. No difficulty in achieving adequate suppression should arise if the following points are borne in mind:

(i) Individual filter components must work adequately at the highest frequency ranges involved.

(ii) All filter leads must be as short as possible.

(iii) The earthing point of the filter must be mechanically rigid and provide a good R.F. earth connection.

Radio interference from wheels and tyres occurs during dry weather and is caused by static electricity build up and subsequent discharge. This may be cured by earthing the wheels via spring connections to the chassis and by painting the wheels[13] with a special conductive paint.

An indication of the difficulties[7,14] of ignition interference suppression can be found by considering the variety of commercial suppressors available for each part of the ignition system (see Table 2.3[15]). It is possible with suitable component combinations to reduce interference to satisfactory levels as laid down by governmental regulations. However no general rule is available for optimum reduction of ignition interference for optimum cost. Ignition interference is the most prominent form of electromagnetic disturbance even from the most "quiet" vehicles.

2.2 In-Car and External Interference

Vehicle interference affects two kinds of radio receiver users, those inside the vehicle and those within the interference zone surrounding the vehicle. In-car interference is primarily due to pickup from the car aerial which is transferred with normal radio emissions to the vehicle tuner. External interference effects concerns direct radiation from the vehicle body, etc. See Table 2.4 for possible secondary factors of in-car and external interference.

If there exists a point source of interference, one would expect that suppression would bring about equal reductions from in-car and external measurements if conductive and radiative (both electric and magnetic fields) effects were similarly suppressed. However, if the source cannot be represented in such a simple fashion, the different coupling mechanisms would vary over its surface. This leads to different suppression results[16]. Consider the H.T. circuit of the ignition system, the major contributor to vehicle interference. The circuit extends for approximately a metre around the engine compartment with an interference source at each end, i.e. the distributor and the spark plugs. One of these may be more closely coupled to the car aerial system (via bonnet, etc.) than the other which may influence external interference. Thus ignition interference suppression may not render equal suppression for the two measurement regions, and for completeness both methods should be used to ensure complete suppression in all aspects of vehicle interference.

2.3 Interference Measurement Standards

Various measurement techniques have been designed to monitor interference from in-car and external vehicle tests.

External measurements are required by British governmental regulations to be within certain limits. These are covered[17] by British Statutory Instruments (B.S.I. 2023/1217); "The Wireless Telegraphy (Control of Interference from Ignition Apparatus) Regulation 1952/1973"; and by British Standard 833:1970 "Specification for Radio Interference Limits and Measurements for Electrical Ignition Systems of Internal Combustion Engines". In an effort to standardise instruments and measurement procedures various international bodies have their own recommendations. Examples are the International Special Committee on Radio Interference (C.I.S.P.R. Recommendation 18/2)[18] which is part of the International Electrotechnical Commission (I.E.C.), and the United Nations Economic Commission for Europe (E.C.E. Regulation 10)[19].

The motor industry of the U.S.A. is exceedingly conscious of interference problems and manufacturers are directed by various interference measurement procedures from such bodies as the Society of Automotive Engineers (S.A.E. Standard J551C)[20], and the Institute of Electrical and Electronics Engineers (I.E.E.E. Standard 263)[21]. The actual interference limits and instrumentation techniques for these standards are different[22], but their respective aims are similar - to reduce the amount of radiation from motor vehicles to such an extent that reception of broadcast transmissions are not impaired. See fig. 2.1[23] for comparison of national field strength limits as found in the year 1961.

Table 2.6[18] indicates a few of the available external interference measurement procedures. The procedure consists of positioning the vehicle in a clear, reflection free site and measuring radiation levels by means of an antenna (dipole, discone etc.) positioned at set horizontal and vertical distances. The obvious disadvantages are that the antenna is liable to be in the near field zone for low frequencies which may confuse results[21] and it is difficult to position the antenna in the maximum radiation lobe of the interference. The antenna response at high frequencies (∿100MHz) is affected by ground reflections. However complete characterisation of a radiating vehicle in three dimensions as well as frequency is impractical, and compromises are necessary.

In-car interference tests require a different approach, measurement procedures[24] are implemented by motor manufacturers themselves to determine if vehicle receiver efficiency is reduced by radiation pickup from the antenna, etc. The antenna lead is connected to a standard length of 50Ω coaxial cable which connects to an R.F.I. measurement receiver. The Ford Motor Company employs such a system with a C.I.S.P.R. recommended receiver[5] (Table 2.5). A measured interference level of 26dB, relative to 1μv, indicated by the receiver is considered as the limit for adequate reception. This procedure is similar to the Ford Capri measurement system reported in section 5.1.

2.4 Broadband Interference Measurement

Radio frequency interference is usually termed as narrowband or broadband in nature. The former concerns one frequency source, e.g. local oscillator, and the latter a complete spectrum excitation, e.g. commutator arc. The nature of R.F.I. from vehicle ignition systems is broadband. Such interference is referred to as noise for the source energy Fourier components are spread over a complete frequency range in a similar manner to "white noise".

A mathematically convenient method of describing broadband noise phenomena is by means of an amplitude probability distribution function. Graphically this is approached by plotting signal level with the probability that this level will be exceeded for a specific frequency and bandwidth.

The amplitude probability distribution of ignition noise is well documented[25,26,27,28] (see fig. 2.2[22]).

The measurement of narrow and broadband signals involves the specification[29] of:

(i) Measurement frequency.

(ii) Logarithmic/linear amplitude measurement.

(iii) Intermediate frequency bandwidth.

(iv) Signal detection method.

The first two specifications are applicable to both types of interference, but the others have particular importance in the measurement of broadband signals.

The bandwidth of measurement determines the amount of signal energy accepted by the measurement receiver and hence the indicated signal level. The response of the receiver effective bandwidth (normally that of the intermediate receiver amplifier) outside the 3dB bandwidth must be taken into consideration for this contributes to the indicated signal level[30]. If $G(f)$ is the equivalent voltage transfer function of the filter, the impulse bandwidth is given by $\int_0^\infty |G(f)|^2 \, df$[31], where f is the frequency variable. The 6dB bandwidth of most filters may be used as an approximation to the impulse bandwidth. For synchronously tuned I.F. filters this has been measured to be a factor of 1.5 greater[44] than the 3dB bandwidth. The Marconi TF2370 spectrum analyser, used in the following experiments, was measured to have such a ratio of between 1.23 and 1.35 (see Section 4.2).

Detection of broadband interference is by one of the following methods[29]:

(i) Peak (maximum amplitude).

(ii) Quasi-peak (weighted peak).

(iii) Average (voltage or logarithm).

(iv) Root mean square (power).

The modes of detection bear a relation to the amplitude probability density function (see fig. 2.2). Results taken using one of these detection modes may give a truer representation of the effect interference may have upon communications equipment. All modes of detection are affected by bandwidth.

Peak and quasi-peak detection are most widely used. Peak detection is by record of maximum amplitude disturbance and is dependent upon period of measurement. Quasi-peak detection involves a weighted average that is sensitive to peak disturbance (and a small dynamic range below this) and the disturbance repetition rate. Average measurement is by electronic averaging techniques. Root mean square measurement is difficult to achieve and is not normally used.

Bandwidth controls the amount of energy directed toward the receiver detection circuits. Power measurement varies as 10 log (Bandwidth Ratio). A similar relationship holds for root mean square and peak detection, but is increased by a factor 2 to account for the voltage variable. The peak detection circuits of the TF2370 spectrum analyser (and most others) are weighted to give a power indication which is correct for narrowband signals. Results are given in power relative to 1 milliwatt into 50Ω (dBm), and vary as 20 log (Bandwidth Ratio) (see Section 4.2).

TABLE 2.1

Primary sources of R.F.I. from motor vehicles. Audible characteristics included.

Ignition System	-	Crackle sound. Related to engine speed, stops instantly when ignition is switched off.
Generator/Alterator	-	High pitched whine. Does not stop instantly when ignition is switched off.
Regulator	-	Irregular rasping sound. Does not stop instantly when ignition is switched off.
Windscreen Motor and other Brush Type Motors	-	Irregular crackle. Occurs when motor is switched on.
Dashboard Instruments	-	Irregular hissing/crackling sounds. Varies with jarring of dashboard.
Indicators	-	Clicks. When activated.
Wheels and Types	-	Irregular hiss. Varies with road condition during dry weather.

TABLE 2.2

Secondary sources of R.F.I. which accentuate primary interference.

Engine	-	Corners of engine block, air cleaner, distributor shaft, control cables, battery cable.
Chassis	-	Struts, exhaust system, axles.
Body	-	Bolted wings, bumpers, engine grill.

TABLE 2.3

Ignition Interference Suppression Components

Low Tension (LT)	-	Ignition coil low pass filter	
		Distributor low pass filter	
High Tension (HT)	-	Resistive cable	x
		Inductive cable	
		Resistive/inductive cable	
		Screened H.T. cable	
		Single resistor in H.T. lead	
		Resistive spark plugs	x
		Inductive spark plugs	
		Shielded spark plugs	
		Shielded/Resistive plug connectors	x
		Resistive Plug boats	x
		Distributor Screen	x
		Resistive rotor	x
		Distributor turret resistors	x

x denotes a component used in experimentation for this thesis.

TABLE 2.4

(Further to Table 2.2)

Factors of secondary in-car interference:

(a) Radiation radiated to antenna via body (especially bonnet).

(b) Interference on battery line.

(c) R.F. earthing of vehicle tuner chassis.

(d) R.F. earth of antenna lead to tuner.

(e) Feedthrough to antenna lead core.

(f) Control wires.

Factors of secondary external interference:

(a) Vehicle geometry.

(b) R.F. earthing of body to chassis.

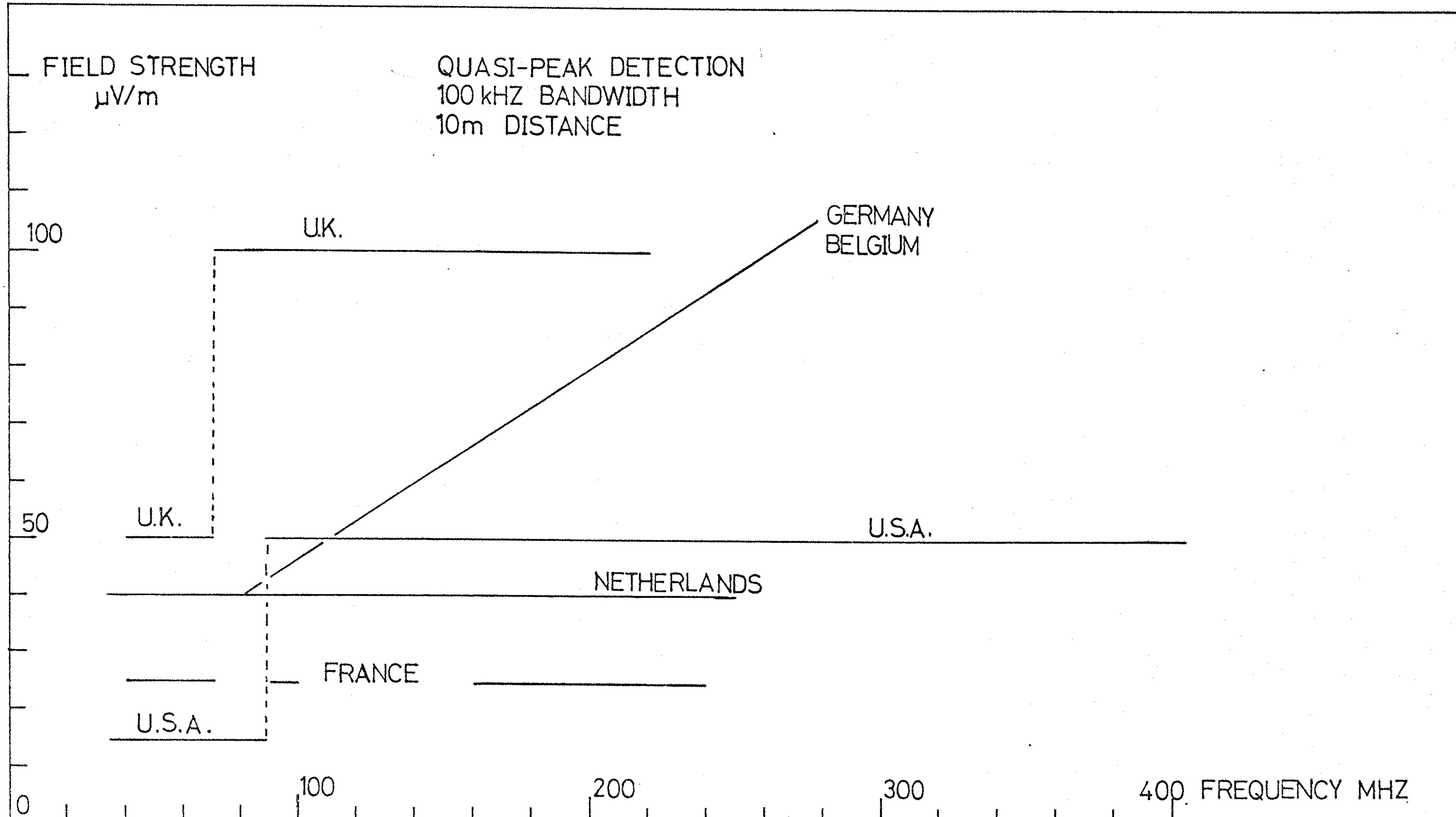
(c) Reflections due to earth conductivity and atmosphere.

(d) Exhaust pipe.

TABLE 2.6

INTERFERENCE STANDARD MEASUREMENT REQUIREMENTS

	TEST PARAMETERS					
STANDARD	AREA	ANTENNA TYPE	HEIGHT	ORIENTATION	DISTANCE	CONDITION
S.A.E. J551a	30m Clear	Dipole	3m	Horizontal	10m	1,000r.p.m.
I.E.E.E. 263	30m Clear	Conical Broadband	1m	Primarily Vertical	1m	Idle to race
CANADIAN ELECTRICAL CODE C22.4	60m Clear Circle	Dipole	Frequency Dependent	Vert. to 25MHz Horiz. above		1,500 r.p.m.
C.I.S.P.R. (7)	Ellipse (20 × 17m)	Dipole	3m	Horiz. and Vert.	Focal Points of Ellipse	1,500 r.p.m.



COMPARISON OF FIELD STRENGTH LIMITS FOR VEHICLE INTERFERENCE

FIG. 2·1

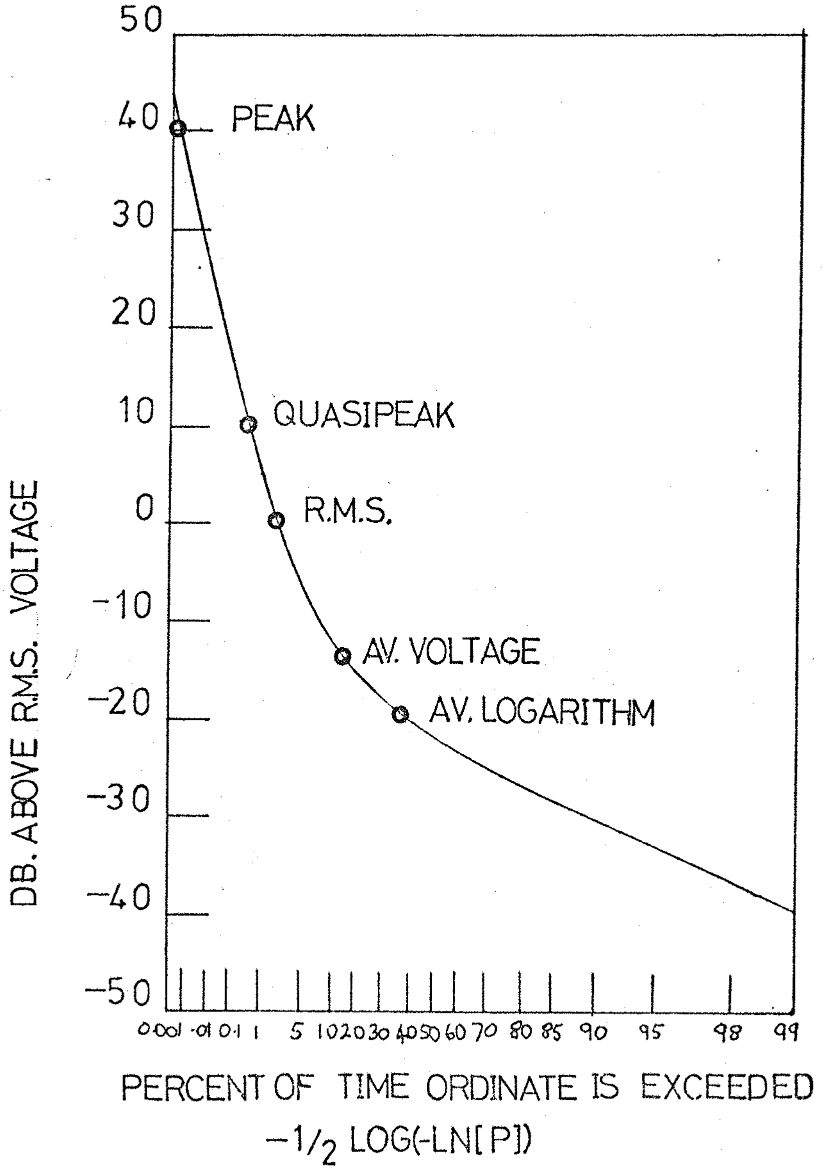
TABLE 2·5

C.I.S.P.R. RECEIVER SPECIFICATIONS

CHARACTERISTICS MHZ	0.015–0.15	0.15 – 30	25 –1000
Bandwidth at 6dB	200 Hz	9 kHz	120 kHz
Charge time constant	45 ms	1 ms	1 ms
Discharge time constant	500 ms	160 ms	500 ms
Mechanical time constant	100 ms	100 ms	100 ms
RF and IF overload factor	24 dB	30 dB	43.5 dB
DC Overload factor	12 dB	12 dB	6 dB

FIG. 2·2

A.P.D. OF MAN-MADE NOISE



CHAPTER 3

RADIO INTERFERENCE AND THE IGNITION SYSTEM

3.1 The Ignition System

Petrol driven engines require an ignitor for the fuel/air mixture within the pressure cylinder to achieve the combustion necessary for adequate operation. The form of ignition commonly used is the electric arc or spark which is produced by the discharge of high voltage across a gap in the vicinity of the fuel/air mixture. Complete combustion occurs if the discharge is of sufficient intensity.

The generation of the high voltage (10kv - 20kv) necessary to produce an adequate ignition arc is normally obtained from electrical energy stored within inductive or capacitive elements. The capacitor discharge ignition system is the more complex and requires a capacitor to be charged to an intermediate voltage (300 - 500v) from the battery voltage (12v), which is then discharged via a step up transformer to the required arcing voltage. However, besides certain operational advantages over the inductive system, such an ignition system requires semiconductor technology and is the expensive alternative. By far the most common form of spark derivation is by the inductive discharge, or Kettering, ignition system. This is the less complex and cheaper alternative. A summary of ignition techniques is given in references [32,33,34,35,36].

A diagram of the conventional Kettering ignition system is given in fig. 3.1 and is re-drawn in fig. 3.2 in a manner suitable for circuit analysis. The ballast resistor is in circuit during normal running of the engine, but is bypassed during starting to increase the available H.T. voltage should the vehicle battery be in poor condition. The low tension supply is switched across the ignition coil primary by means of the contact breaker and cam combination. The contact breaker is to some extent protected by a capacitor which also increases the efficiency of the system. The distributor distributes the H.T. to each of the four spark plugs in turn at half the engine speed to account for the four stroke engine cycle.

To describe the operation of the Kettering system, first assume that the contact breaker points are closed and the ignition coil primary current has reached its maximum ($\sim$5amp.). When in rotation the distributor cam breaks the L.T. circuit, disrupting current through the coil primary which induces a voltage $e = -L_1 dI/dt$, of the order 300v. The rate of change of current dI/dt determines the induced voltage. Voltage transformation to the coil secondary produces an H.T. exceeding 25kv, if it were not for the breakdown of the spark gaps. The secondary leakage capacitance C_1 charges to a voltage necessary to breakdown the distributor gap (5-10kv) due to initially there being a short circuit condition on the plug side of the distributor. The leakage capacitors C_2 and C_3 charge to the breakdown voltage of the spark plug. The discharges are maintained while the ignition coil inductive energy is dissipated for 1-2ms, a while after which the L.T. supply is reconnected by the contact breaker. The complete ignition occurs every 33.3ms (for 1000 engine revolutions per minute), and is applied to each spark plug in turn by the distributor.

In the ignition system described above the main energy storage element is the ignition coil primary. Stored inductive energy is given from the formula, $E = \frac{1}{2} L_1 I^2$, where L_1 is the primary inductance (H) and I the current (amp) flowing through it. Substituting typical values (L_1 = 5mH, I = 4.5A), the approximate stored energy is 50mJ. This energy is transferred by transformer action to the secondary H.T. circuit and is dissipated in the distributor and plug gaps. The spark plug discharge energy has been measured to be approximately 10mJ[37]. The inequality of dissipation may be due to the difference in arc length of the distributor and plug gaps and the radiated energy.

A series of voltage waveforms produced from the ignition coil secondary is given in Chapter 7.

3.2 The Problem of the Arc Discharge

An electrical discharge within a spark gap is a generator of broadband interference. The final spectrum shape is dependent upon various factors concerning the immediate associated circuitry. If the discharge is repetitive, as in the ignition system, the entire frequency spectrum is continuously excited by the impulsive nature of the atomic charge redistribution.

There are various mechanisms responsible for spark gap discharge, but fortunately the derived formulae are similar. Consider the case of a discharge where secondary electrons are produced at the cathode by positive ion bombardment in a uniform electric field. The resulting formula[38] for the electrode current is:

$$i = io \frac{e^{\alpha d}}{1 - \gamma(e^{\alpha d} - 1)}$$

Where:

γ = Number of electrons released from cathode per incident positive ion.

α = Number of ionising collision per centimetre of electrode gap.

d = Discharge path, cm.

io = Saturation current, amp.

The constants γ and α are primarily dependent upon electrode voltage gradient and gas pressure. As the denominator vanishes, i.e. $\gamma(e^{\alpha d} - 1) \rightarrow 1$, the number of ion pairs $(e^{\alpha d})$ produced in the gap by the passage of one avalanche electron is sufficiently large that the resultant positive ions are able to release one secondary electron. The discharge is self-maintaining and the sparking threshold has been reached. Should more than one secondary electron be released, successive avalanches are cumulative and an arc discharge follows after a very short time delay. The overall stability of an electrical discharge depends upon the source impedance applied to the spark gap electrodes. Current and voltage are in phase with a resistive circuit which would produce high current pulses. A reactive circuit designed to produce a voltage maximum with current minimum is more likely to support a stable discharge.

At the onset of any flow of charge within the spark gap there is an associated current variation at the spark gap electrodes which is transmitted to the supply leads and hence radiation occurs from the system. The intensity of this electromagnetic radiation is highly dependent upon the electrical characteristics of the supply leads and electrodes in proximity to the discharge.

The electrical discharge phenomena of a spark gap may be split into two components:

(i) Capacitive discharge. Initial breakdown.

(ii) Inductive discharge.

The former is related to the avalanche effect across the spark gap of the stored charge in the spark electrode capacitance. After this initial discharge of energy, further energy is supplied by the ignition coil and is inductive in nature in such a manner to keep the total H.T. current constant.

Difficulty is found in determining which of the two discharge components produces the most interference[16,39]. The electrode leakage capacitance may be reduced to decrease the capacitive discharge component which generates high current pulses. The inductive discharge is of low current nature but is often disrupted by turbulence and pressure variations.

3.3 Radio Interference Generation and Propagation from the Ignition System

The breakdown of the distributor and spark plug gaps occur within approximately 10μs[37] of each other, the resultant interference pulse from the two sources are virtually inseparable. Dominance of one source over the other can only be adequately found by comparison of the effect of suppression of one source over the other.

Besides the two H.T. sources of interference, it must not be forgotten that the contact breaker is quite capable of arcing when opening and closing whilst initiating the H.T. voltage and reconnecting the L.T. voltage to the coil primary. The initial contact breaker interference pulse is "lost" with those of the H.T. circuit as these are of a much greater magnitude, but the closure occurs approximately half way between the main pulses and is the more conspicuous.

In general, whenever there is a voltage fluctuation within a circuit, there follows electromagnetic radiation. Bearing this in mind it is possible to compile a list of interference sources in time sequence:

(i) Contact breaker separation.
(ii) Initial H.T. voltage rise.
(iii) Distributor gap breakdown.
(iv) Spark plug breakdown.
(v) Erratic H.T. arc at distributor and spark plug.
(vi) Extinction of arc at distributor and spark plug.
(vii) Re-striking of distributor and spark plug arc.
(viii) Contact breaker closure.

The interference sources are coupled capacitively, inductively and conductively to the various components of the engine compartment, and hence to the entire vehicle.

Fig. 3.3 indicates the true composition of the ignition system with continuous and lumped equivalents of the contact breaker, ignition coil, distributor, H.T. leads and spark plug. Such a system is totally unscreened and acts as a frequency selective antenna when activated by electrical discharge within its circuitry.

The distributed components of the H.T. leads, etc., produce a variable impedance network to the secondary spark gaps. An unmatched system produces power reflections which further complicate the radiation spectrum. The effective mismatch length varies from approximately 1 metre to less than a centimetre which affects frequencies in excess of 75MHz (see Section 6.4.2).

From transmission line theory[40], it is known that a lossy transmission line produces little reflection due to the high absorption of incident and reflected signals. Similarly, spark interference may be reduced with the use of a discrete, or better still, continuous resistive network.

3.4 Suppression of Radio Interference from Electrical Discharges within the Ignition System

The simplest and most effective method of suppression is to completely screen the spark gaps and the power supply circuitry. However this has a detrimental effect upon the efficiency of spark generation as the capacitive loading on the ignition coil secondary reduces the H.T. rise time and voltage[42], both of which must be maintained to ensure adequate fuel/air combustion. It would be possible to increase the H.T. voltage and power available from the ignition coil but at the possible expense of increased interference. The cost of screening is prohibitive for commercial vehicles[5], though not necessarily those of military use. Regular maintenance of the screening connections is required to maintain the screening efficiency.

A practical solution uses a combination of capacitive, inductive, resistive and screening suppression. Resistive suppression dissipates energy and lowers the quality factor of stray or intentional reactance. This form of suppression is sometimes incorporated in mains filters to compensate for the wide variation of cable reactance with frequency which would otherwise degrade the suppressive effect. Resistive suppression has a specific application in the vicinity of electrical discharges. With leakage capacitance, e.g. that of a spark plug, an additional resistor close to the arcing point constitutes a low pass filter. The ignition coil initial burst of low frequency energy is undisturbed, but broadband interference is suppressed.

The coaxial capacitance between the centre piece and surround of a standard spark plug is measured to be approximately 12pF (see fig. 3.4). When this is charged to the spark gap breakdown voltage ($\sim$7kv), the accumulated charge is calculated to be 0.084μ with the associated energy of approximately 0.3mJ before the arc discharge commences. If the effective spark gap capacitance is reduced by placing a resistor in the centre piece, the capacitive discharge interference would be reduced and would suppress both capacitive and inductive interference when emerging from the plug itself. The ratio of division of the plug capacitance affects suppression efficiency[42] (the closer to the spark gap the better), and similarly does the resistive length[2]. The latter determines the leakage capacitance across the resistor which reduces the suppressive effect above approximately 200MHz (see fig. 3.5).

The resistive spark plug shield suppressor attenuates high frequency radiation (see fig. 3.6). This component consists of a metal shield which encompasses the porcelain/ceramic projection of the plug and increases the new plug capacitance to over 20pF through a total length of approximately 7cm. The resistive suppressor at the top of the shield and the extra capacitance act as a low pass filter. The most effective low pass filter system constitutes the use of the resistive spark plug and the plug shield.

(see fig. 3.7). The effectiveness of this combination is seen in Chapter 6.

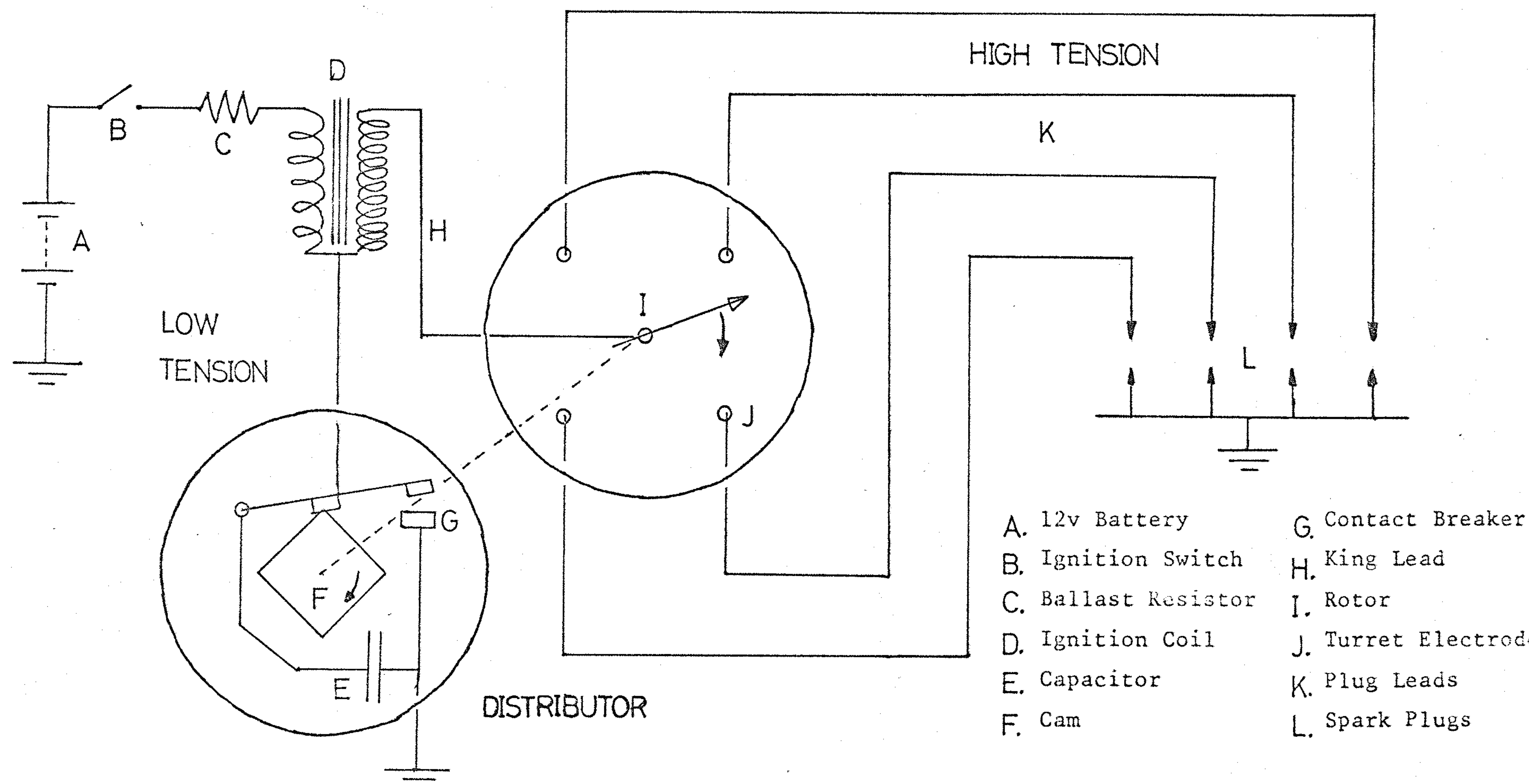
The plug boot resistor located at the top of the spark plug produces similar effects to those of the plug shield with no increased capacitance but with a larger resistance (15kΩ).

The distributor spark gap possess little stray capacitance to earth for it is a series circuit element, similarly the gap capacitance itself is very low (0.1pF) (see fig. 3.8). Low pass filter implementation is thus difficult without introducing new elements to the distributor cap. Resistive suppression (e.g. resistive rotor, distributor turret resistors) would limit the discharge energy, but the system would not be used to its full advantage without extra capacitance to form a low pass filter. However, if part of the distributor cap were metallised, the extra leakage capacitance would complete the filter[2] (see fig. 3.9). With such a system care must be taken not to increase the distribution gap capacitance as this is liable to increase interference levels.

Interference that is left unsuppressed from the arc discharges passes through to the H.T. cable from which it is free to radiate. This would imply that the previously described systems are inefficient. Increased reduction in inductive discharge interference may be necessary. Various types of ignition cable have been designed to substitute wire H.T. cable with varying degrees of success[41]. Some of these are mentioned below:

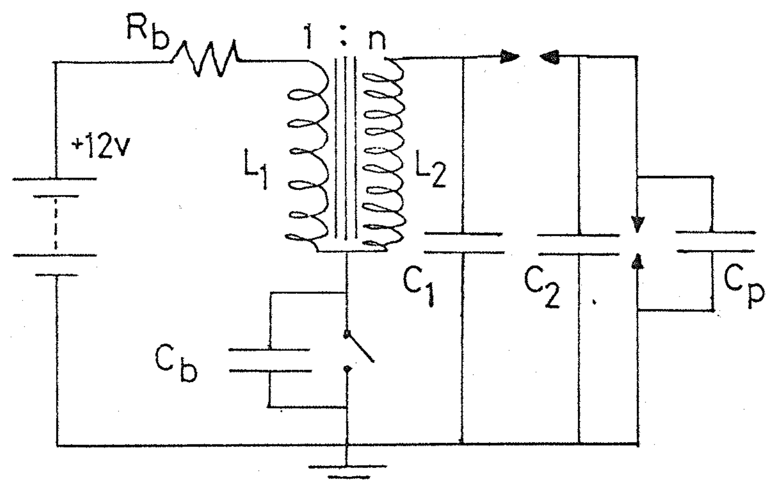
Resistive Cable	- ∿20kΩ/m, carbon impregnated fibre.
High Inductance Wire	- 20-50μm diameter.
Magnetic and Dielectric Absorption Cable	- Increasing impedance with frequency.
Pseudo-Resonant Cable	- Increasing impedance with frequency.
Skin Effect Cable	- Increasing impedance with frequency.

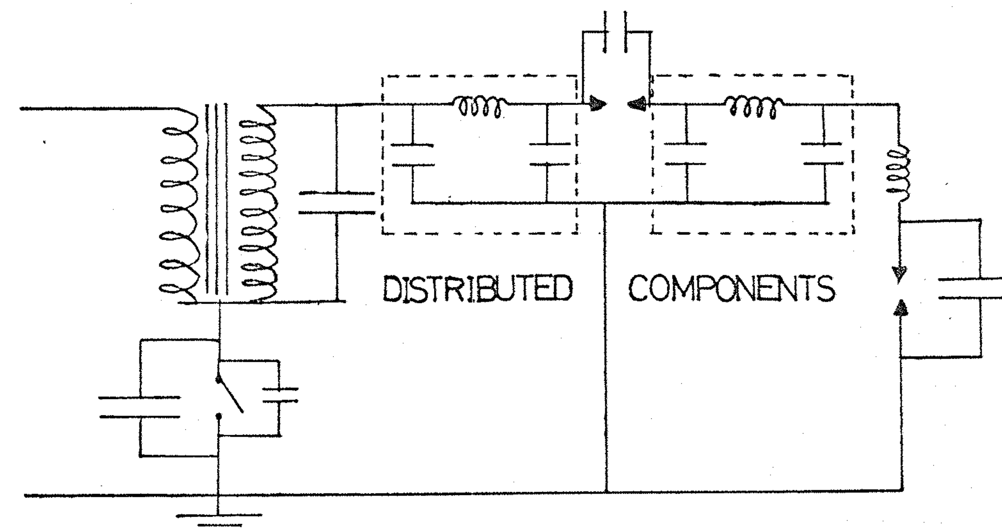
The last three types of cable are dependent upon the change of electrical and magnetic characteristics of their component materials with frequency. In effect a low pass filter is formed from the cable. High inductance wire is occasionally used, but has a serious drawback of being mechanically weak. Resistive cable is the most popular amongst motor manufacturers, but suffers from high temperature degradation, whereas the complex impedance cables offer higher temperature stability.



KETTERING IGNITION SYSTEM

FIG. 3·1



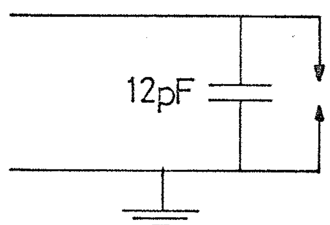


C_b. Contact Breaker Capacitor (∿0.1μF)
C_p. Spark Plug Capacitance (∿12pF)
C_1. King Lead Capacitance (∿3pF)
C_2. Plug Lead Capacitance (∿5pF)

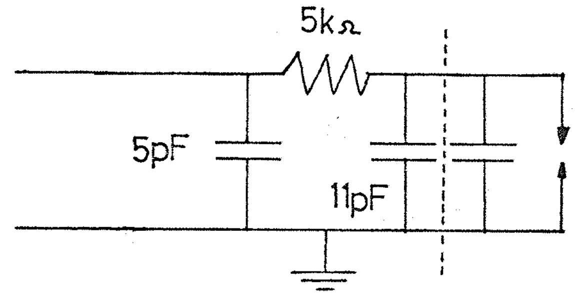
L_1. Primary Inductance (∿5mH)
L_2. Secondary Inductance (∿50H)
n . Coil Turns Ratio
R_b Ballast Resistor (∿1.5Ω)

EQUIVALENT IGNITION SYSTEM CIRCUIT FIG. 3·2

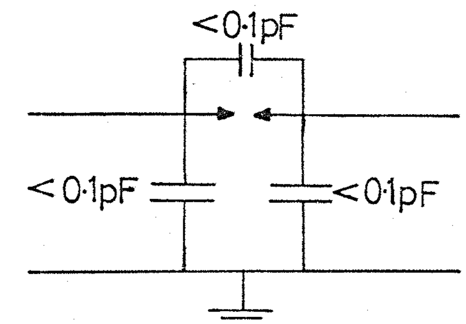
R.F. EQUIVALENT IGNITION SYSTEM CIRCUIT FIG. 3·3



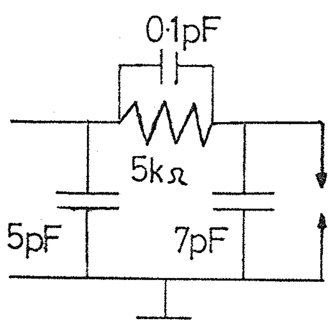
SPARK PLUG
FIG.3·4



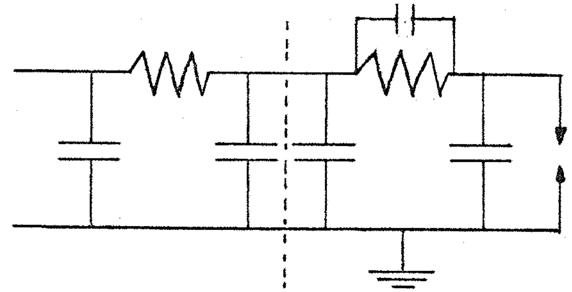
PLUGSHIELD + PLUG
FIG.3·6



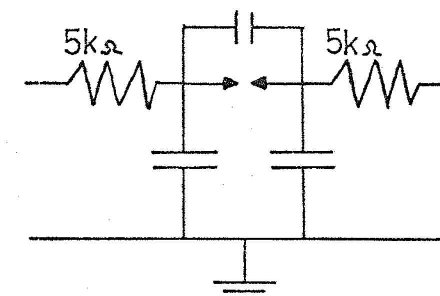
DISTRIBUTOR
FIG.3·8



RESISTIVE PLUG
FIG.3·5



PLUGSHIELD + RESISTIVE PLUG
FIG.3·7



RESISTIVE ROTOR + TURRET RESISTOR
FIG.3·9

ELEMENTS OF THE IGNITION SYSTEM (APPROX. VALUES OF COMPONENTS)

FIGS. 3·4 — 3·9

CHAPTER 4

INTERFERENCE MEASUREMENT PROCEDURE

4.1 Procedure Description

Two measurement systems were used to provide ignition interference results for analysis. One consisted of a commercial vehicle, a Ford Motor Company Capri (Mk.2), and the other an ignition system model mounted inside a laboratory. These are respectively called the Ford Capri and the Earth Cone systems, and are fully described in Chapter 5.

Various types of ignition suppression components were used to reduce interference. All measurements were taken relative to an ignition system suppressed only with resistive H.T. cable, bearing the commercial name of SIPCON. Such a comparison is used throughout to class the effectiveness of suppression against the standard[22].

The desired suppression component combination is attached to the ignition system. For the Earth Cone system, interference is measured across the earth resistor, R_e, and for the Ford Capri system measurement takes place from the output transformer of a broadband probe. Connection to a spectrum analyser, a Marconi TF2370,[43] is by suitable length of coaxial cable of characteristic impedance 50Ω. Measurements were made independently on each system.

The spectrum analyser display employed two modes, making it possible to view two dissimilar frequency responses or just one with increased definition. Normally the former mode was used, one display represented the interference response of the SIPCON reference system, and the other the system under test.

Ignition interference is impulsive by nature and produces a time and frequency domain related response on the spectrum analyser display due to the swept frequency response of the amplification stages. The memory facility was used to accumulate the individual impulse spectra into a proper frequency-amplitude characteristic over a period of time of approximately five minutes. The resultant display is the interference signature of the ignition system and suppression components under test.

The spectrum analyser was employed in its logarithmic amplitude response capacity using power weighted peak signal detection. The problem of which frequencies to monitor was solved by considering the three most common entertainment wavebands i.e. Long Wave, Medium Wave and V.H.F. The analyser[43] is capable of measurement from 30Hz to 110MHz. The entire wave band is displayed in each measurement and the difference between the reference (SIPCON) level and that of the combination under test are taken at a centre-frequency. The results were compared for both systems and interpreted for relationships between suppression components, combinations and cost efficiency (see Chapters 6 and 9).

The wavebands, frequency ranges and centre frequencies are given below:

(i)	Long Wave (L.W.)	125 - 325kHz	225kHz centre frequency
(ii)	Medium Wave (M.W.)	0.5 - 1.5MHz	1MHz centre frequency
(iii)	V.H.F. Band (V.H.F.)	85 - 105MHz	95MHz centre frequency

4.2 Bandwidth Factor

A choice of bandwidths was available from the spectrum analyser for the three frequency ranges considered. These are 500Hz, 5kHz and 50kHz. The chosen bandwidth for all frequency ranges was 50kHz, for this increased the sensitivity of the analyser for broadband signals. The half power or 3dB response bandwidth is not used for broadband interference. The shape factor of the filter outside the 3dB bandwidth determines the impulse bandwidth which is governed by the entire frequency response.

Calibration results are normalised to dBμv/MHz using the formula[44]:

$$S = V - B + 107\text{dB}.$$

Where, S is in dBμv/MHz, V in measured dBm (relative to 1mW into 50Ω and B is in dBMHz and is called the bandwidth factor.

SIPCON reference levels are given in dBμv/MHz and other suppression combinations are given in dB above or below the reference level.

The bandwidth factor is given by $20 \log \frac{BW_i}{1MHz}$ dBMHz for power weighted voltage measurements, where BW_i is the impulse bandwidth. True power measurement is difficult to achieve and would result in $10 \log \frac{BW_i}{1MHz}$. The definition of BW_i is given in Section 2.4, and may be found experimentally to varying degrees of accuracy by the following methods:

1. Measure the area under the intermediate frequency amplifier response to a calibration signal and divide by signal amplitude.
2. Measure 6dB bandwidth.
3. Measure the area of the detector response to an impulse and divide by amplitude.
4. Measure the response to a known modulated signal.

Methods 1 and 2 were compared with the following results for the 5kHz and 50kHz bandwidths:

	Analyser B.W.	Estimated $B.W._i$	B.W. ratio
Method 1	50kHz	61.5kHz	1.23
	5kHz	6.75kHz	1.35
Method 2	50kHz	56 kHz	1.14
	5kHz	6.3kHz	1.26

Method 1 was chosen to give the most accurate estimation of the bandwidth ratio for it approximated to the theoretical calculation of the impulse bandwidth.

The resultant formula for normalising results to dBμv/MHz is:

$$S = V + 131 \quad \text{dB}\mu\text{v/MHz} .$$

Where V is the analyser reading in dBm for a bandwidth of 50kHz.

4.3 Calibration Results

Calibration interference levels were taken for the reference system for the Ford Capri and Earth Cone measurement systems. Results for Long Medium and V.H.F. wavebands are given below in dBm units and are converted to dBμv/MHz.

	Ford Capri		Earth Cone	
L.W.	-40dBm	91dBμv/MHz	-21dBm	110dBμv/MHz
M.W.	-50dBm	81dBμv/MHz	-23dBm	108dBμv/MHz
V.H.F.	-55dBm	76dBμv/MHz	-45dBm	*86dBμv/MHz

*Using special filter to avoid spectrum analyser overload, see section 8.1.2.

Complete interference spectrum curves are given in figs. 4.1 and 4.2 for the frequency range 0-105MHz. Discrepancy in interference levels with those listed above is due to analyser overload and subsequent distortion of the frequency spectrum. The sensitivity of the analyser was kept as low as possible to avoid possible distortion. This is most apparent in V.H.F. results where a change of sensitivity did not always give an equal change in indicated results.

Preliminary tests showed that the calibration and subsequent results were only due to interference from the ignition system, and this was due to secondary H.T. interference. This was verified on the Earth Cone by inspecting all frequency ranges with the ignition system turned off. Contact breaker interference was found later to be approximately 40dB below the H.T. interference over the frequency range. The Ford Capri represented a more complex problem in that besides the ignition system, other electrical apparatus was necessary for the adequate function of the vehicle engine. Ignition interference impulses are repetitive, one large pulse following by another of smaller amplitude (contact breaker interference), whereas alternator and other vehicle interference has a more erratic and higher repetition frequency response. Such interference was greater than 50dB below ignition interference. This was verified with the car radio which only produced interference of the ignition characteristic. Contact breaker interference was higher than that of the Earth Cone relative to the H.T. impulse, but was not less than 20dB below the reference level.

An example of ignition and contact breaker interference is given in fig. 4.3 for the SIPCON system used on the Earth Cone. From the frequency sweep rate of the analyser it is possible to calculate the time period of the ignition impulses.

4.4 Suppression Variables and Cost

Various combinations of suppressors were used to suppress interference from the ignition system. Nine ignition components were tried individually and collectively and are given in Table 4.1, their position within the ignition system was indicated in Chapter 3.

The cost of ignition interference suppression is a variable which is dependent upon the nature of the interference source and the type of suppressor chosen. The manufacturing cost of such components may well be £2.53 for some types of vehicles which is borne by the motor manufacturers themselves. Table 4.2 indicates the approximate manufacturing costs(5) of ignition components and others of use with different interference sources. The listed suppressors do not represent every possible component available and also some vehicles may require special fittings. It can be seen that H.T. ignition interference components constitute just over half the total interference suppression cost.

The variation of suppression may be graphically represented by plotting interference reduction in decibels versus suppression cost. The relative effects are thus seen, aiding interpretation of results. A graph is produced for each waveband with two response plots, as each type of H.T. cable produced a distinct set of results (see figs. 6.1 - 6.3 and 6.5 - 6.7).

For the case of the resistive plug boot, which is a substitute for the resistive plugshield, a graph is drawn of results for all three wavebands when used with the wire H.T. system (see figs. 6.4 and 6.8).

TABLE 4.1 IGNITION SUPPRESSION COMPONENTS

Ignition Component	Code	Measurement System		Manufacturer	Value
		Ford Capri	Earth Cone		
Rotor	A	-	-	FOMOCO	-
Resistive Rotor	B	EVL4/6-E	EVL4/6-E	BERU	5kΩ
Resistive Plug Shields	C	2LE304	2LE304	BERU	5kΩ
H.T. Distributor Resistors	D	VES401	VES401	BERU	5kΩ
Wire H.T. Cable	E	-	-	-	-
Resistive H.T. Cable	F	SIPCON	SIPCON	MOTORCRAFT	17kΩ/m
Spark Plugs	G	BF32	AG3	MOTORCRAFT	-
Resistive Spark Plugs	H	BFR32	AGR31	MOTORCRAFT	5kΩ
*Resistive Plug Boots	I	-	-	-	15kΩ

* The resistive plug boot is commonly used with wire H.T. leads. It is not included with suppression combinations including resistive H.T. leads.

TABLE 4.2 VEHICLE INTERFERENCE SUPPRESSION COMPONENTS AND MANUFACTURING COST

Ford Type No.	Suppression Component	Cost £	Unsuppressed* Cost £		Actual Cost £
SIPCON RIST 0415	Resistive H.T. Cable 12p/m	0.24	5p/m	0.10	0.14
11425981	Resistive Rotor	0.13		0.10	0.03
72GB18K842CB	L.T. Filter Assembly	0.65		-	0.65
72GB14324BA	Wire Assy. Engine to Frame	0.15		-	0.15
73AB12A012-AA	4 H.T. Distrib. Resistors @ 18p.	0.72		-	0.72
73EB18825-AB	4 Resistive Plug Shields @ 36p.	1.44	@ 5p.	0.20	1.24
AGR31/BFR32	4 Resistive Spark Plugs @ 20p.	0.80	@ 10p.	0.40	0.40
71HM12A019AA	Coil Capacitor	0.51		-	0.51
73EB12K000DA	Distributor Screen	0.50		-	0.50
71BB10A3800A	Alternator Suppressor	0.45		-	0.45
71BB17K499AA	Windscreen Motor Suppressor	0.90		-	0.90
		£ 5.79		£ 0.80	£ 4.99

* Unsuppressed component cost.

N.B.

The Resistive plug boot not included as it is a substitute for the resistive plugshield. Manufacturing cost is approximately 7p. each.

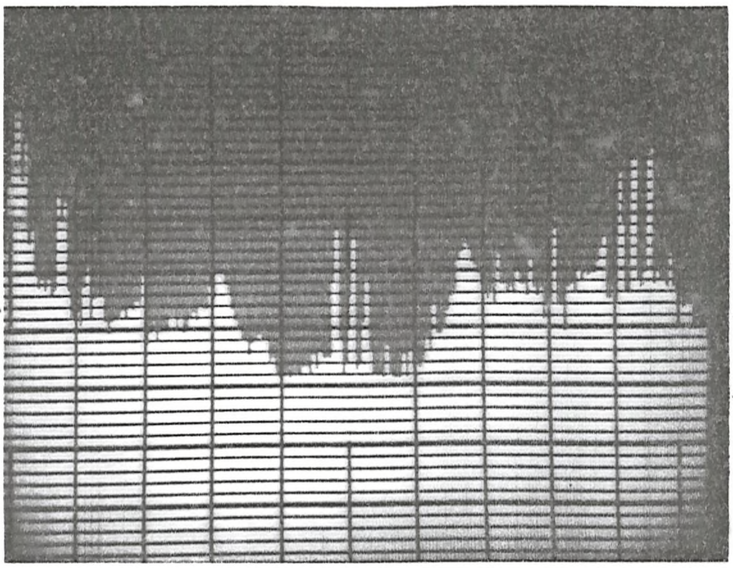


Fig. 4.1

Ford Capri
SIPCON reference
0dBm datum
50kHz B.W.
10MHz/div.
10dB/div.
(50MHz centre)

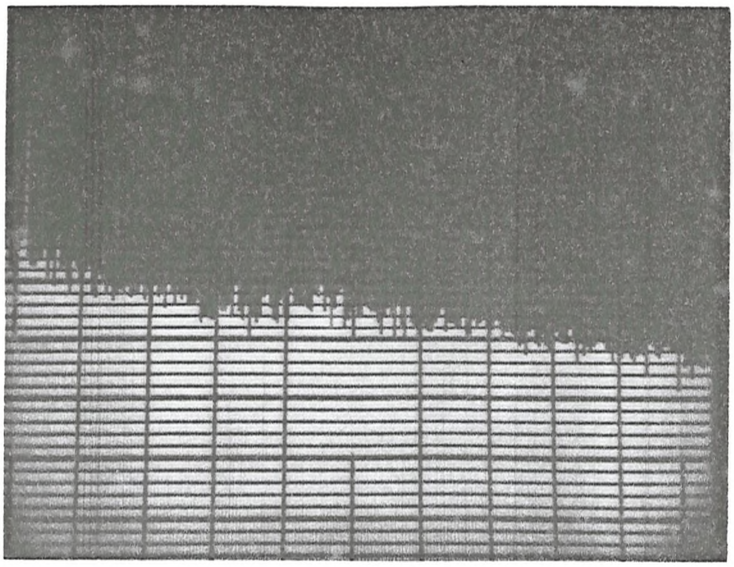


Fig. 4.2

Earth Cone
SIPCON reference
+20dBm datum
(as above)

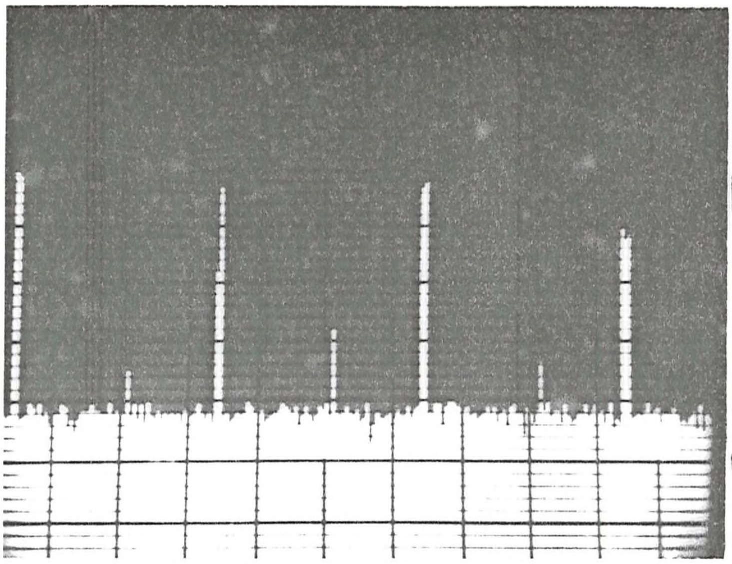


Fig. 4.3

Individual
interference spectra
from Earth Cone
100ms sweep time
(30MHz centre)

CHAPTER 5

MEASUREMENT SYSTEMS - FORD CAPRI AND EARTH CONE

5.1 Ford Capri Interference Measurement

5.1.1 Interference Received by Car Tuner

The antenna of the car radio is situated on one of the front wings of the Ford Capri; such a position is alongside the engine and ignition system and is prone to interference pickup. The intensity of this pickup and of the broadeast signal determines whether or not radio reception is impaired. The method of transmission of interference is of a complex nature involving inductive, capacitive and conductive coupling [45] which are dependent upon all aspects of positioning and construction of the antenna system.

Direct measurement of the interference at the antenna lead was obtained by connecting an R.F. probe across the tuner antenna input. The frequency response was flat from 0.1MHz to 100MHz and the output compatible for a 50Ω instrumentation system. The design of the input stage was such that the car tuner signal strength was reduced as little as possible. The receiver was tuned to mid-frequency within each waveband, although the choice of waveband had little effect on results. The car radio (3 waveband model) was manufactured by Blaupunkt of Mannheim, West Germany.

5.1.2 R.F. Probe

The probe was operated from a 12v battery and consisted of a bootstrapped F.E.T. source and transistor emitter follower which fed an integrated circuit wideband amplifier [46] (See fig. 5.1). Two broadband transformers were used for signal coupling. To allow for low gain of the wideband amplifier (26dB @ 0.1MHz, 8dB @ 100MHz) and signal loss at the input stage for high frequencies, the circuit was loosely tuned to give a frequency response of ± 1dB gain from 0.1MHz - 100MHz. This was measured using the tracking generator of the TF2370 spectrum analyser, the input circuit was matched by a 50Ω resistor across the probe input terminals. Thus effectively the probe itself had a gain of 6dB because of its high input impedance. This was measured to be the equivalent of 240kΩ in parallel with 5pF. The output transformer provided a good match to the 50Ω coaxial cable.

5.1.3 Measurement System

The measurement system is set out in fig. 5.2. A 16 metre length of coaxial cable was used between the spectrum analyser and the Ford Capri to minimise its effect upon interference measurements. There was on average a 4dB variation in interference results taken with the analyser in the car and those taken outside. When the coaxial earth (i.e. mains earth) was connected to the car it was noticed that broadeast signal strength was enhanced on M.W. and L.W. bands. However when separate earth system was used with the output transformer secondary left floating, there was interference leakage for zero probe input. This leakage was of similar magnitude to the interference being measured, but of different spectrum shape. The system was then reconnected for continuous earth. Such an earth system is similar to that used by the Ford Motor Company[47] for measurement of in-car interference, but here there is direct connection of the antenna lead to the interference instrumentation. Such a direct connection leads to serious mismatch conditions with the frequency dependent impedance of the antenna lead and antenna (see next section).

The additional length of low loss (30pF/m) coaxial cable needed to connect the probe to the radio antenna input was 40cm and provided an extra shunt capacitance of 12pF. When combined with the probe capacitance of 5pF, the total antenna shunt capacitance was approximately 17pF. Such a length of cable was unavoidable as the probe could not have been connected closer to the antenna socket of the car radio owing to the dimensions of the tuner casing and housing compartment. A subjective test on the car radio indicated that its loss in sensitivity due to the antenna loading was similar to that experienced when connecting a commercial antenna extension lead of 60cm.

An alternative form of interference measurement may involve direct measurement of the 3 band tuner intermediate frequencies (470kHz, and 10.7MHz). Such a system would not load the antenna input, but would require the disconnection of the V.H.F. automatic frequency control circuit and L.W. and M.W. automatic gain control circuit. Furthermore, high amplitude impulses (e.g. those from the unsuppressed ignition system) would overload the R.F. input stages of the tuner, producing non-linear effects.

The car radio provided an indication as to the level of suppression obtained but such an analysis was not undertaken.

The Ford Capri was kept in one position during experimentation. Parked vehicles close to the antenna affected interference results at V.H.F., and were rejected.

5.1.4 Comparison with Ford In-car Measurement System

The Ford Motor Company has produced various test reports[47] for in-car measurement under regulation E.C.E. 10 (See Section 2.3). The advised V.H.F. interference level is below 26dB relative to 1μv for the measurement system and apparatus adopted. Quasi-peak detection and a 120kHz bandwidth is used to C.I.S.P.R. specifications. If certain assumptions are made, i.e. 20dB loss[48] in sensitivity when using quasi-peak detection instead of peak, and a bandwidth ratio similar to that used on the spectrum analyser (1.23), the resultant normalised interference level is approximately 65dBμv/MHz. This level is the average obtained from the vehicles and suppression systems listed in the test reports (including SIPCON suppressed systems), and should be comparable to V.H.F.

results from the Ford Capri system.

The Ford Capri V.H.F. calibration level is 76dBμv/MHz, which is reduced to 70dBμv/MHz because of the 6dB gain of the interference probe. The 5dB difference between the two systems is explained by differing impedance mismatches in the antenna system, whilst the SIPCON reference level for V.H.F. is not exactly 26dB relative to 1μv in the Ford Motor Company system.

5.1.5 Ford Capri Measurement Procedure

The Ford Capri engine idled from between 1350-1650 r.p.m. Interference levels were found to be independent from engine speed in this range, though further deviation would probably lead to differing results [49]. An engine warm-up time of about 5 minutes was necessary before first commencing experimentation for the ignition system to settle down. Results were not taken during wet weather. The measurement procedure is given in Chapter 4.

5.2 Earth Cone Interference Measurement

5.2.1 Earth Current Method

A complete ignition system is mounted upon an inverted cone to measure the earth current which is related to the radio frequency interference radiated from the ignition cables, etc. The earth current method for ignition interference measurement differs from normal test procedures in that the ignition system is not enclosed within a vehicle, nor does it rely upon vehicle operation. Ignition interference may be monitored by the earth current in the time or frequency domains.

The particular form of earth current measurement in this project was developed by Professor E. Fromy [50]. It is based on the measurement of the earth current induced into a horizontal earth plane by the magnetic (H) field component of the radiation field from a vertical antenna system. For the simple case of a vertical monopole of length less than half a wavelength situated in the centre of the inverted cone, the resultant wave will induce radial currents. Their sum on any circle centred from the cone centre is related to the power P transmitted by the monopole by the equation, $P = 40Ie^2$, where Ie is the total earth current (See fig. 5.3). The expression can be used to measure power radiated from power supply leads, but as the radiating system becomes more complex, the simple power law is no longer valid. However if only relative measurement is required results are valid provided there is no change in radiation pattern, only intensity.

The earth current calibration curve for a one metre diameter cone and vertical monopole is flat from below 30MHz to 100MHz, after which the response decreases at the rate of 6dB/octave(50). The method has certain advantages(51) over the conventional field strength and field strength substitution methods which require separate measurements in various directions and are susceptible to external interference. The earth current method is relatively immune from reflections and outside interference and is an integrating method of power measurement.

The practical measurement of the earth current involves the use of an earth resistor, Re , which is situated between the bottom tip of the cone and the earth plane below. Consider a vertical monopole in the centre of the cone producing a concentric magnetic field, H , which induces a current density, J , on the horizontal cone surface. The induced current flows over the surface of the cone, through the earth resistor, Re , to the earth plane below. Substitution of an ignition system for the antenna produces earth currents of a complex nature, but the principle is similar.

It is desirable to match the resistor, Re , to the characteristic impedance of the cone which is given by $60\sin\theta$ ohms(50), where θ is the angle of the cone inclined to the horizontal and is designed to be 20^o. It is thus calculated to be approximately 20Ω. The spectrum analyser and its input coaxial cable is of 50Ω characteristic impedance and if Re was made a convenient value close to 50Ω (47Ω resistor), the total impedance would be such as to match the system.

5.2.2 Construction of Earth Current Apparatus

The cone was assembled from sections of tin-plated sheet steel to form the approximate shape of a cone. The cone is supported by an external wooden framework and its top made rigid by an internal sheet of plywood (See fig. 5.4).

The earth cone is positioned above an earth plane consisting of $15m^2$ of tin-plated sheet steel and copper gauze soldered together. Screw connections are situated on the cone tip and the earth plane to secure the earth resistor. Power is delivered to the cone by a supply tube containing necessary cables. An R.F. short circuit is avoided by fitting 50 toroids to the tube to increase the tube impedance to approximately 200Ω.

5.2.3 Ignition System Assembly

The entire ignition system is mounted on a circular aluminium plate which is insulated from the cone by means of nylon pillar washers pushed through the fixing bolts. The metal plate is secured to the centre of the cone surface.

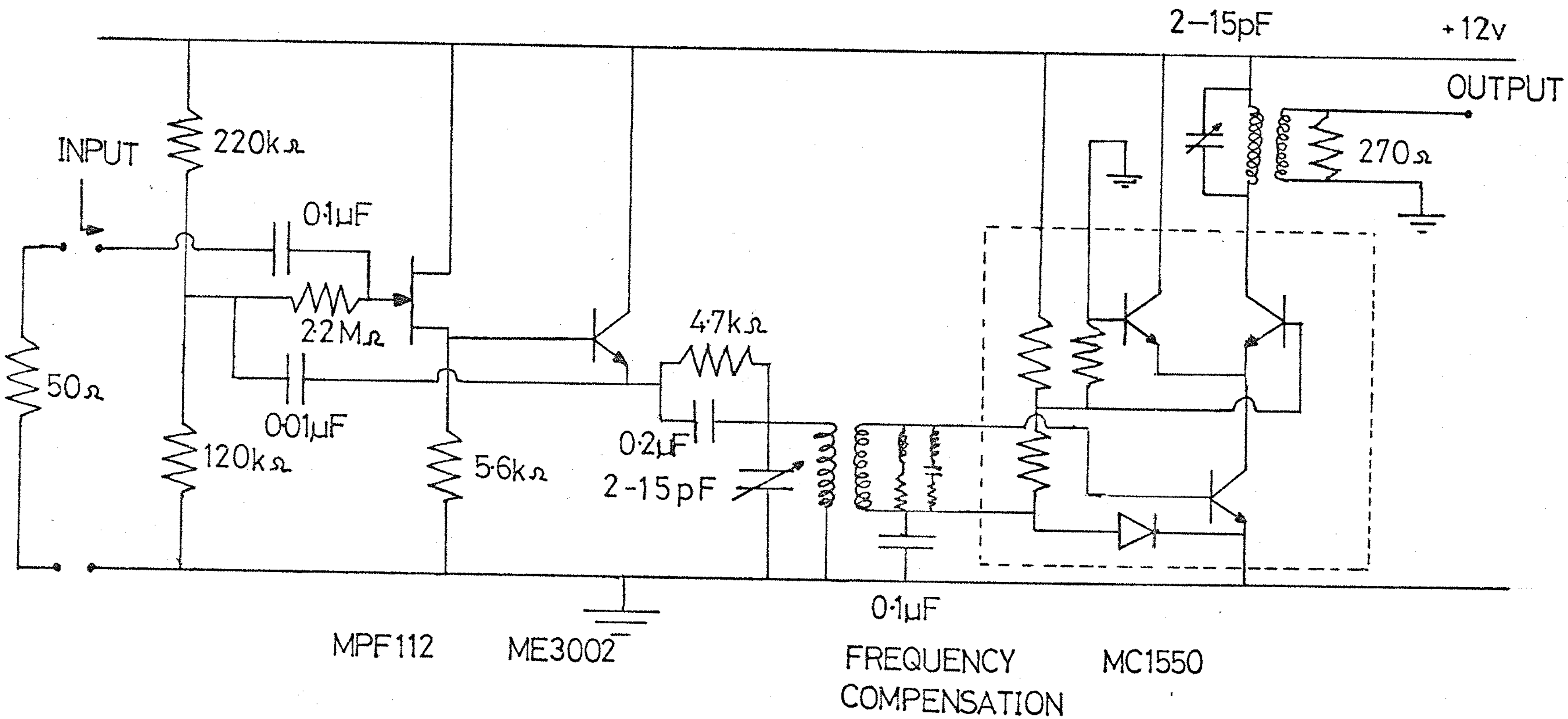
The distributor is powered by a 240v a.c. induction motor (interference free) to run at such a speed to represent the normal running of a four cylinder engine at 1450 r.p.m. If necessary the speed could be varied by a variac control situated on a nearby equipment bench.

An ignition ballast resistor of 1.5Ω was wound from resistance wire and mounted in a system control box with fuses, on/off switch, etc. An interference suppression box consisting of various mains filters was situated beneath the assembly plate to suppress interference pickup from the power system. See fig. 5.5.

An airtight spark plug chamber was fitted on the assembly plate. The spark plugs were held in position and it was possible to pressurise the air inside the chamber to 5×10^5 N/m^2 (80lb/in^2) to simulate normal cylinder pressurisation. Unfortunately this pressure was too low to have any effect on the interference spectrum, a pressure on order of magnitude higher would have perhaps been more fruitful.

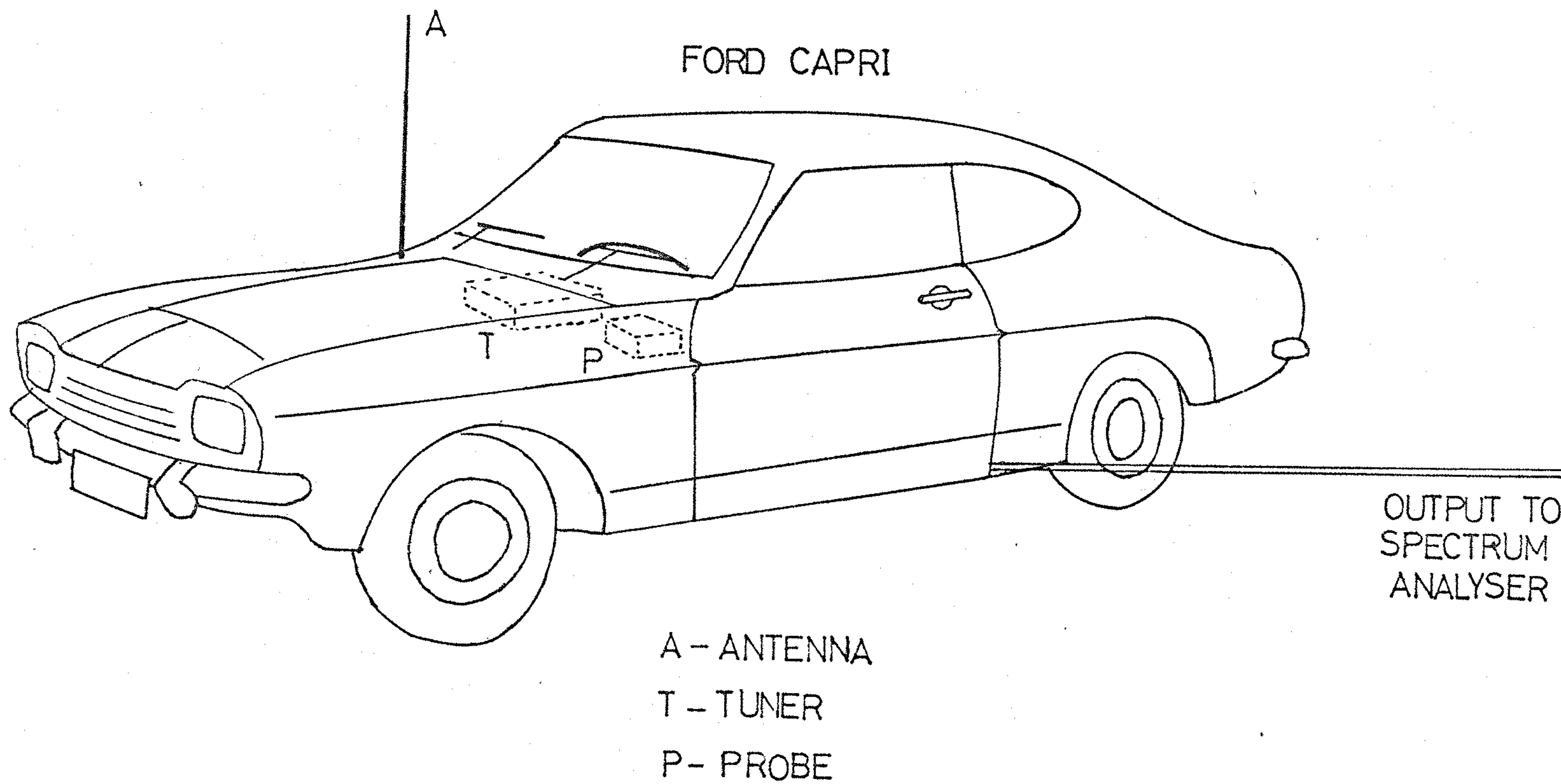
Virtually no "warm-up" time was necessary to produce repeatable results. The ozone level within the plug chamber did not affect results.

See fig. 5.6 for the completed construction of the cone, earth plane and ignition system.



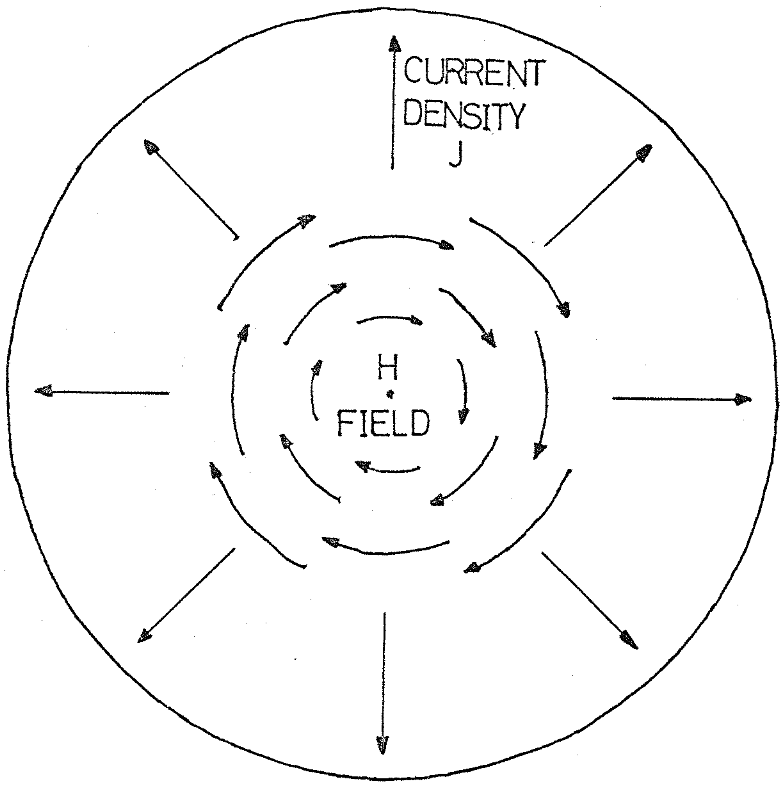
R.F. PROBE CIRCUIT

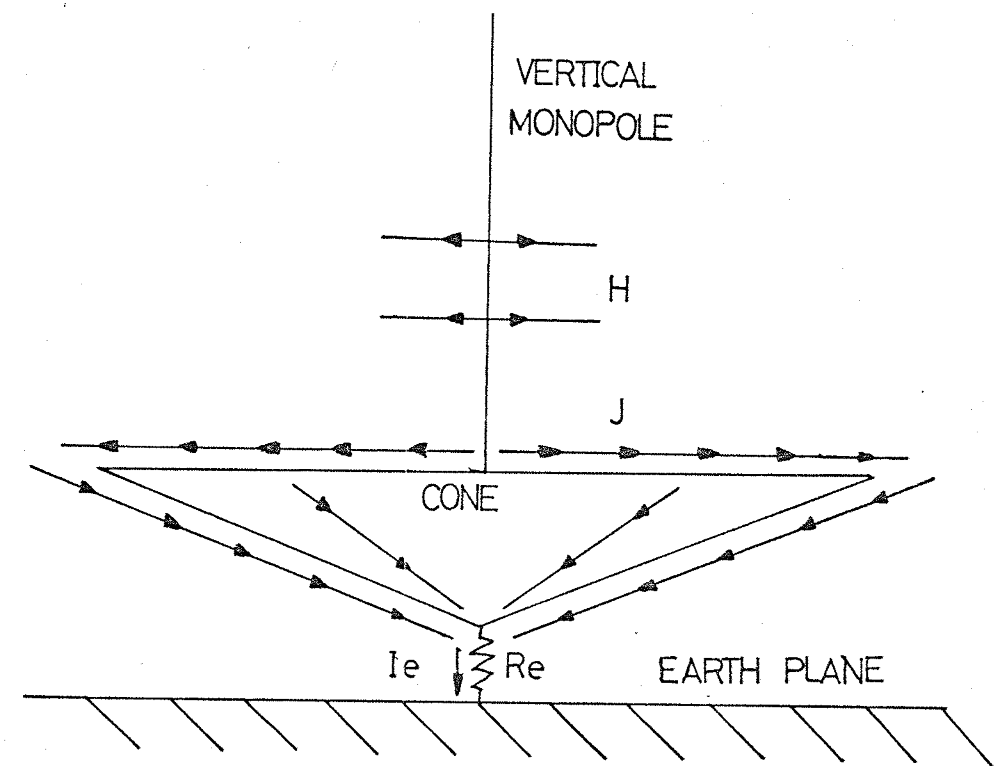
FIG. 5·1



FORD CAPRI MEASUREMENT SYSTEM

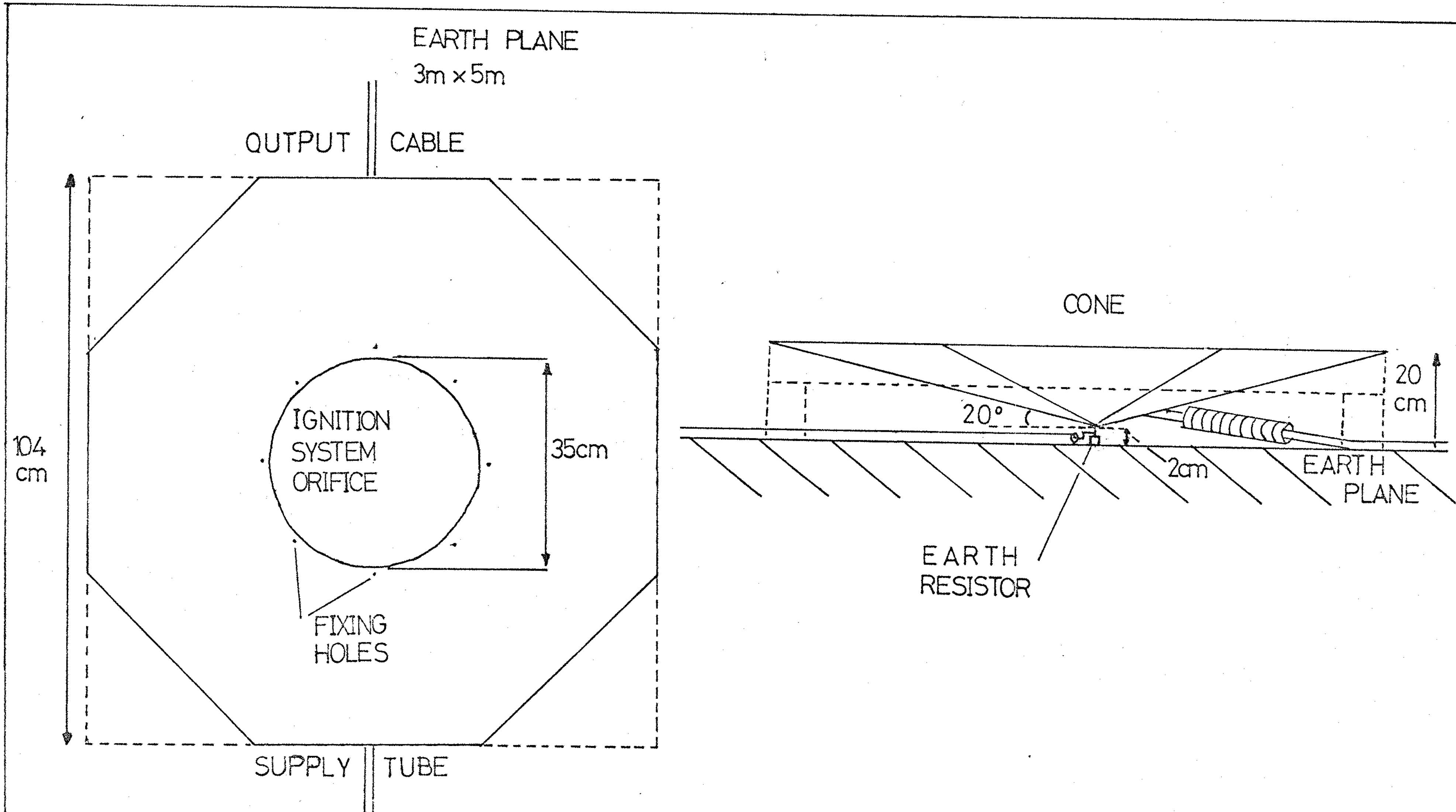
FIG. 5·2





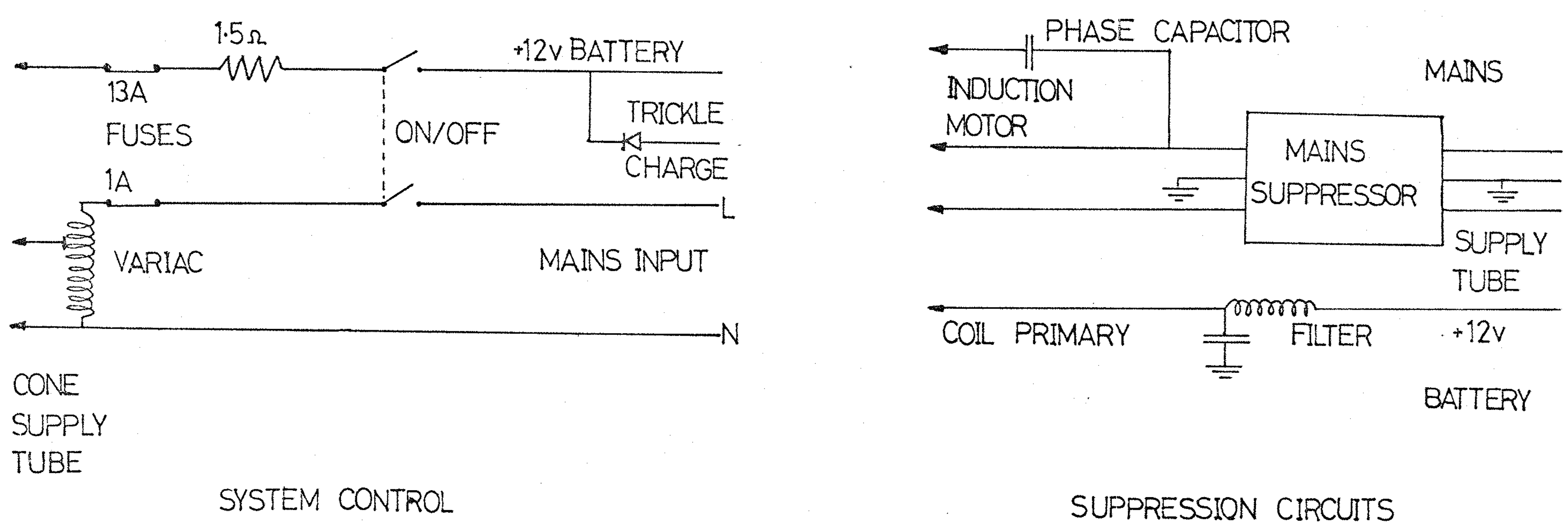
EARTH CURRENT CONE

FIG. 5·3



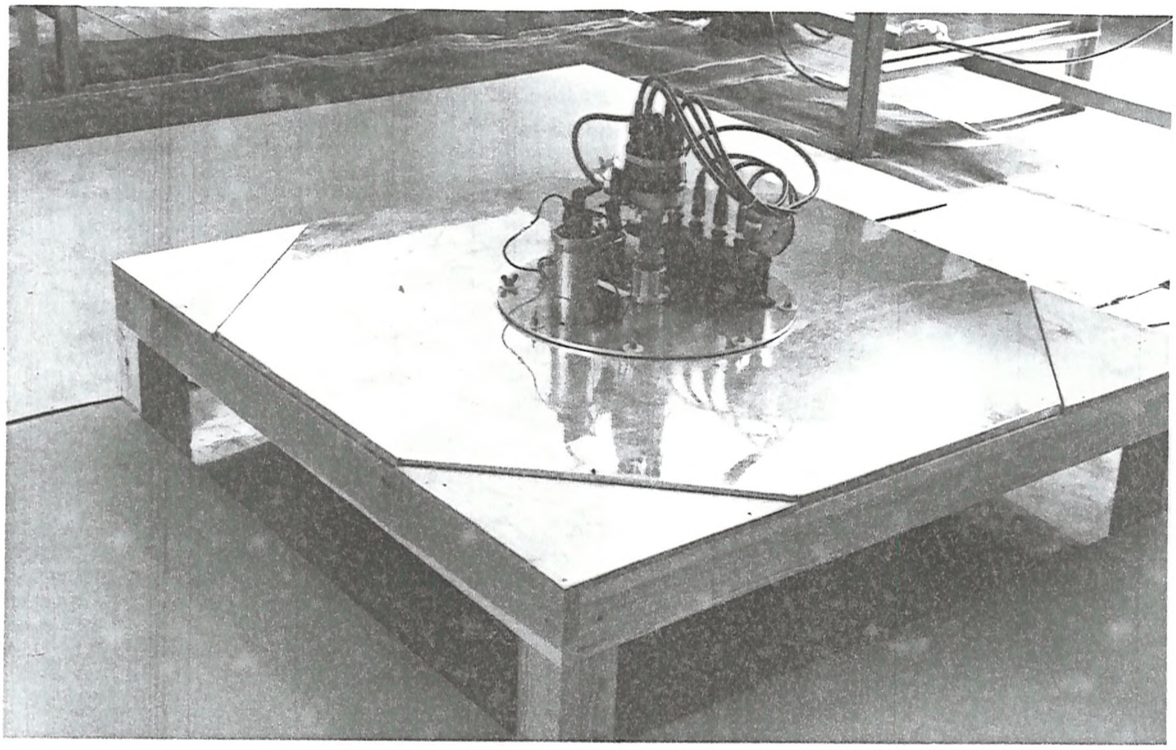
PHYSICAL REALISATION OF EARTH CONE

FIG. 5·4



EARTH CONE ELECTRICAL SUPPLY SYSTEM

FIG. 5·5



EARTH CONE AND IGNITION SYSTEM (Earth plane in background)

FIG. 5.6

CHAPTER 6

RESULTS

A detailed analysis into the effect of individual suppression components is given in the conclusion, Chapter 9.

Results are given in graph form in figs. 6.1 - 6.8 and are drawn from the data presented in Appendices 1.1 - 1.3. A response is plotted for each of the cable systems against interference, relative to the reference level, and manufacturing cost of the suppression components. The component combination were given in code form on the SIPCON response and may be related to that of the wire system by subtracting £0.14 from the manufacturing cost. The component code was given in Table 4.1 and is repeated below for ease of reference.

A - Rotor

B - Resistive Rotor

C - Resistive Plugshields

D - H.T. Distributor Resistors

E - Wire H.T. Cable

F - SIPCON H.T. Cable

G - Spark Plugs

H - Resistive Spark Plugs

I - Resistive Plugboots

6.1 Interference Results from Ford Capri

(By inspection of figs. 6.1 - 6.4).

6.1.1 Wire H.T. Cable System

Results fluctuate considerably from zero to maximum suppression and is marked for Medium Wave (∿45dB). The resistive rotor is most successful in suppression, but when used with four distributor resistors no advantage is gained. Plugshields have best relative effect at V.H.F., and their effect is enhanced at low frequencies when used with the resistive rotor. Resistive spark plugs are successful for simple suppression systems involving four distributor resistors.

Resistive plug boots appear to be more efficient than the resistive plugshields, and affect suppression most when used with the resistive spark plug including other suppressors. There is least variation of suppression for V.H.F. as in the previous graphs.

6.1.2 Resistive H.T. Cable System

Interference levels are relatively insensitive to suppression component variations. Medium Wave is most active with a suppression fluctuation of 10dB, where rotor suppression is accentuated for combinations including distributor resistors + resistive spark plugs and plugshields.

6.1.3 Comment on Results from Ford Capri

The maximum available suppression from the wire H.T. system reaches the SIPCON reference level for the Medium and V.H.F. wavebands. Long Wave suppression only equals this level through the use of plugboots.

The resistive rotor can cause a suppression variation of nearly 30dB. It also is beneficial when used with the SIPCON system to achieve optimum Medium Wave suppression.

6.2 Interference Results from Earth Cone

(By inspection of figs. 6.5 - 6.8).

6.2.1 Wire H.T. Cable System

Long and Medium Waveband results produce little suppression fluctuation, whereas those of V.H.F. exhibit a 45dB range. The resistive rotor is effective in all frequency bands, especially at V.H.F. Distributor resistors have little effect at low frequencies, but this is reversed at V.H.F. Plugshields, resistive spark plugs and plugboots are ineffective on Long Wave, but their performance improves with increasing frequency. The resistive rotor occasionally has a detrimental effect when used with plugboots.

6.2.2 Resistive Cable H.T. System

There is no variation of results for Long Wave and practically none for Medium Wave, whereas V.H.F. is the most sensitive with 20dB suppression. The resistive rotor may decrease suppression performance, but is used to optimum effect with resistive spark plugs at V.H.F.

6.2.3 Comment on Results from Earth Cone

V.H.F. results from the Earth Cone are similar in nature to those from the Ford Capri. The difference between the interference levels from the wire H.T. system on Long and Medium Wavebands is a maximum of 6dB from the SIPCON reference. There is no apparent dominant suppression component, other than the resistive rotor, for the two wavebands. No comparison is possible with the Ford Capri results, see Section 8.2.

Detailed investigations outside the three wavebands were not undertaken. However several tests revealed that V.H.F. results were applicable for frequencies down to 5-10MHz, after which those from the Long and Medium Wavebands were valid.

6.3 Results for Optimum Suppression and Cost for Ford Capri and Earth Cone

Examination of the results from the two measurement systems indicate the ignition interference suppression components that provide optimum suppression and manufacturing cost. The three most successful combinations for each of the three wavebands are indicated in Tables 6.1 and 6.2. If similar suppression is obtained for several combinations, the cheapest version is given priority. This condition for optimum suppression and cost in one waveband is not necessarily correct for the other two.

TABLE 6.1 OPTIMUM FORD CAPRI RESULTS

Waveband	Suppression Components									Manufacturing Cost £	Suppression dB
	A	B	C	D	E	F	G	H	I		
Long Wave	x					x	x			0.14	0
Long Wave		x				x	x			0.17	0
Long Wave	x					x		x		0.40	0
Medium Wave		x		x		x		x		1.29	10
Medium Wave		x	x			x	x			1.41	10
Medium Wave		x	x			x		x		1.81	10
V.H.F.		x	x			x		x		1.81	2
V.H.F.		x	x	x	x		x			1.99	2
V.H.F.	x		x	x		x	x			2.13	2

TABLE 6.2 OPTIMUM EARTH CONE RESULTS

Waveband	Suppression Components A	B	C	D	E	F	G	H	I	Manufacturing Cost £	Suppression dB
Long Wave		x	x					x		1.67	2
Long Wave		x	x	x				x		2.39	2
Long Wave	x					x	x			0.14	0
Medium Wave		x	x					x		1.67	10
Medium Wave		x	x	x				x		2.39	6
Medium Wave		x	x				x			1.27	5
V.H.F.		x	x	x			x			1.99	20
V.H.F.	x		x	x		x	x			2.10	18
V.H.F.	x		x	x		x		x		2.50	16

6.4 Further Results

The Earth Cone measurement system lent itself to further experimentation with ignition component variations for its various elements were easily altered.

6.4.1 Ignition Component Variations with SIPCON H.T. Cable

Four used resistive spark plugs of varying resistences (3.5 - 6kΩ) were compared with new AGR22 plugs. Interfence spectrum change was negligible.

A normal unsuppressed rotor was modified so as to present a smaller surface area to the distributor H.T. electrodes. The rotor arc length was decreased from 2cm to 1cm and finally filed down to a sharp point. Results showed a slight suppression of 1-2dB above 100MHz[52]. The duration of the ignition spark remained unaltered by this variation. A pitted contact breaker did not increase interference levels.

A test was carried out to see if a change in ignition coil affected results. An old coil was available and was smaller.

CHARACTERISTICS OF IGNITION COILS

	Primary		Secondary		Ballast Resistor
Original	4mH	1.1Ω	40H	7kΩ	1.5Ω
Old	5.8mH	1.4Ω	65H	7.5kΩ	2.75Ω

The old coil produced similar results to the original, except that there was no trace of the slight resonance that was detected on the original coil at 50MHz. See Earth Cone Calibration Curve (fig. 4.2).

A high resistance ignition cable was available (Ford RIST 0415, 40kΩ/m) and was substituted for SIPCON cable (17kΩ/m). No difference was found in results.

6.4.2 Effect of Variation of Wire H.T. Cable Length

If the propagation delay time of a signal transmitted along a cable is longer than its fastest rise time[45], resonance effects will occur. This is equivalent to quarter wavelength resonance[40]. The ignition H.T. cable is excited at all frequencies and exhibits resonance phenomena in its radiation characteristics. The propagation delay time of a cable is affected by its construction, curvature and ground capacitance, and have the effect of lowering the resonant frequencies.

An experiment to measure these resonance variations within the ignition system was attempted by altering the lead lengths and noting the change or absence of resonance frequency. See below for length variations and SIPCON lead lengths for comparison.

Plug No.	Wire	Shortened Wire	SIPCON
1	50cm	20cm	55cm
2	50cm	25cm	55cm
3	60cm	30cm	60cm
4	75cm	30cm	75cm
Coil	30cm	30cm	30cm

With the original ignition leads the lowest resonance obtained was 86.8MHz. When No. 4 lead was shortened this resonance disappeared revealing a lower amplitude resonance at 89MHz which disappeared with the shortening of the No. 3 lead. The shortening of the remaining two plug leads decreased interference levels above 50MHz.

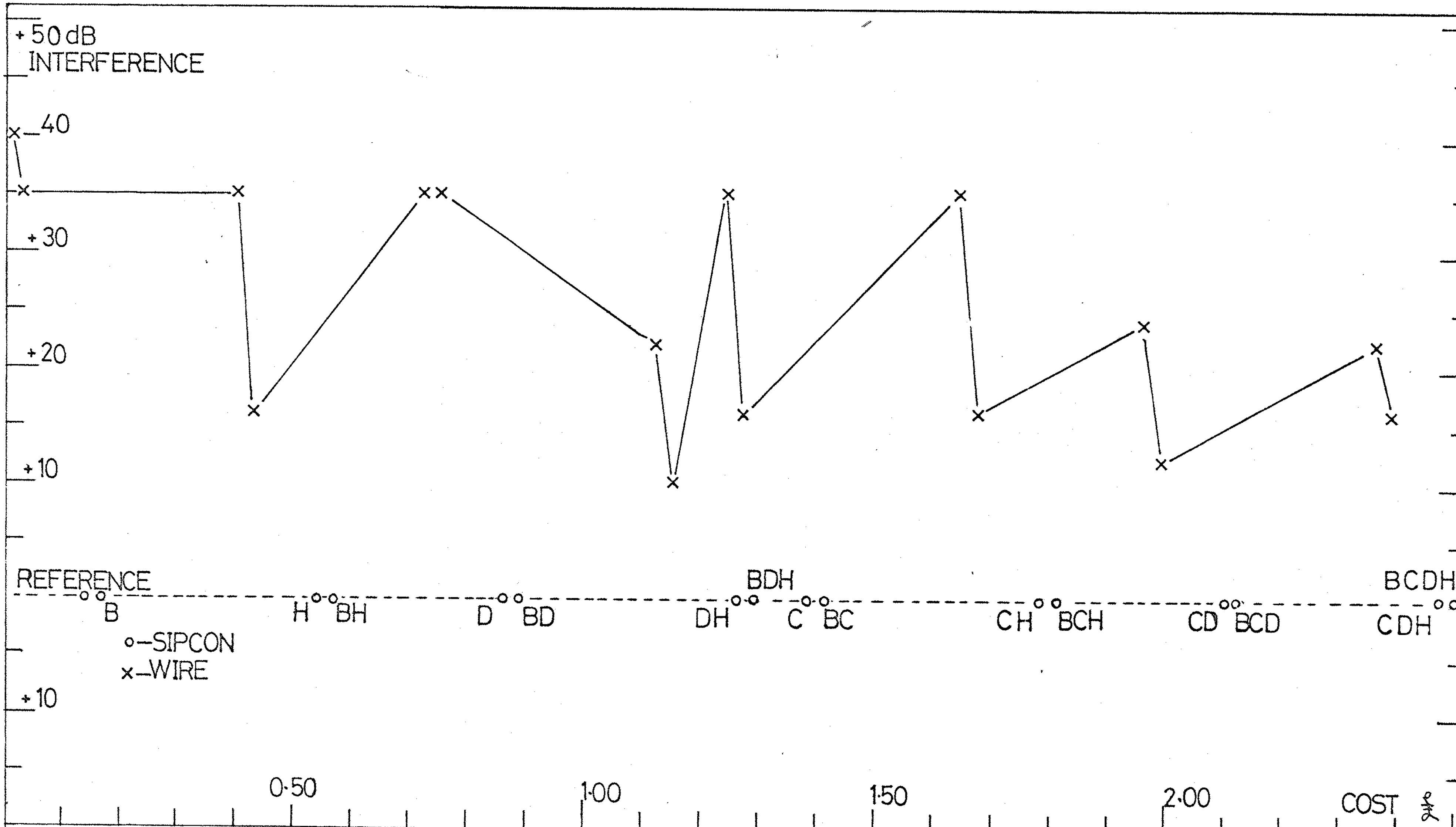
The effect of shortening the leads was to increase the resonant frequency and to generally decrease interference.

Similar results were obtained by connecting a solitary resistor in the No. 4 lead. Resonance is further decreased with a resistor in the No. 3 lead.

6.4.3 Performance of SIPCON System 10MHz-2GHz

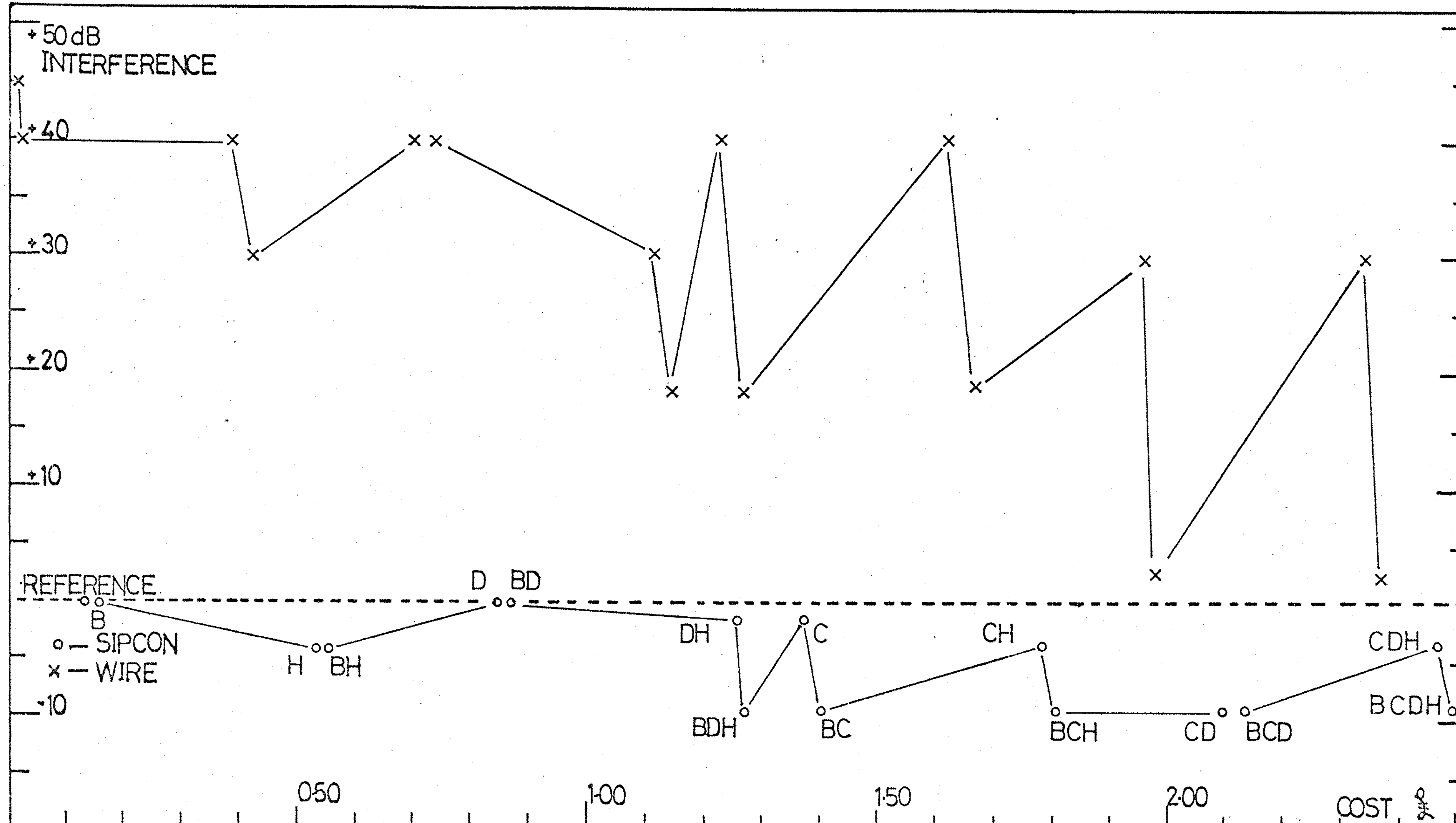
A Hewlett Packard 851B spectrum analyser was substituted for the Marconi TF2370 so as to measure a far greater frequency range extending from 10MHz to 2GHz. See fig. 6.9 for the resultant interference plot. Results are normalised to dBμv/MHz. The 3dB bandwidth used was 100kHz. Results are similar to those taken from the TF2370 and there appeared to be negligible gain compression. There was little signal persistence on the 851B screen but this was overcome by marking the interference spectra levels on the display screen as they appeared.

The spectrum falls off at the rate of approximately 6dB/octave and is likely to be due to the decreasing sensitivity[50] of the Earth Cone with frequency. (Section 5.2.1).

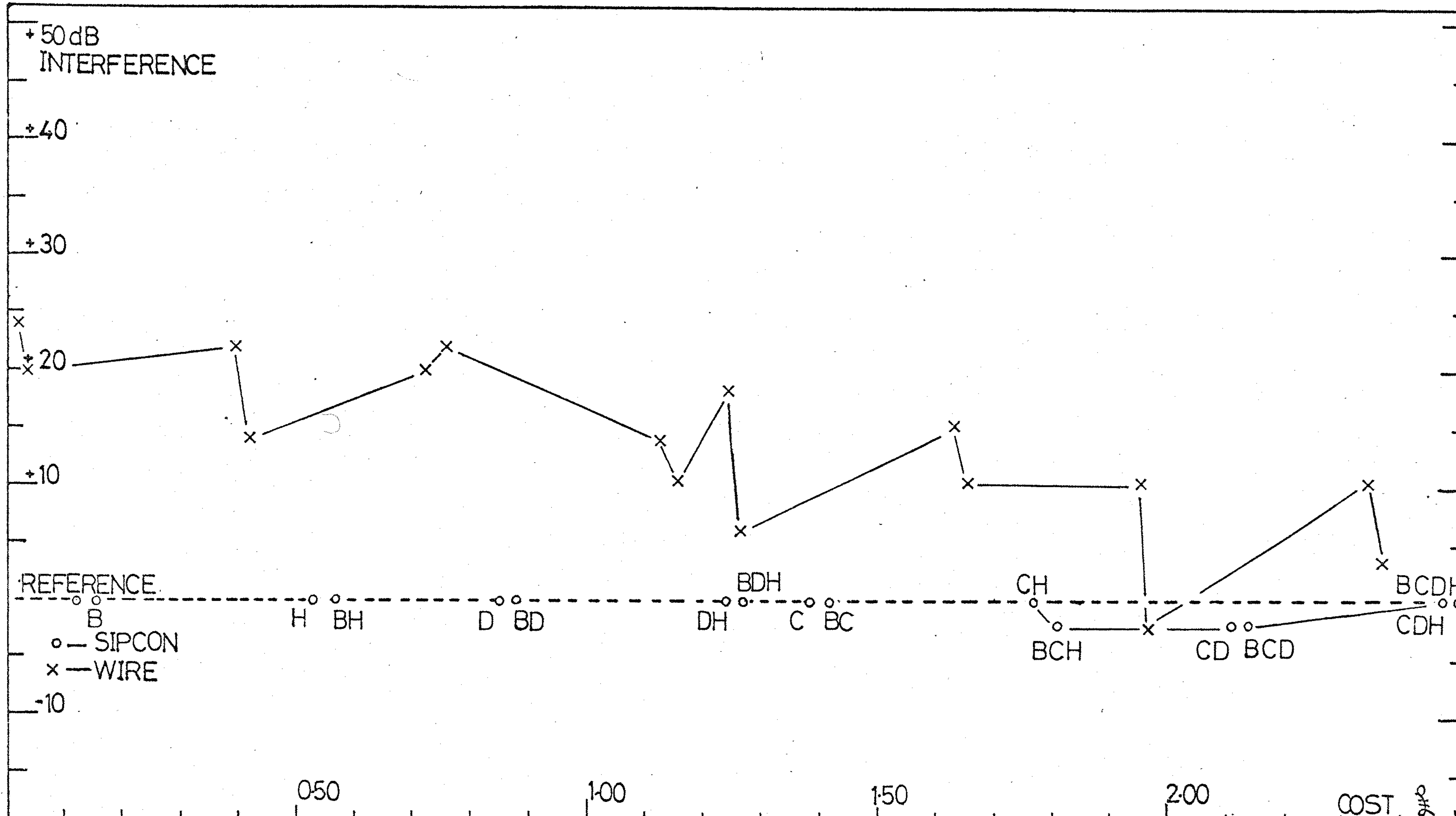


LONG WAVE SUPPRESSION–FORD CAPRI INTERFERENCE [Re. SIPCON] VS. COST

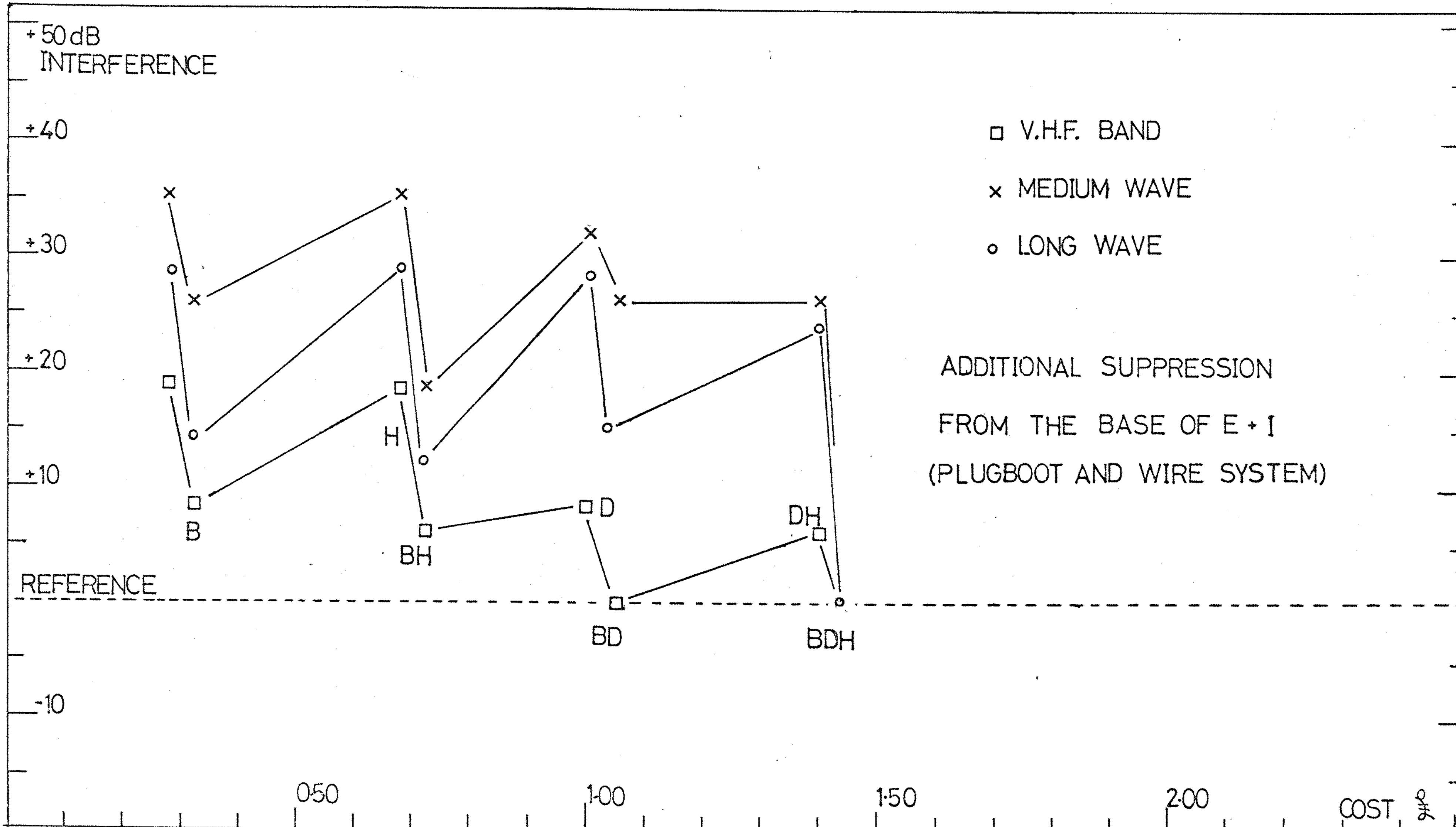
FIG. 6·1



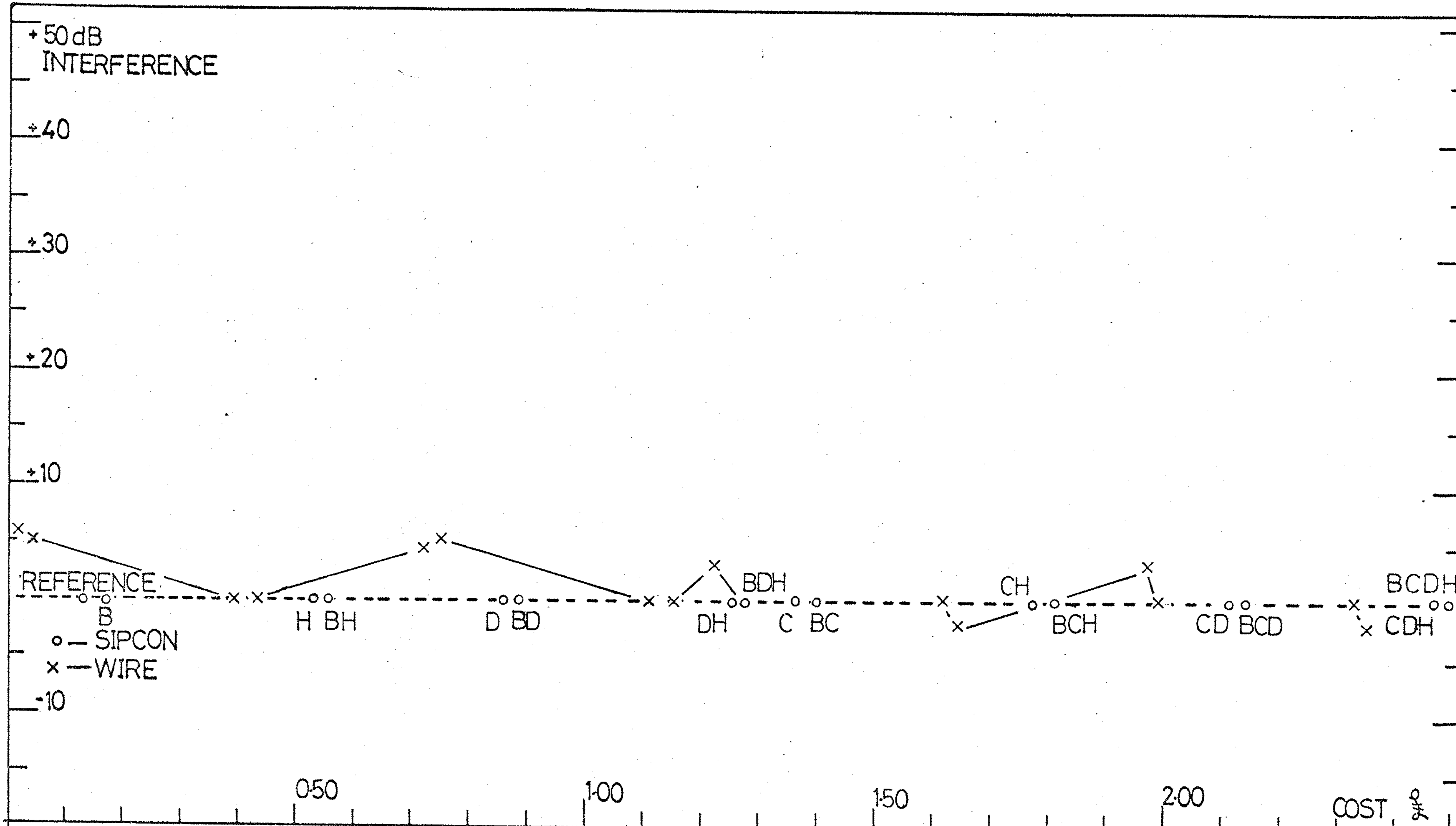
MEDIUM WAVE SUPPRESSION—FORD CAPRI INTERFERENCE [Re. SIPCON] VS. COST FIG. 6·2



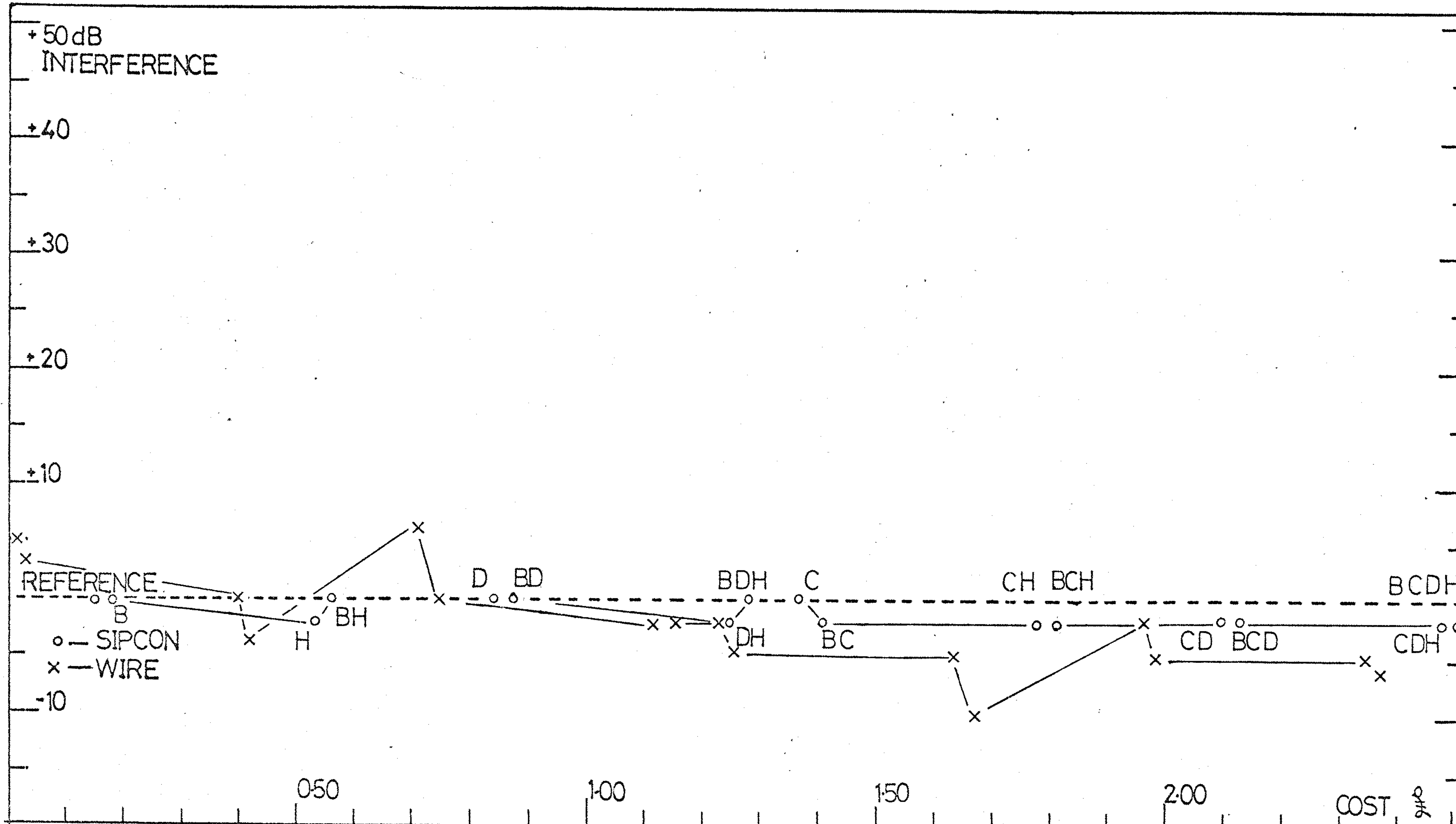
V.H.F. BAND SUPPRESSION — FORD CAPRI | INTERFERENCE [Re. SIPCON] VS. COST | FIG. 6·3



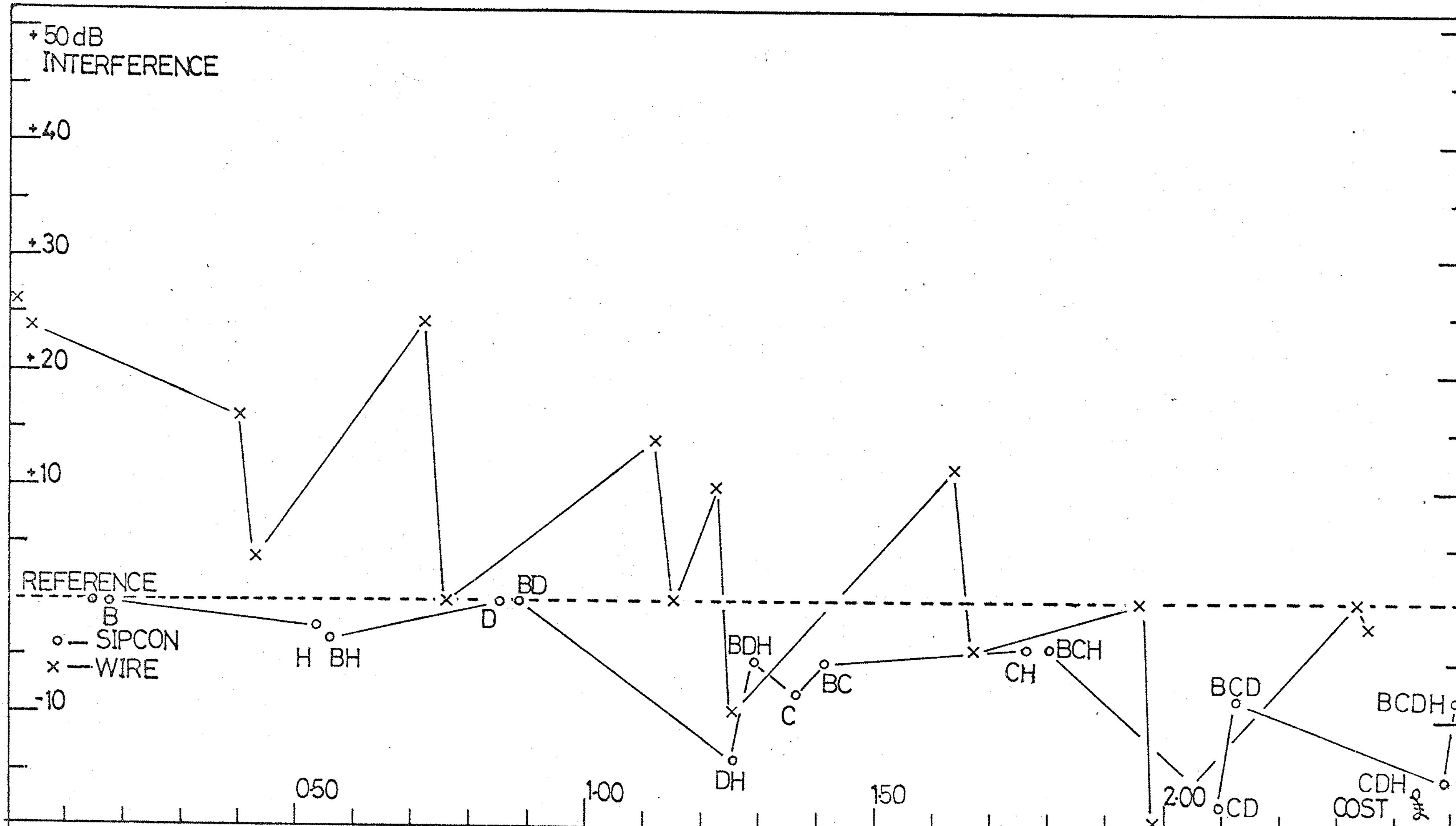
ALL BAND SUPPRESSION (E + I) — FORD CAPRI INTERFERENCE [Re. SIPCON] VS. COST | FIG. 6·4



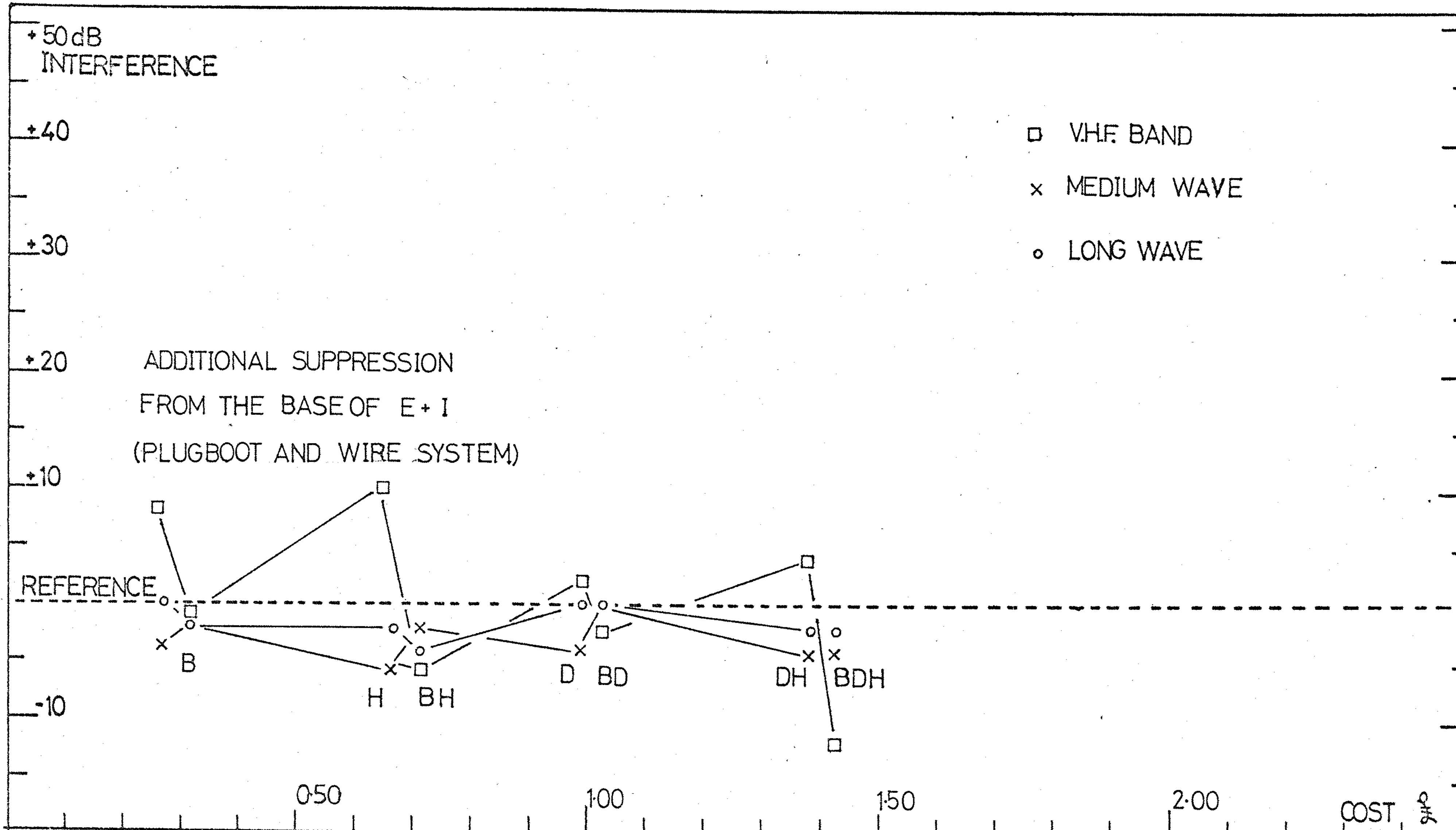
LONG WAVE SUPPRESSION — EARTH CONE | INTERFERENCE [Re. SIPCON] VS. COST | FIG. 6·5



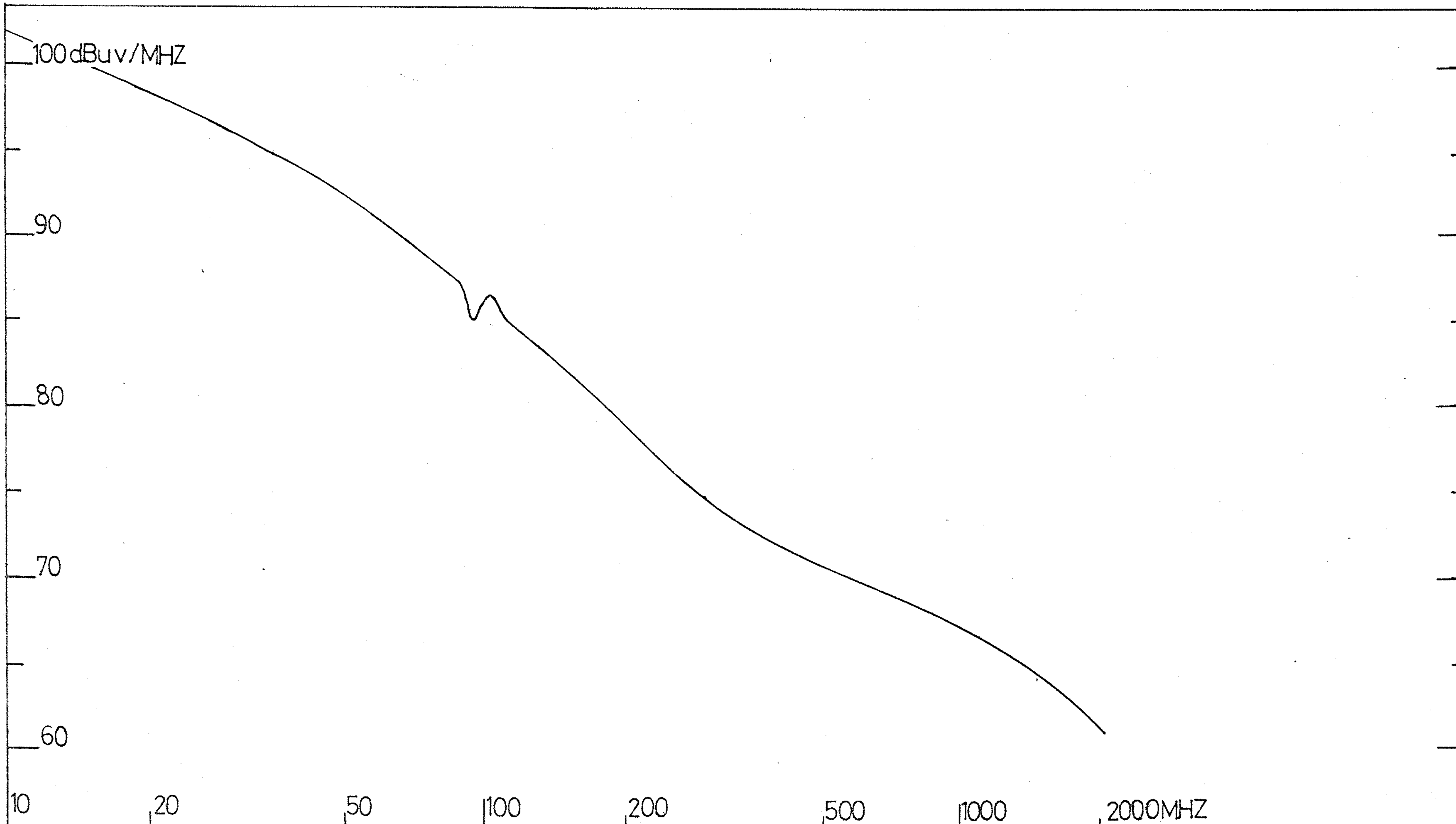
MEDIUM WAVE SUPPRESSION–EARTH CONE INTERFERENCE [Re. SIPCON] VS. COST FIG. 6·6



V.H.F. BAND SUPPRESSION — EARTH CONE INTERFERENCE [Re. SIPCON] VS. COST FIG. 6·7



ALL BAND SUPPRESSION (E+I) — EARTH CONE INTERFERENCE [Re. SIPCON] VS. COST FIG. 6·8



EARTH CONE INTERFERENCE 10MHZ - 2GHZ.dBuv/MHZ VS. FREQUENCY.

FIG. 6.9

CHAPTER 7

IGNITION SYSTEM VOLTAGE MEASUREMENTS

7.1 Earth Cone H.T. Voltage Measurements

7.1.1 Measurement Procedure

Various voltage measurements were taken from the Earth Cone ignition system using a Tektronics E.H.T. probe. The H.T. waveforms were displayed on a delayed trigger oscilloscope to enable viewing of any section of the ignition process. The SIPCON system was used.

The H.T. voltage waveforms were of a complex nature and could initially be divided into two parts. The least important is produced by the contact breaker closing and connecting the full battery supply across the ignition coil primary. The main waveform occurs as the contact breaker opens which disrupts the primary current flow, and initiates the coil secondary pulse which would eventually breakdown the distributor and plug spark gaps.

The secondary waveforms were found to be erratic in nature and difficult to photograph. Some contained very little useful information though occasionally it was possible to view exceptionally complex waveforms.

7.1.2 Coil Voltage Waveform

The ignition time period for each spark was found to be 28.5ms and the contact breaker closed 16ms after the time of opening.

A typical discharge is given in fig. 7.1. A negative voltage swing is first seen after the contact breaker opens and at approximately 7kv the distributor gap breaks down. The arc discharge lasts for about 1ms after which the residual oscillatory energy in the coil secondary is dissipated. During closure of the contact breaker a 1kv pulse is transformed to the coil secondary.

Fig. 7.2 indicates detail of electrical discharge across the coil secondary. The discharge voltage across the distributor and plug spark gaps gives a total discharge voltage of just over 1kv. This voltage exhibits slight curvature and minor damped oscillation.

7.1.3 Spark Plug Voltage Waveform

When the distributor gap breaks down, H.T. voltage is applied to the spark plug which breaks down at a slightly less strike voltage than the distributor. The arc discharge voltage is approximately 460v, and gradually increases in magnitude. After approximately 1ms the discharge extinguishes (See fig. 7.3). Damped oscillation immediately after discharge is due to feedthrough coupling from the ignition leads and not from the plug itself.

A modified distributor rotor tip was used in an attempt to alter the 1ms discharge time, but this was found to be independent of rotor surface area. The normal overlap time of the rotor and distributor turret electrode is calculated to be between 0.5 and 0.7ms for an engine speed of 1450 r.p.m. It appears that the distributor arc length varies so as to maintain the spark plug discharge.

Towards the end of the discharge in fig. 7.3 there is discharge instability which is one of the causes of radio frequency interference.

There is no change of results with suppression component variations.

7.2 Dipole and Earth Voltage Measurements on Earth Cone

A dipole antenna and the earth voltage developed across the earth resistor Re monitored, in the time domain, the high frequency waveforms produced by the ignition process. A dual trace oscilloscope was used. The vertical dipole was 30cm in length and was positioned 2m away from the ignition system. The voltage developed across Re produced a waveform related to the radiated power which had already been measured by the spectrum analyser in previous experiments for frequency domain analysis.

The resistive SIPCON cable suppression was used.

High frequency voltage fluctuations were not visible from the H.T. voltage results of the previous section. However with dipole and earth current waveforms the low frequency perturbations are decreased revealing high frequency effects. (See figs. 7.4, 7.5 and 7.6 for the resultant waveforms). Vertical calibration is not given for it bears no useful information, only the shape and comparison of the waveforms being important. The top trace is that of the dipole and has similar form to the ignition process as seen on previous H.T. waveforms. There is high frequency enhancement. The lower trace is that of the earth voltage. The similarity between the traces is that a fluctuation in one leads to a fluctuation in the other. The initial H.T. rise causes a low frequency perturbation, after which there is R.F.I. producing perturbations which last for approximately 0.2ms. However as the discharge process continues there is the likelihood of yet more perturbations, but this is more or less confined to the region of discharge extinction. Similar results were found, but of a much lower level, of interference produced by contact breaker closure.

7.3 Ford Capri H.T. Voltage Measurements

A similar series of H.T. voltage measurements were taken on the Ford Capri as on the Earth Cone system (see figs. 7.7, 7.8 and 7.9). The strike voltages were comparable but the discharge voltages, though of similar average magnitude, bear different discharge curvature. The spark plug discharge voltage increases at a faster rate than that of the Earth Cone. The coil voltage bears less oscillation after extinction, but during discharge there is an apparent increase and then decrease in arc voltage. Arc curvature is more prominent in this system than in the Earth Cone. This variation is likely due to the combustion process at the spark gap of the plug, and arc voltage interaction between the two spark gaps.

7.4 Voltage Fluctuation at Point of Spark Gap Breakdown

An attempt was made to produce consistent H.T. Voltage results at the moment of a spark gap striking by using an electronic trigger system to replace the contact breakers. Such a system was installed under a replacement centre piece on the Earth Cone system. Whilst the original distributor and spark plugs were replaced by a stationary distributor and a simulated spark plug. Trigger and power cables were supplied through the supply tube at the base of the cone. The spark plug consisted of a brass surround fitted with a plug of P.T.F.E. through which the centre electrode was positioned. The dimensions of the surround were chosen so as to simulate a spark plug capacitance of 11pF. (See fig. 7.10 for the electronic trigger circuit).

Several interference measurements were taken with the system and were mainly inconclusive. For example, when the variation of interference levels with a change in spark gap length was measured, suppression was found to increase with decreasing length. When results were repeated, the previous levels were not reproduced. The reasons for measurement inconsistency was probably due to electrode surface variations.

Success was had with H.T. measurements involving voltage fluctuations during the initial striking of a spark gap. A commercial spark gap[54] was available containing a transport gas (N_2H_2) with a 75×10^{-3}cm gap. This was compared with a 62.5×10^{-3} cm air gap. The simulated spark plug was taken out of circuit, and the simulated distributor used as the spark gap and measurement point. The H.T. probe was connected to the 'live' side of the distributor. The resultant H.T. fluctuations at the striking point are given in figs. 7.11 and 7.12, the ignition point being at two graticule lines left of centre. Oscilloscope triggering took place at the moment of discharge. The sweep fluctuated ±3kv before the spark gap voltage settled down to the arc voltage which was positioned halfway up the oscilloscope screen. The greatest fluctuations occur before 0.2μs after the commencement of discharge. The character of the two discharges are found to be unalike in that the air discharge exhibits an early voltage plateau and then reverts to a similar oscillatory behaviour as the N_2H_2 spark gap.

In a different series of experiments the simulated distributor and spark plug (62.5×10^{-3} cm spark gaps) were reconnected and two H.T. probes were positioned on the ignition coil secondary and at the spark plug. Results were taken at commencement of discharge (see fig. 7.13) for the dual trace oscilloscope response. The trace that originates at the bottom left is that of the coil secondary H.T., and appears settled after 20μs. From the top left, the absolute value of the plug voltage is increasing as the stray capacitance becomes charged, and discharge occurs 10μs (approximately) after the coil. The voltage across each spark gap settled to approximately 400v. The traces of the arc voltage responses are seen to be correlated.

The probes used had a × 1000 attenuation factor and an equivalent input impedance of 100MΩ in parallel with 3pF. Voltage feedthrough, bypassing the probes, was found to be of negligible proportions.

7.5 Interdependence of Spark Instability

From the evidence of the previous section it may be possible that spark instability can be transformed from one spark gap to the other. Similarly, interference reducing components at one source may hinder the stability of the other[2].

Consider the inductive region of an ignition system arc discharge. The distributor and spark plug have similar responses to the H.T. voltage, and the overall response as measured by the coil secondary voltage is the sum of the two. It also carries information concerning coincident spark plasma collapse. This effect has been viewed in previous experiments using two high voltage probes and the electronically triggered ignition system. A permanent record of the process could not be obtained due to the effect being faint and erratic.

The combined arc voltage of the two spark gaps is typically 900v, which during plasma collapse, may be reduced to less than 200v. Individual plasma collapse would only reduce the combined voltage by at most 450v, which is observable on the plug H.T. waveform. This is evidence of interdependence of spark instability.

Interference radiated by the capacitive and inductive components of an electrical discharge may be of similar levels. Dominance of one over the other is difficult to ascertain[39,16], but it is probable that instability interdependence occurs in both.

Earth Cone

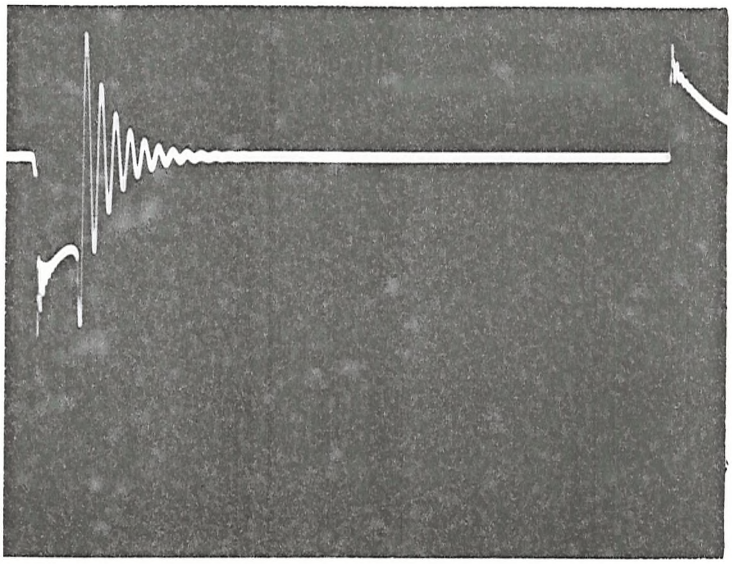


Fig. 7.1

Coil waveform

2ms/div.

1kv/div.

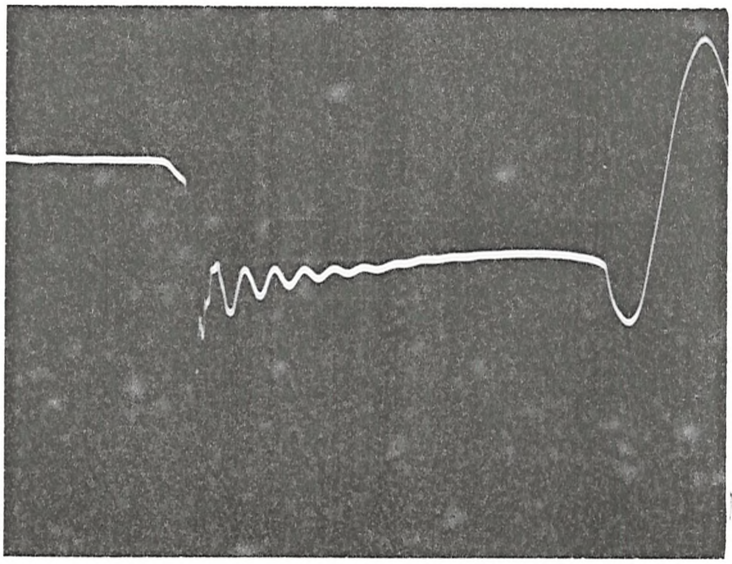


Fig. 7.2

Coil waveform

0.2ms/div.

1kv/div.

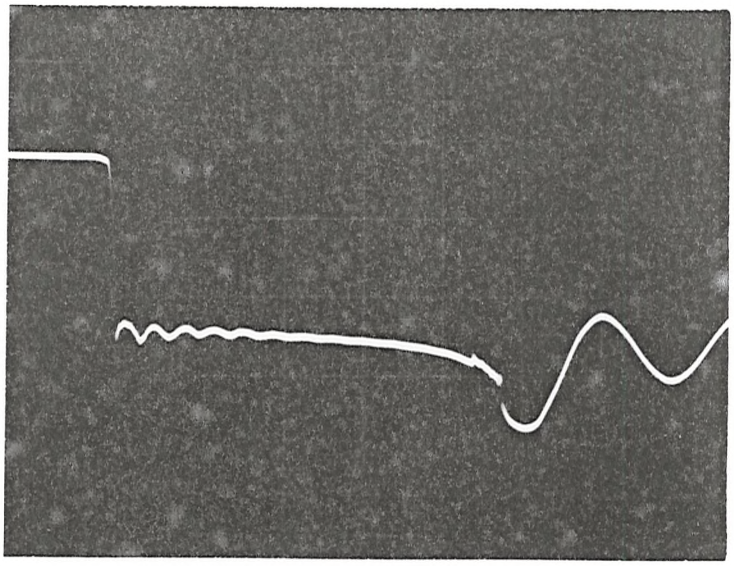


Fig. 7.3

Spark Plug waveform

0.2ms/div.

200v/div.

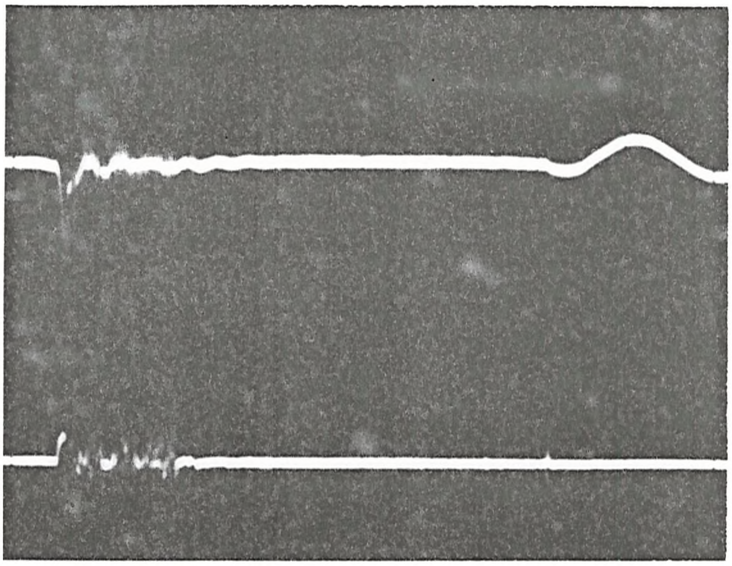


Fig. 7.4
Dipole and interference waveforms
0.2ms/div.

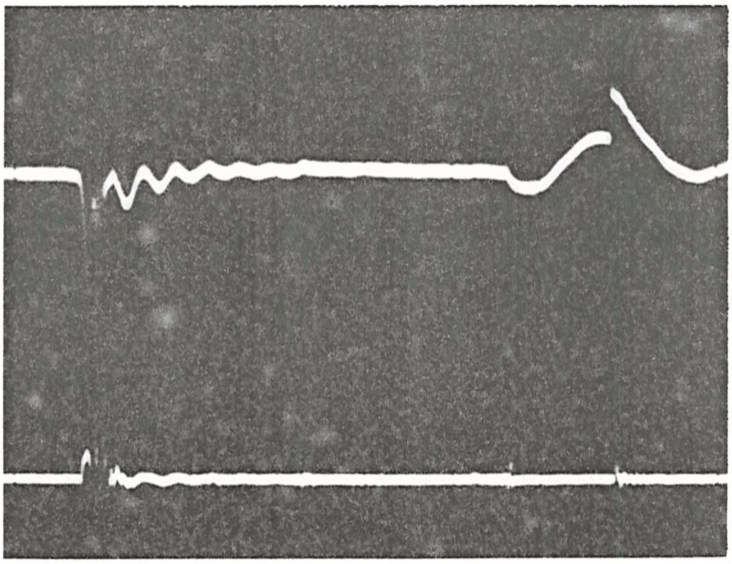


Fig. 7.5
As above
(re-strike after extinction)

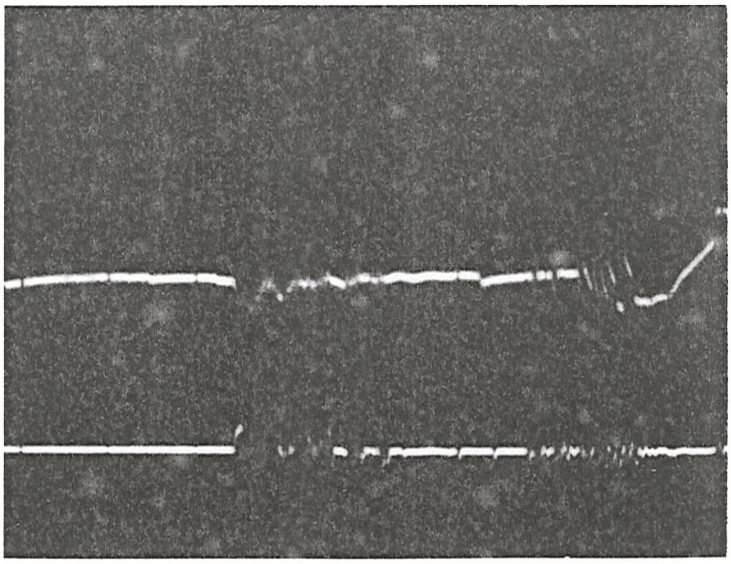


Fig. 7.6
As above
(Erratic arc)

Ford Capri

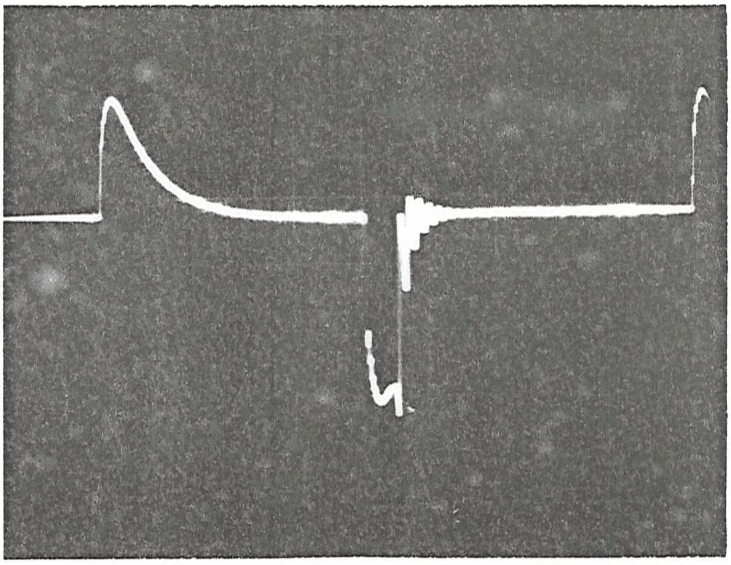


Fig. 7.7
Coil waveform
2.5ms/div.
500v/div.

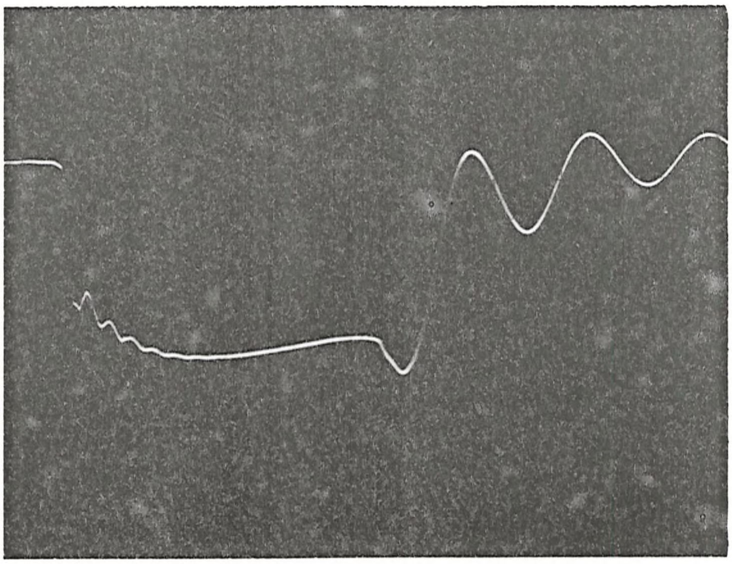


Fig. 7.8
Coil waveform
0.2ms/div.
500v/div.

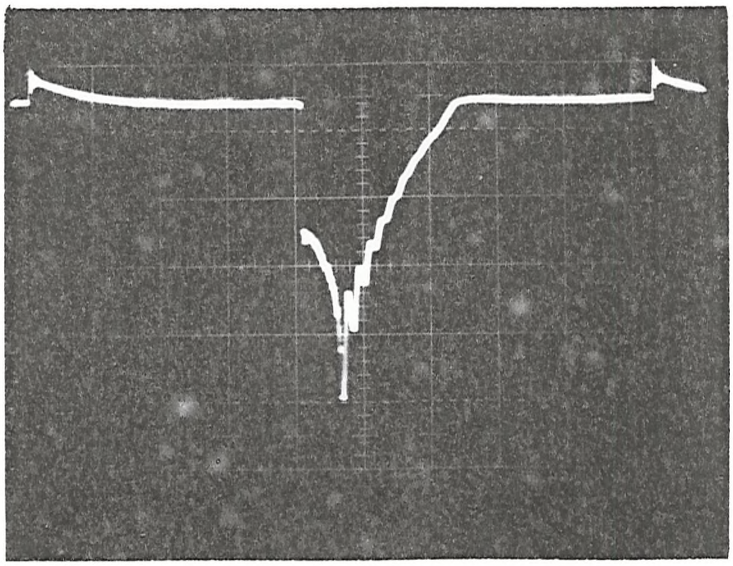
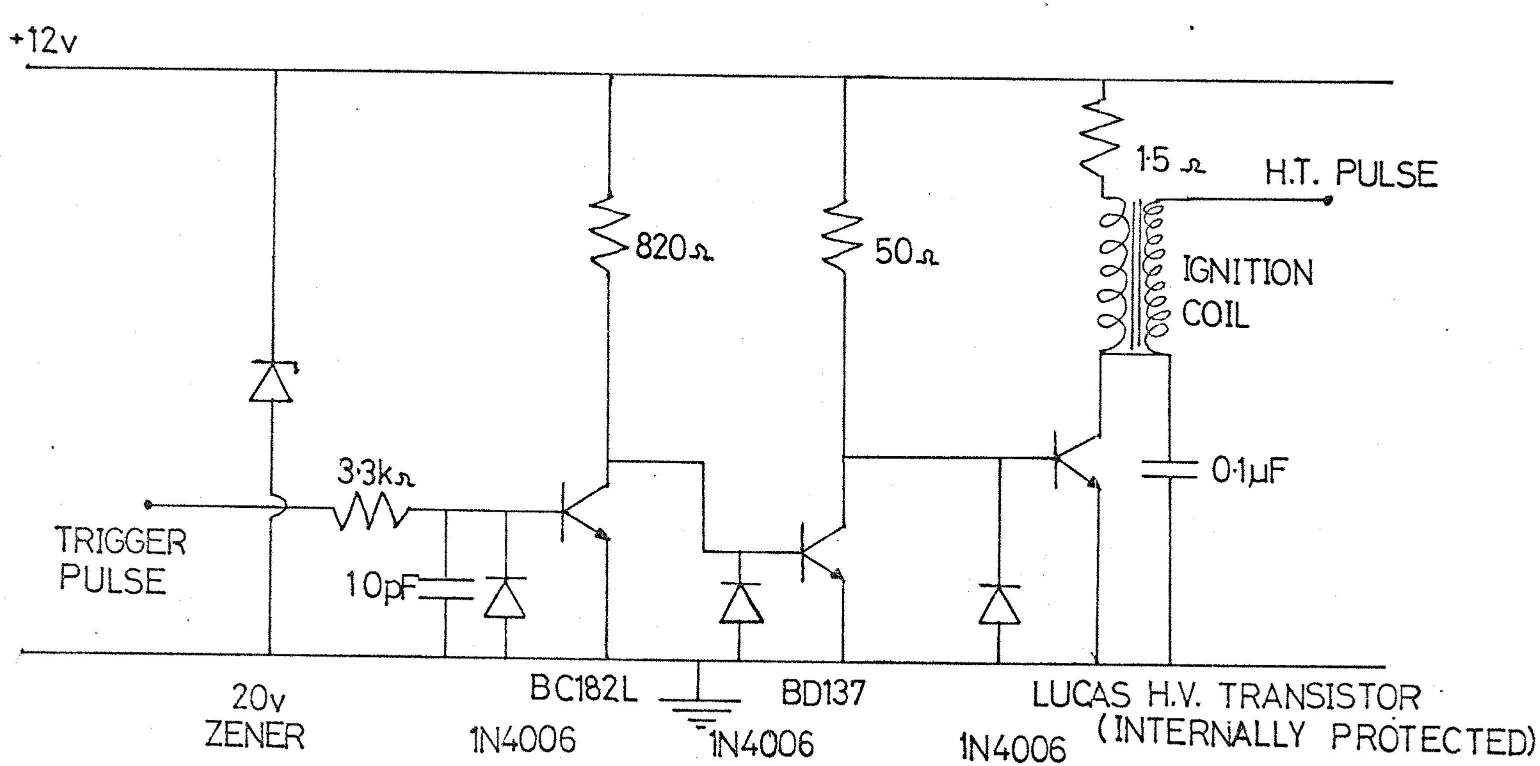


Fig. 7.9
Spark Plug waveform
2ms/div.
200v/div.



TRANSISTORISED IGNITION SYSTEM

FIG. 7·10

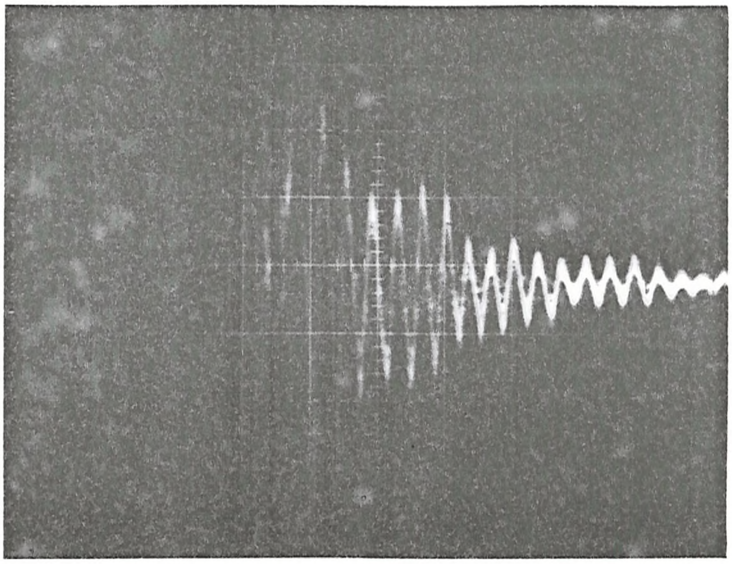


Fig. 7.11
N_2H_2 discharge
0.1μs/div.
1kv/div.

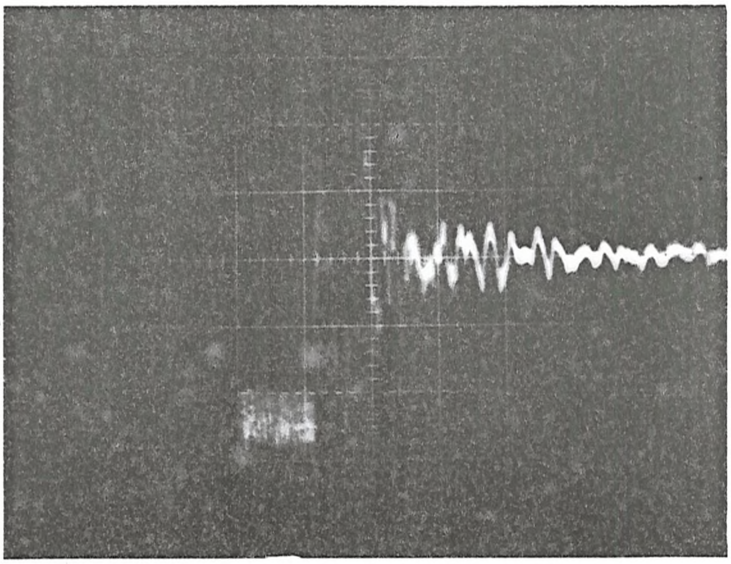


Fig.7.12
Air discharge
0.1μs/div.
1kv/div.

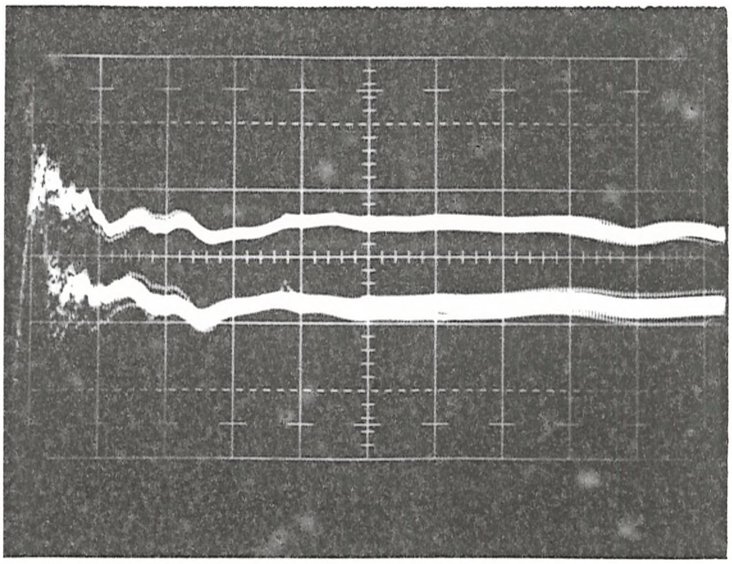


Fig. 7.13
Upper. Distributor discharge
20μs/div.
100v/div.
Lower. Plug Discharge
50v/div.

CHAPTER 8

ACCURACY OF MEASUREMENTS

8.1 Broadband Signal Response of the Spectrum Analyser

8.1.1 Analyser Gain Compression

The Marconi TF2370 Spectrum Analyser was used throughout the experimental procedure to form frequency-amplitude displays for interference levels. It was apparent from the start of experimentation that there was a broadband frequency overload problem. This was evident by the failure of a broadband frequency response to follow a change in sensitivity of the analyser.

The manufacturers specifications [43] quote a spurious response level 70dB below a signal level of -40dBm at the analyser input mixer for both single and double signal (500Hz apart, equal amplitude) conditions. Experiments using a pulse generator as a broadband frequency source suggest that the analyser broadband response distortion is worse than that for individual signals. A broadband signal of a continuous power level greater than -50dBm at the input mixer resulted in an overload condition in the form of gain compression. This level may well be different for other forms of impulse signal.

The operation of the analyser input circuitry and normal operation setting deserves further explanation. The gain and attenuation circuitry of the analyser are located in the radio and intermediate frequency (R.F. and I.F.) sections, and the attenuation combination is automatically selected for best I.F. amplifier noise characteristics in relation to the bandwidth, 'top of screen' datum level and display mode. Normal analyser usage for broadband R.F.I. employed a bandwidth of 50kHz, a display mode of 10dB/dm, and a 'top of screen' datum range of -30dBm to +30dBm. Under these conditions the quoted [43] level at the first input mixer is -20dBm for a signal amplitude referred to the datum. This is 20dB greater than the quoted (-40dBm) signal level for a -70dB spurious response. A level of -40dBm at the first mixer thus refers to -20dB below the analyser screen top, similarly the suggested -50dBm response for broadband interference is -30dB below.

8.1.2 V.H.F. Filter

Gain compression may be adequately rectified with the use of a filter, which has the desired bandwidth, centre frequency and skirt characteristics. The filter reduces the overloading effect of the frequencies outside the band of measurement. Such a filter was found necessary for the V.H.F. results taken from the Earth Cone to avoid gain compression.

A linear phase, equi-ripple filter[53] was used in order to preserve the amplitude and phase linearity of the interference spectrum. It was thought that any abrupt change in phase of the interference spectrum within the analyser bandwidth would give erroneous results.

The filter was designed to have 0.5 degree ripple, an insertion loss of 0.2dB, a centre frequency of 98MHz and a 3dB bandwidth of 22.8MHz (see figs. 8.1 and 8.2) for the capacitor coupled 4th order network, and the frequency response. The filter was coupled by an auto transformer to match the dissimilar input and output impedances to 50Ω. The approximate transmission loss was measured to be less than 1dB which is attributed to component (mainly capacitive) loss at the high frequency of operation. See Appendix 4 for filter design procedure.

8.2 Low Frequency Irregularity in Earth Cone Frequency Response

Calibration[50] of the Earth Cone system is based upon the measurement of the earth current induced in the cone top surface by a vertical $\lambda/4$ antenna situated at its centre. The resonance effect enhances the earth current. At low frequencies (<30MHz) the $\lambda/4$ length was too long to be practical and the metal earth plane lies in the near field. This must considerably alter the intended response of the measurement system, and hence cause the erratic results given in Chapter 6 for the Earth Cone in the Long and Medium Waves. These results do not bear any similarity to those of the Ford Capri and Earth Cone V.H.F. section.

The earth current is induced by the magnetic (H) vector field of the omni-directional spherical and vertically polarised wave as it sweeps across the cone surface for a centrally positioned simple antenna. Any variation in centralisation would alter the symmetry of the transmitted wave and thus cause irregularities[51] in the sensitivity of the measurement system. As the height of the antenna is increased the upper elements become more remote and causes a decrease in sensitivity. The $\lambda/4$ antenna is a special case which involves resonance phenomena.

An ignition system situated on a circular plate constitutes a complex antenna system which bears no similarity to a $\lambda/4$ antenna at any frequency and cannot be calibrated. For this reason a reference interference level was used to compare results.

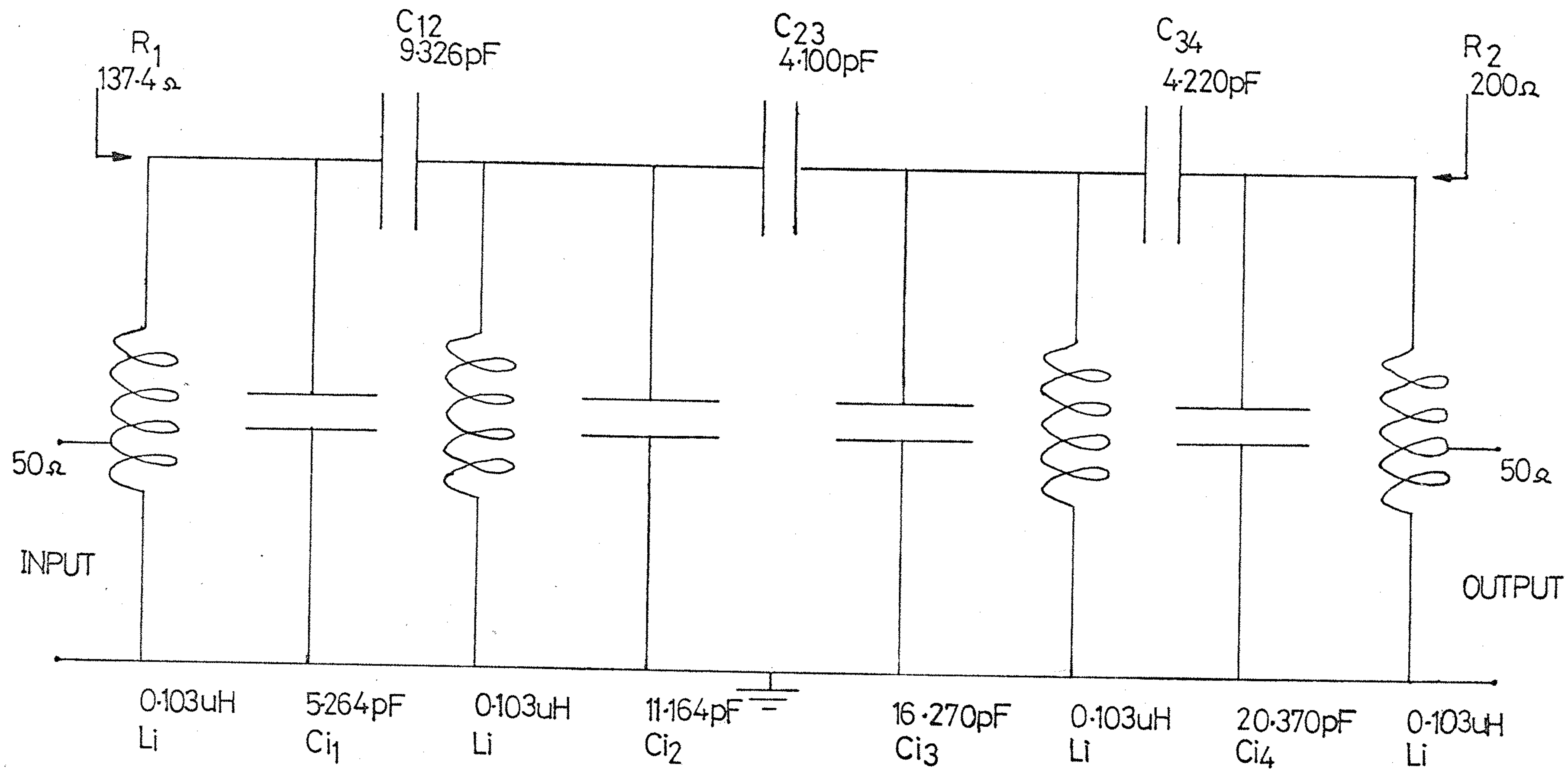
8.3 Repetitive Accuracy in Measurement

Measurements from the spectrum analyser were made by taking the difference of results between the suppressed system under test and the reference SIPCON system by means of the electronic screen graticule. The reference spectrum was either marked on the analyser screen or stored on a separate memory. Depending upon the amplitude distribution content of the spectrum, there was little difficulty in producing accurate difference results. The amplitude response is built up of individual interference spectra over a period of several minutes, though even after this time a clear cut spectrum may not be possible. 'Rogue' interference pulses were neglected as being uncharacteristic of the suppressed system under test. Confusion between rogue and normal spectra may lead to erroneous difference results.

Various experiments were attempted on the Earth Cone ignition system to determine whether the position of the ignition leads affected the interference levels. It was found that V.H.F. results were most sensitive, and out of the two types of cable the wire H.T. cable was most affected. Increased height led to increased interference. With the cable as low as possible, suppression occurred at frequencies lower than 50MHz. Throughout all experiments it was attempted to preserve the positioning of the H.T. cables.

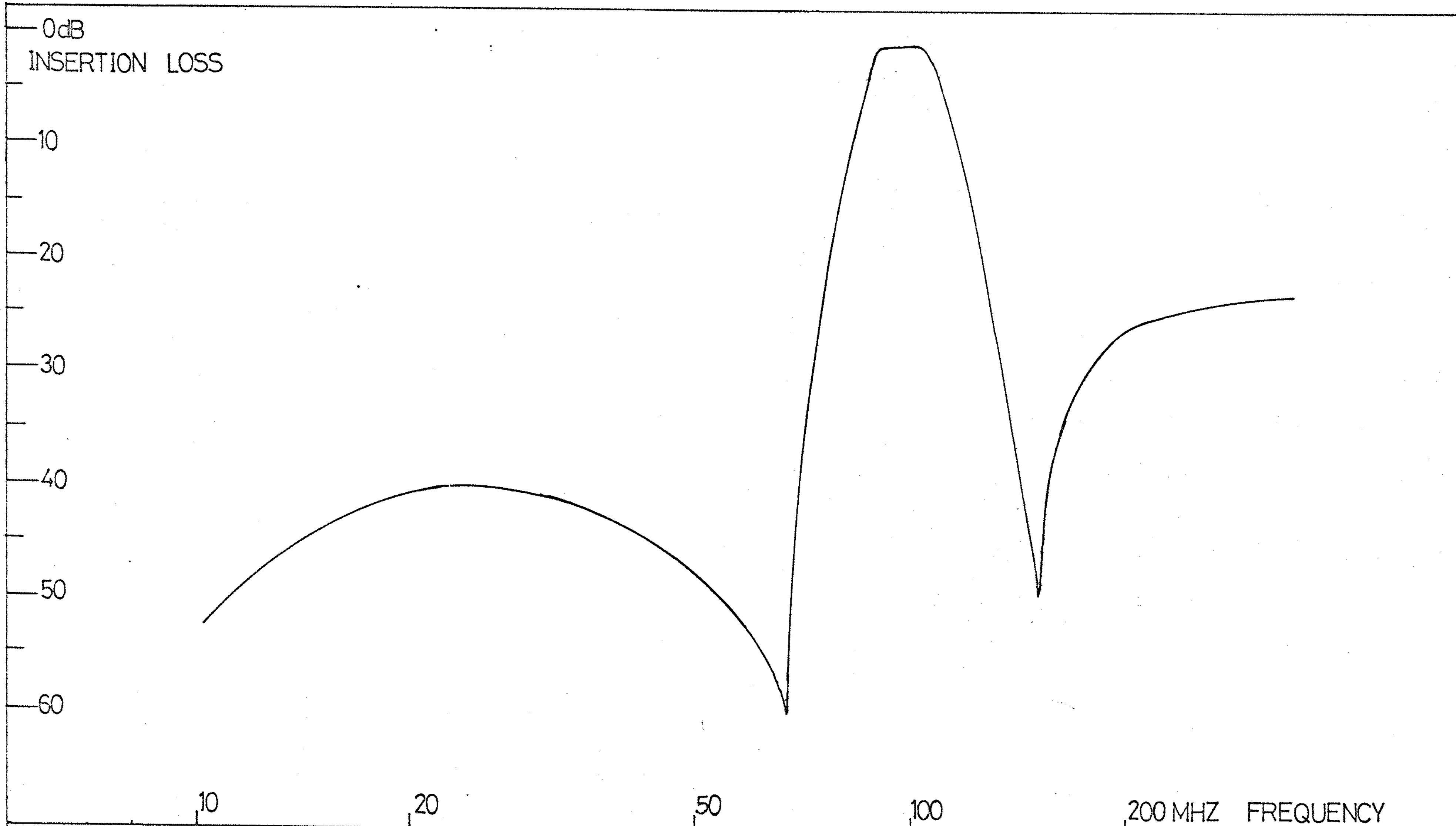
Amplitude error generated by the analyser itself is small and absolute error is cancelled during subtraction of interference levels. The remainder is due to the non-linearity of the analyser logarithmic response over the dynamic level range (∿55dB) and is at most[43] ±0.5dB.

Considering the above possible sources of error, and from practical experience from the system, results were repeatable ±2dB for the Ford Capri and ±1dB for the Earth Cone. The greatest error was with the Ford Capri as these measurements were dependent upon many indirect factors. It must be borne in mind that this is a day to day variation, for a series of results taken together repetitive accuracy is far greater.



LINEAR PHASE V.H.F. FILTER

FIG. 8·1



V.H.F. FILTER RESPONSE. INSERTION LOSS VS. FREQUENCY

FIG.8·2

CHAPTER 9

CONCLUSION

9.1 Overall Effect of Interference Suppressors upon the Ignition System

The effectiveness of a component is found by considering the suppression gained by its addition to the ignition system (see Appendices 2 and 3). Tables 9.1 and 9.2 are produced from these results and contain the percentage contribution for each interference source and suppressor. A summary is given in Table 9.3 which indicates the source most susceptible to suppression and the most effective suppressors to employ.

It is found that the relative distributor and spark plug interference levels vary with waveband and that suppression at the spark plug has a higher probability of being effective. In the latter case, a component placed immediately above the plug produces on average more suppression than one at the spark gap. A distributor suppressor placed on the coil side is more successful than on the plug side.

The performance of the SIPCON H.T. cable systems are difficult to analyse for the total suppression is small, and is non-existent for Long Wave.

There is little relationship between the Ford Capri and Earth Cone systems for Long and Medium wavebands. The V.H.F. waveband results are similar in that the dominance of interference sources and components are retained for both systems.

Appendices 2 and 3 contain information as to how successful suppression follows from one dominant source to another. A simple example for the Ford Capri is the suppression of distributor interference by only one component before action at the spark plug has any effect. A similar effect occurs for the Earth Cone (V.H.F) but here two distributor suppressors are necessary.

For certain combinations of suppressors it is possible to increase interference levels and to have both the distributor and spark plugs as apparently dominant sources. Also it is possible to find combinations which do not react until a key component is added.

Optimum Ford Capri and Earth Cone suppression combinations are given in Tables 6.1 and 6.2.

TABLE 9.1

FORD CAPRI RESULTS INDICATING DISTRIBUTOR AND SPARK PLUG SUPPRESSION

Combination	I			II			III		
Waveband	LW	MW	VHF	LW	MW	VHF	LW	MW	VHF
Total Suppression dB	264	356	180	278	326	222	0	90	6
Distributor %	55	58	51	45	47	47	-	38	33
Resistive Rotor %	63	62	54	69	54	52	-	71	0
Distributor Resistor %	37	38	46	31	46	48	-	29	100
Spark Plug %	45	42	49	55	53	55	-	62	67
Resistive Plug %	50	31	23	58	63	43	-	28	-50
Plugshield %	50	69	77	-	-	-	-	72	150
Plugboot %	-	-	-	42	37	57	-	-	-

Suppression Component combinations:

I - Wire H.T. cable (base). Resistive rotor, distributor resistors, resistive plugs, plugshields.

II - Wire H.T. cable (base). Resistive rotor, distributor resistors, resistive plugs, plugboots.

III - SIPCON H.T. cable (base). Resistive rotor, distributor resistors, resistive plugs, plugshields.

Wavebands:

L.W. - Long Wave V.H.F. - Band II

M.W. - Medium Wave

TABLE 9.2

EARTH CONE RESULTS INDICATING DISTRIBUTOR AND SPARK PLUG SUPPRESSION

Combination	I			II			III		
Waveband	LW	MW	VHF	LW	MW	VHF	LW	MW	VHF
Total Suppression dB	64	104	310	62	67	304	0	18	98
Distributor %	22	22	55	3	5	49	-	0	33
Resistive Rotor %	71	104	63	200	67	65	-	-	-38
Distributor Resistor %	29	-4	37	-100	33	35	-	-	138
Spark Plug %	78	78	45	97	95	51	-	100	67
Resistive Plug %	64	44	31	47	44	33	-	45	27
Plugshield %	36	56	69	-	-	-	-	55	73
Plugboot %	-	-	-	53	56	67	-	-	-

TABLE 9.3

A SUMMARY OF TABLES 9.1 AND 9.2. MAJOR INTERFERENCE SOURCES AND MOST SUCCESSFUL SUPPRESSORS

	Ford Capri			Earth Cone		
Combination	I	II	III	I	II	III
Distributor	x					
Resistive Rotor	x	x		x	x	
Distributor Resistor			x[B]			x
Spark Plug		x	x	x[A]	x	x
Resistive Plug		x[A]				
Plugshield	x		x	x[C]		x
Plugboot					x	

A - Except for V.H.F.

B - Except for M.W.

C - Except for L.W.

9.2 The Character of Interference Suppression

The time sequence of the individual sources of ignition interference is given in Section 3.3. From Chapters 6 and 7, and also Section 9.1, it is possible to arrange each source in the approximate order of relative significance:

1. Spark plug breakdown.*
2. Erratic H.T. arc at distributor and spark plug.*
3. Distributor gap breakdown.*
4. Extinction of arc at distributor and spark plug.*
5. Re-striking of distributor and spark plug arc.*
6. Contact breaker separation.
7. Initial H.T. voltage use.*
8. Contact breaker closure.

*Affected by H.T. suppression components.

To suppress interference in the most efficient manner, suppression components must be directed to each dominant source in turn. Interdependence would lead to indirect results. The capacitive and inductive positions of the arc discharge may require separate suppression components. Interference levels frequently appear in discrete levels, reference may be made to graphs 6.1 - 6.8. This is a practical indication of the success of suppression following from one dominant source to the other, while at the wrong source it has little effect.

It must be borne in mind that the dominant interference source, be it related to the distributor, spark plug or otherwise, may change with frequency[2]. This may not be due to the source characteristic itself, but to the surrounding (spectrum shaping) ignition and engine components. Evidence of this is seen in graphs 6.1 - 6.4 from the Ford Capri which are not exactly similar in characteristic for each of the three wavebands. The optimum suppression component combination for one waveband does not necessarily imply an interference minimum for the other two bands. A short series of experiments indicated that Long and Medium Wave results were valid up to the 5-10MHz region, higher frequencies appearing to follow suppression as found in the V.H.F. band.

The construction and layout of both vehicle ignition system and engine determines:

a. Total interference level.

b. Resonance and other frequency effects.

c. Suppression efficiency.

d. Interdependence of suppression.

For each vehicle within a particular model there is a small, but definite, difference of the above variables. When one considers the whole spectrum of motor vehicles currently available, the task of certainty of suppression is important. Results taken from the Ford Capri and Earth Cone systems refer to their own specific environment and cannot be referred to other vehicles with 100% confidence of success. Statistical analysis(55) of the results taken from several similar vehicles is necessary to ensure a satisfactory degree of confidence.

9.3 Possible New Form of Suppressed Ignition System

When considering the various methods of reduction of radio interference from car ignition systems, the use of the resistive H.T. lead appears to be the cheapest and the most reliable in results. However, this lead does not provide a complete resistive path for the ignition coil secondary circuit. There are still regions which remain of metal construction (see Section 3.3), e.g. mechanical connectors, spark plug centre rod, etc. The remaining metal parts decrease the effectiveness of suppression by producing a variation in the ignition circuit impedance which is a source of radiation. There is interaction between these discontinuities which enhances or reduces the radiative effect.

A solution would be to use an entirely resistive ignition system consisting of resistive materials chosen for specific characteristics for application in the various parts of the ignition system. Brief criteria would read as follows:

H.T. lead connectors	-	Resilient, medium temperature stable.
H.T. leads	-	Resilient, medium temperature stable.
Rotor	-	Resilient, stable sparking surface.
Spark plug centre rod	-	High temperature stable, stable sparking surface.
Distributor turrets	-	Resilient, stable sparking surface.

The common factor of these proposed materials is that they must retain their suppressive resistance under the variety of conditions experienced by the ignition system. Most forms of resistors, as used in conventional suppressors, are of the high stability carbon type, and are approximately the size of a normal ½watt resistor. The short length of these resistors decreases their suppression value at high frequencies(2), and any lengthening of the resistor substance would result in a fragile component.

A possible solution would be to use a resistive metal alloy, perhaps similar to 70Ni - 30Cr alloy(56) of resistivity $1.2 \times 10^{-4}\Omega$cm, but the component would have to use may turns of alloy wire to achieve the necessary resistance at the expense of capacitive and inductive effects. Materials science technology has produced a new spectrum of resistive polymers of varying qualities(57), e.g. vitreous carbon and carbon fibre. Vitreous carbon (resistivity $50 \times 10^{-4}\Omega$cm) is a carbon polymer prepared from phenolic resins from which the gaseous degradation products have been expelled. It exhibits superior mechanical qualities to other forms of carbon such as, graphite, pyrolytic graphite and electrode graphite. A much higher resistivity is also gained, making vitreous carbon feasible for use as the centre rod inside a spark plug to provide continuous suppression. A metal connection at the spark gap may be necessary to avoid excessive temperature deterioration and general wear.

Carbon fibres are well known as a constructional material in many industries and are made by heat treatment of organic textile fibres. A solid construction may be formed with the use of special resins so that the final construction is strong and resilient. The effective resistivity of the construction is low and depends upon the number of fibres in continuous contact along its length. Additional preparation is needed to raise the homogeneous impedance (e.g. production of short strands as in glass fibre with a resistive bonding resin). The finished material may be suitable to be moulded into the form of a distributor rotor for continuous suppression.

Conductive polymer/metal composites[58] consist of a high resistivity polymer ($10^{14}\Omega$cm resistivity) and a conductive filler (e.g. nickel) in such proportions to give a programmable resistivity in the range between $10^{-4} - 10^{1}\Omega$cm. It is thus easy to manufacture temperature stable resistors to any desirable resistance and reasonable dimensions.

Spark and high temperature effects may prove destructive to the resistive surfaces so that it will be desirable to use a stable metal coating on the electrode surfaces. Resistive suppression at the spark gap itself is crucial for the reduction of the capacitive discharge component, so that care must be taken to keep this protective coating to a minimum.

In Chapter 6, resistive H.T. leads were found to reduce interference received by the car tuner by 40dB when compared with wire H.T. leads in the worst case situation. When used with other standard ignition suppressors a maximum further suppression of 12dB may be attained. The efficiency of these extra suppressors is in doubt because of the inter-dependence mechanism and should be improved in most cases with a non-interactive system utilising continuous suppression.

APPENDIX 1

SUPPRESSION RESULTS. (Analysed in Chapter 6)

Appendix 1.1 Results from the Ford Capri System with A,B,C,D,E,F,G, and H as Variables.

Manufacturing cost £	Suppression Component Code								Suppression, dB		
	A	B	C	D	E	F	G	H	L.W.	M.W.	V.H.F.
0.14	1					1	1		0	0	0
0.54	1					1		1	0	-4	0
0.00	1				1		1		+40	+45	+24
0.40	1				1			1	+35	+40	+22
0.17		1				1	1		0	0	0
0.57		1				1		1	0	-4	0
0.03		1			1		1		+35	+40	+20
0.43		1			1			1	+16	+30	+14
0.86	1			1		1	1		0	0	0
1.26	1			1		1		1	0	-2	0
0.72	1			1	1		1		+35	+40	+20
1.12	1			1	1			1	+22	+30	+14
0.89		1		1		1	1		0	0	0
1.29		1		1		1		1	0	-10	0
0.75		1		1	1		1		+35	+40	+22
1.15		1		1	1			1	+10	+18	+10
1.38	1		1			1	1		0	-2	0
1.78	1		1			1		1	0	-4	0
1.24	1		1		1		1		+35	+40	+18
1.64	1		1		1			1	+35	+40	+15
1.41		1	1			1	1		0	-10	0
1.81		1	1			1		1	0	-10	-2
1.27		1	1		1		1		+16	+18	+6
1.67		1	1		1			1	+16	+18	+10
2.10	1		1	1		1	1		0	-10	-2
2.50	1		1	1		1		1	0	-4	0
1.96	1		1	1	1		1		+24	+30	+10
2.36	1		1	1	1			1	+22	+30	+10
2.13		1	1	1		1	1		0	-10	-2

Manufacturing cost £	Suppression Component Code								Suppression, dB		
	A	B	C	D	E	F	G	H	L.W.	M.W.	V.H.F.
2.53		1	1	1		1		1	0	−10	0
1.99		1	1	1	1		1		+12	+2	−2
2.39		1	1	1	1			1	+16	+2	+3

Appendix 1.2 Results from the Earth Cone System with A,B,C,D,E,F,G and H as Variables

Manufacturing cost £	Suppression Component Code								Suppression, dB		
	A	B	C	D	E	F	G	H	L.W.	M.W.	V.H.F.
0.14	1					1	1		0	0	0
0.54	1					1		1	0	-2	-2
0.00	1				1		1		+6	+5	+26
0.40	1				1			1	0	0	+16
0.17		1				1	1		0	0	0
0.57		1				1		1	0	0	-3
0.03		1			1		1		+5	+3	+24
0.43		1			1			1	0	-4	+4
0.86	1			1		1	1		0	0	0
1.26	1			1		1		1	0	-2	-14
0.72	1			1	1		1		+4	+6	+24
1.12	1			1	1			1	0	-2	+13
0.89		1		1		1	1		0	0	0
1.29		1		1		1		1	0	0	-6
0.75		1		1	1		1		+5	0	0
1.15		1		1	1			1	0	-2	0
1.38	1		1			1	1		0	0	-8
1.78	1		1			1		1	0	-2	-4
1.24	1		1		1		1		+3	-2	+10
1.64	1		1		1			1	0	-5	+12
1.41		1	1			1	1		0	-2	-6
1.81		1	1			1		1	0	-2	-6
1.27		1	1		1		1		0	-5	-10
1.67		1	1		1			1	-2	-10	-4
2.10	1		1	1		1	1		0	-2	-18
2.50	1		1	1		1		1	0	-2	-16
1.96	1		1	1	1		1		+3	-2	0
2.36	1		1	1	1			1	0	-5	0
2.13		1	1	1		1	1		0	-2	-8
2.53		1	1	1		1		1	0	-2	-9
1.99		1	1	1	1		1		0	-5	-20
2.39		1	1	1	1			1	-2	-6	-2

Appendix 1.3 Plugboot Results for Ford Capri and Earth Cone. (Wire H.T. system and plugboots with other components except plugshields).

Appendix 1.3.1 Results from Ford Capri System

Manufacturing cost £	Suppression Component Code					Waveband		
	A	B	D	G	H	L.W.	M.W.	V.H.F.
0.28	1			1		+28	+35	+18
0.68	1				1	+28	+35	+18
0.31		1		1		+14	+26	+8
0.71		1			1	+12	+18	+6
1.00	1		1	1		+28	+32	+8
1.40	1		1		1	+24	+26	+6
1.03		1	1	1		+15	+26	0
1.43		1	1		1	0	0	0

Appendix 1.3.2 Results from Earth Cone System

Manufacturing cost £	Suppression Component Code					Waveband		
	A	B	D	G	H	L.W.	M.W.	V.H.F.
0.28	1			1		0	-4	+8
0.68	1				1	-2	-6	+10
0.31		1		1		-2	-2	-1
0.71		1			1	-4	-2	-6
1.00	1		1	1		0	-4	+2
1.40	1		1		1	-2	-4	+4
1.03		1	1	1		0	0	-2
1.43		1	1		1	-2	-4	-12

APPENDIX 2

SUPPRESSION RESULTS OBTAINED BY THE ADDITION OF A SUPPRESSOR TO THE IGNITION SYSTEM OF THE FORD CAPRI.

Whenever a suppression component is added to the ignition system, the change in interference level is recorded using the original system as a base. This method of analysis is different to that of Appendix 1 in that the reference system is a variable. The manufacturing cost is used to identify the suppressor and the suppression combination. The resultant tables are divided into two for suppression obtained from the distributor and spark plug, and are further analysed in Chapter 9. Where a positive suppression is found, the additional component is detrimental.

Appendix 2.1 Results with A,B,C,D,G, and H as Variables using the Wire H.T. System.

Manufacturing cost £	Distributor Suppression, dB			Spark Plug Suppression, dB		
	L.W.	M.W.	V.H.F.	L.W.	M.W.	V.H.F.
0.00 - 0.40				5	5	2
0.00 - 0.03	5	5	4			
0.00 - 0.72	5	5	4			
0.00 - 1.24				5	5	6
0.03 - 0.43				19	10	6
0.03 - 0.75	0	0	+2			
0.03 - 1.27				19	22	14
0.40 - 0.43	19	10	8			
0.40 - 1.12	13	10	8			
0.40 - 1.64				0	0	7
0.43 - 1.15	6	12	4			
0.43 - 1.67				0	12	4
0.72 - 1.12				13	10	6
0.72 - 1.96				11	10	10
0.72 - 0.75	0	0	+2			
0.75 - 1.15				25	22	12
0.75 - 1.99				23	38	24
1.12 - 1.15	12	12	4			
1.12 - 2.36				0	0	+4
1.15 - 2.39				+6	16	7
1.24 - 1.64				0	0	3
1.24 - 1.27	19	22	12			
1.24 - 1.96	11	10	8			
1.27 - 1.67				0	0	+4
1.27 - 1.99	4	16	8			
1.64 - 1.67	19	22	5			
1.64 - 2.36	13	10	5			
1.67 - 2.39	0	16	7			
1.96 - 2.36				2	0	0
1.96 - 1.99	12	28	12			
1.99 - 2.39				+4	0	+5
2.36 - 2.39	6	28	7	+4	0	+5
Total source suppression, dB	144	206	92	120	150	88

Appendix 2.2 Results with A,B,D,G,H and I as Variables using the Wire H.T. System.

Manufacturing cost £	Distributor Suppression, dB			Spark Plug Suppression, dB		
	L.W.	M.W.	V.H.F.	L.W.	M.W.	V.H.F.
0.00 - 0.40				5	5	2
0.00 - 0.03	5	5	4			
0.00 - 0.72	5	5	4			
0.00 - 0.28				12	10	6
0.03 - 0.43				19	10	6
0.03 - 0.75	0	0	+2			
0.03 - 0.31				21	14	12
0.40 - 0.43	19	10	8			
0.40 - 1.12	13	10	8			
0.40 - 0.68				7	5	4
0.43 - 1.15	6	12	4			
0.43 - 0.71				4	12	8
0.72 - 1.12				13	10	6
0.72 - 1.00				7	8	12
0.72 - 0.75	0	0	+2			
0.75 - 1.15				15	22	12
0.75 - 1.03				20	14	22
1.12 - 1.15	12	12	4			
1.12 - 1.40				+2	4	8
1.15 - 1.43				10	18	10
0.28 - 0.68				0	0	0
0.28 - 0.31	14	9	10			
0.28 - 1.00	0	3	10			
0.31 - 0.71				2	8	2
0.31 - 1.03	+1	0	6			
0.68 - 0.71	0	3	10			
0.68 - 1.40	4	9	12			
0.71 - 1.43	12	18	6			
1.00 - 1.40				4	6	2
1.00 - 1.03	13	6	8			
1.03 - 1.43				15	26	0
1.40 - 1.43	24	26	6			
Total source suppression, dB	126	154	100	152	172	122

Appendix 2.3 <u>Results with A,B,C,D,G, and H as Variables using the SIPCON H.T. System.</u>

Manufacturing cost £	Distributor Suppression, dB			Spark Plug Suppression, dB		
	L.W.	M.W.	V.H.F.	L.W.	M.W.	V.H.F.
0.14 - 0.54				0	4	0
0.14 - 0.17	0	0	0			
0.14 - 0.86	0	0	0			
0.14 - 1.38				0	2	0
0.17 - 0.57				0	4	0
0.17 - 0.89	0	0	0			
0.17 - 1.41				0	10	0
0.54 - 0.57	0	0	0			
0.54 - 1.26	0	+2	0			
0.54 - 1.78				0	0	0
0.57 - 1.29	0	6	0			
0.57 - 1.81				0	6	0
0.86 - 1.26				0	2	0
0.86 - 2.10				0	10	2
0.86 - 0.89	0	0	0			
0.86 - 1.29				0	10	0
0.86 - 2.13				0	10	2
1.26 - 1.29	0	8	0			
1.26 - 2.50				0	2	0
1.29 - 2.53				0	0	2
1.38 - 1.78				0	2	0
1.38 - 1.41	0	8	0			
1.38 - 2.10	0	8	2			
1.41 - 1.81				0	0	2
1.41 - 2.13	0	0	2			
1.78 - 1.81	0	6	2			
1.78 - 2.50	0	0	0			
1.81 - 2.53	0	0	+2			
2.10 - 2.50				0	+6	+2
2.10 - 2.13	0	0	0			
2.13 - 2.53				0	0	+2
2.50 - 2.53	0	0	+2			
Total source suppression, dB	0	34	2	0	54	4

APPENDIX 3

SUPPRESSION RESULTS OBTAINED BY THE ADDITION OF A SUPPRESSOR TO THE IGNITION SYSTEM OF THE EARTH CONE.

The construction of this Appendix is similar to that of Appendix 2.

Appendix 3.1 Results with A,B,C,D,G, and H as Variables using the Wire H.T. System.

Manufacturing cost £	Distributor Suppression, dB			Spark Plug Suppression, dB		
	L.W.	M.W.	V.H.F.	L.W.	M.W.	V.H.F.
0.00 - 0.40				6	5	10
0.00 - 0.03	1	2	2			
0.00 - 0.72	2	0	2			
0.00 - 1.24				3	7	16
0.03 - 0.43				5	7	20
0.03 - 0.75	0	3	24			
0.03 - 1.27				5	8	34
0.40 - 0.43	0	4	12			
0.40 - 1.12	0	2	3			
0.40 - 1.64				0	5	4
0.43 - 1.15	0	+2	4			
0.43 - 1.67				2	6	8
0.72 - 1.12				4	8	11
0.72 - 1.96				1	8	24
0.72 - 0.75	+1	6	24			
0.75 - 1.15				5	2	0
0.75 - 1.99				5	5	20
1.12 - 1.15	0	0	13			
1.12 - 2.36				0	3	13
1.15 - 2.39				2	4	2
1.24 - 1.64				3	3	+2
1.24 - 1.27	3	3	20			
1.24 - 1.96	0	0	10			
1.27 - 1.67				2	5	+6

Manufacturing cost £	Distributor Suppression, dB			Spark Plug Suppression, dB		
	L.W.	M.W.	V.H.F.	L.W.	M.W.	V.H.F.
1.27 - 1.99	0	0	10			
1.64 - 1.67	2	5	16			
1.64 - 2.36	0	0	12			
1.67 - 2.39	2	+4	+12			
1.96 - 2.36				5	4	2
1.96 - 1.99	3	3	20			
1.99 - 2.39				2	1	+18
2.36 - 2.39	2	1	2			
Total source suppression, dB	14	23	172	50	81	138

Appendix 3.2 <u>Results with A,B,D,G,H and I as Variables using the Wire H.T. System.</u>

Manufacturing cost £	Distributor Suppression, dB			Spark Plug Suppression, dB		
	L.W.	M.W.	V.H.F.	L.W.	M.W.	V.H.F.
0.00 - 0.40				6	5	10
0.00 - 0.03	1	2	2			
0.00 - 0.72	2	0	2			
0.00 - 0.28				6	9	18
0.03 - 0.43				5	7	20
0.03 - 0.75	0	3	24			
0.03 - 0.31				7	5	25
0.40 - 0.43	0	4	12			
0.40 - 1.12	0	2	3			
0.40 - 0.68				2	6	6
0.43 - 1.15	0	+2	4			
0.43 - 0.71				4	2	10
0.72 - 1.12				4	8	11
0.72 - 1.00				4	10	22
0.72 - 0.75	+1	6	24			
0.75 - 1.15				5	2	0
0.75 - 1.03				5	0	2
1.12 - 1.15	0	0	13			
1.12 - 1.40				2	2	9
1.15 - 1.43				2	2	12
0.28 - 0.68				2	2	+2
0.28 - 0.31	2	+2	9			
0.28 - 1.00	0	0	6			
0.31 - 0.71				2	0	5
0.31 - 1.03	+2	+2	1			
0.68 - 0.71	2	+4	16			
0.68 - 1.40	0	+2	6			
0.71 - 1.43	+2	2	6			
1.00 - 1.40				2	0	+2
1.00 - 1.03	0	+4	4			
1.03 - 1.43				2	4	10
1.40 - 1.43	0	0	16			
Total source suppression	2	3	148	60	64	156

Appendix 3.3 Results with A,B,C,D,G, and H as Variables using the SIPCON H.T. System.

Manufacturing cost £	Distributor Suppression, dB			Spark Plug Suppression, dB		
	L.W.	M.W.	V.H.F.	L.W.	M.W.	V.H.F.
0.14 - 0.54				0	2	2
0.14 - 0.17	0	0	0			
0.14 - 0.86	0	0	0			
0.14 - 1.38				0	0	8
0.17 - 0.57				0	0	3
0.17 - 0.89	0	0	0			
0.17 - 1.41				0	2	6
0.54 - 0.57	0	+2	1			
0.54 - 1.26	0	0	12			
0.54 - 1.78				0	0	2
0.57 - 1.29	0	0	3			
0.57 - 1.81				0	2	1
0.86 - 1.26				0	2	14
0.86 - 2.10				0	2	18
0.86 - 0.89	0	0	0			
0.89 - 1.29				0	0	6
0.89 - 2.13				0	2	8
1.26 - 1.29	0	+2	+8			
1.26 - 2.50				0	0	2
1.29 - 2.53				0	2	3
1.38 - 1.78				0	2	+4
1.38 - 1.41	0	2	+2			
1.38 - 2.10	0	2	10			
1.41 - 1.81				0	2	+2
1.41 - 2.13	0	0	2			
1.78 - 1.81	0	0	0			
1.78 - 2.50	0	0	12			
1.81 - 2.53	0	0	5			
2.10 - 2.50				0	0	+2
2.10 - 2.13	0	0	+10			
2.13 - 2.53				0	0	1
2.50 - 2.53	0	0	7			
Total source suppression	0	0	32	0	18	66

APPENDIX 4

V.H.F. FILTER DESIGN PROCEDURE[53,59]

The following specifications are required:

1. Phase ripple 0.5° (equi-ripple).
2. Centre frequency fm = 98MHz.
3. 3dB bandwidth $\Delta f \approx$ 20MHz.
4. Equal inductances for ease of implementation.
5. Capacitive coupling.
6. Fourth order response for adequate rejection characteristics.

Reference is made to fig. 8.1 for filter component identification.

It was found that inductions of inductance 0.103μH were easily produced from a three turn, 16 s.w.g., 0.6cm diameter coil. Each turn is spaced by the wire diameter.

The tabulated[53] values for the filter are given as:

$q_1 = 0.4934$

$q_n = 0.7182 = q_4$

$k_{12} = 1.6320$

$k_{23} = 0.7181$

$k_{34} = 0.7391$

De-normalisation is given by the following equation:

$$fm^2 = \frac{1}{Ci\ Li 4\pi^2} \quad \text{(Ci is the nodal capacitance)} \qquad (1)$$

$$C_{12} = \frac{\Delta f}{fm} k_{12}\ Ci\ , \quad C_{23} = \frac{\Delta f}{fm}\ k_{23}\ Ci\ , \text{ etc.}$$

(C_{12}, etc. are the coupling capacitances) (2)

$$\text{Filter Q factor} = \frac{R_1}{2\pi\ Li\ fo\ q_1} = \frac{R_2}{2\pi\ Li\ fo\ q_n} \tag{3}$$

(R_1 and R_2 are the input and output impedances respectively)

$$Ci_1 = Ci - C_{12} \tag{4}$$

$$Ci_2 = Ci - C_{12} - C$$

$$Ci_3 = Ci - C_{23} - C_{34} \tag{5}$$

$$Ci_4 = Ci - C_{34} \tag{6}$$

(Ci_1, etc., are the tuning capacitances in parallel with Li).

From equation (1), Ci is calculated to be 24.59pF.

The total filter Q must be approximately 5. If we choose a convenient value of 200Ω for R_2 , the Q factor is calculated from equation (3) to be approximately 4.3. This leads to a value of 137.4Ω for R_1 , and 22.8MHz for Δf.

Direct substitution into the above equations leads to the coupling and tuning capacitance values.

REFERENCES

1. G.E.C. Wedlake. S.O.S., The Story of Radio Communication.

2. R.A. Shepherd, J.C. Gaddie, D.L. Nielson. New Techniques for Suppression of Automobile Ignition Noise. I.E.E.E. Vehic. Tech. VT-25 No. 1 Feb. 1976.

3. F.L.H.M. Stumpers. Electromagnetic Compatibility. Bull. A.S.E./U.C.S. 65(1974)16.

4. J. Germain. Extender Operation - Ignition Noise Suppression Built Right into Radio Receiver. I.R.E. Trans. Vehic. Comms. VC-11 1962.

5. Ford Motor Company - private communication.

6. A.G. Tettman, B.J. Seaman. Visits to J. Lucas, Birmingham (28/9/72) and to Cologne (5/6/72). Ford Motor Company Report.

7. Giving Two Way Radio its Voice. Champion Spark Plug Corporation Publication.

8. Automobile Radio Interference Suppression - Interauto Publication.

9. Ford Audio Manual. In-car Entertainment Series.

10. G.D. Roessler. The EMI/RFI Knitted Wire Mesh Basket. Frequency Technology. March 1969.

11. A.W. Judge. Modern Equipment for Automobiles.

12. J.H. Pluck. A Simple Approach to R.F. Suppression and Shielding. Proc. I.R.E.E. Aust. 1970.

13. Teknit Catalogue Design Guide. E.M. Shielding Products, Electrically Conductive Materials and Components.

14. W. Topping. Tackle the tackle. Good Motoring. May 1976.

15. BERU Catalogues 733 and 734.

16. J.M. Waldron. Vehicle Generated Electromagnetic Interference. Proc. I.R.E.E. Aust. Aug. 1970.

17. A.S. McLachlan, J.H. Ainley, R.J. Harry. Radio Interference - A Review. Wireless World 1974.

18. G.L. Maxam, O.T. McCarter, D.E. Schofield. Electromagnetic Interference and the Automobile. S.A.E. Paper 730129.

19. D.W. Morris. Conformity with Statutory Regulations Relating to Radio Interference from Road Vehicles. I.M.E. Symp. Automobile Electrical Equipment 1972.

20. I.E.E.E. Standard No. 263. Measurement of Radio Noise, Generated by Motor Vehicles, and Affecting Mobile Communications Receivers in the Frequency Range 25-1000 Mc/s. I.E.E.E. Trans. Vehic. Comms. Vol. VC-15 Oct. 1966.

21. A.J. Rosa. H.F. and V.H.F. Automobile Ignition Measurements. I.E.E.E. EMC. Symp. Session IIE. 1970.

22. F. Bauer. International Efforts to Control Radio Spectrum Pollution from Motor Vehicles. S.A.E. Paper 730058.

23. A.H. Ball, W. Nethercot. Radio Interference from Ignition Systems. I.E.E. Paper No. 3550E May 1961.

24. Ford Motor Company Reports EQ1039 and EQ1093.

25. R.J. Matheson. Instrumentation Problems Encountered making Man-made Electromagnetic Noise Measurements for Predicting Communications System Performance. I.E.E.E. EMC. Vol. 12. No. 4. 1970.

26. H.P. Hsu, R.M. Storwick, D.C. Schlick, G.L. Maxam. Measured Amplitude Distribution of Automobile Ignition Noise. I.E.E.E. EMC. Vol. 16. No. 2. 1974.

27. R.B. Schulz. A.P.D. of V-8 Ignition Emanations. I.E.E.E. EMC. Vol. 16. No. 2. 1974.

28. E. Coute. Measurement and Statistical Processing Technique for Impulse Noise Generated in Motor Vehicle Ignition Systems. Conf. Dig. Pap. Europ. Conf. Electrotech. 1974.

29. E. Jacobs. Broadband Noise: Its Physical Nature and Measurement. I.E.E.E. EMC. Symp. Rec. 1970.

30. Hewlett Packard Application Note 150-2.

31. R.B. Andrews. An Impulse Spectral Intensity Measurement System. I.E.E.E. Vol. I.M. 15 No. 4. Dec. 1966.

32 J.R. Walkinson. Electronic Ignition Techniques Wireless World July 1974.

33. R.T. Lovrenich and J.T. Hardin. Electrical to Thermal Conversion in Spark Ignition. S.A.E. Paper 670114.

34. J.P. Norbye. Hot Sparks Today and Programmed Hot Sparks Tomorrow Road and Track. May 1976.

35. J.T. Hardin, N.F. Sieja. Application Engineering of a Maintenance Free Capacitor Discharge Ignition System. S.A.E. Paper 720008.

36. P.C. Kline. Some Factors to Consider in the Design and Application of Automobile Ignition Systems. S.A.E. Paper 700083.

37. M.J. Werson, E.M. Stafford. A Fresh Look at Spark Ignition in a Petrol Engine. Journal of Automotive Engineering. Feb. 1974.

38. Meek, Craggs. Electrical Breakdown in Gases.

39. J.R. Neubauer. Vehicular Interference Radiation Measurement Technique. I.E.E.E. Vehic. Comms. Vol. VC-15. No. 2. Oct. 1966.

40. R.W.P. King. Transmission Line Theory.

41. F. Mayer. Antiference Wires, Cables and Filters. I.E.E.E. EMC. Vol. 8. No. 3. Sept. 1968.
Also, R.F.I. Suppression Components: State of the art; New Developments. I.E.E.E. EMC. Vol. 18. 1976.

42. R.R. Burgett, R.E. Massol, D.R. Van uum. Relationship Between Spark Plugs and Engine Radiated Electromagnetic Interference. S.A.E. Paper 74011.

43. TF2370. 110MHz Spectrum Analyser Operating Manual. No. EBS2370-015 Marconi Instruments.

44. Hewlett Packard Application Note 142.

45. R.J. Mohr. Induced Noise in the Reference Ground of Electronic Systems. E.D.N. July 1969.

46. Motorola Application Note AN247A.

47. See references 6 and 24.

48. A.H. Ball, W. Nethercote. Radio Interference from Ignition Systems. I.E.E.E. Paper No. 3550E May 1961.

49. R.A. Shepherd. Measurements of Amplitude Probability Distributions and Power of Automotive Ignition Noise at H.F. I.E.E.E. Vehic. Tech. V.T.23 No. 3. Aug. 1974.

50. E. Fromy. Earth Current Method for Laboratory Measurement for Power Radiated in the Range 30-1000MHz. I.E.E.E. EMC. REC. 10th.
(Also, La Mésure en Laboratoire des Rayonnements Radioelectriques des Appareils Electriques Perturbateurs par la Methode de Courant de Masse. Révue Génerale de l'Electricite. May 1961).

51. A. de Jong. Methods for Measuring Radio Interference on Frequencies above 30MHz. I.E.E.E. EMC. Symp. Res. 11th.

52. H.P. Hsu, D.C. Schlick. Effect of Distributor Gap on Radiated Ignition Interference. I.E.E.E. EMC. Symp. 11th.

53. De Verl S. Humphreys. The Analysis, Design and Synthesis of Electrical Filters. (S.469).

54. H. Melcher. Series Spark Gap FS/O for Coil Ignition Systems in Motor Vehicles. Siemens Rev. Vol. 41. No. 11. Nov. 1974.

55. C.I.S.P.R. Recommendation No. 18/2, Appendix II. Statistical Analysis of the Results of Measurement.

56. C.D. Starr. State of the Act of Electrical Resistance Conductors Parts 1 and 2. Nos. 3 and 4. Insulation 1969.

57. F.C. Cowlard. A New Form of Carbon. Component Technology. Vol. 4. No. 6. Feb. 1971.

58. R.D. Conneliussen, R.P. Vusy. Conductive/Polymer Metal Composites. Composite Matter in Engineering. May 1972.

59. A.I. Zverev. Handbook of Filter Synthesis.

LIST OF TABLES

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